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SUBJECTIVE ASSESSMENT OF CHURCH ACOUSTICS

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Abstract
The relations between subjective assessment of listening conditions in churches and objective acoustic parameters were investigated. Measurements of binaural impulse responses were made in several churches. A listening room was realized for listening tests using a stereo-dipole configuration. Measured binaural IRs were cross-talk cancelled and auralized with three anechoic motifs (classical symphonic, romantic symphonic and sacred choral music). A panel of subjects performed paired comparison indicating their preferences. Acoustical aspects that influence subjective preference were identified by factor analysis.

INTRODUCTION

Churches are acoustically complex. Their dimensions and shape vary from simple auditorium-like churches to complicated baroque structures with curved walls, side chapels, vaults and domes. The range of sounds during liturgical service varies (speech, organ music, singing). Concerts also take place in churches, especially in Italy where adequate performance spaces lack.

The reverberation in most churches requires PA systems to render the spoken word sufficiently intelligible. Organ and choral music requiring longer reverberation are well suited in churches. Sacred music benefits from the mood created by church acoustics. Critical listening conditions are observed when orchestral music is played in churches, reverberation being higher than the ideal. But musicians and listeners often give positive comments. Psychological, musical and acoustic aspects may contribute to a positive judgment.

Relations between geometry, acoustics, and subjective preference in concert halls and opera houses have been investigated by listening tests involving several subjects. Techniques include on-site listening tests [1], simulated sound fields [2], and recording music in concert halls and playing it back [3]. One subjective investigation for churches [4] involved subjects attending live performances. Comparisons between different places, even with the same listeners and musicians, are arduous because listeners have a short acoustic memory. The judgment is also influenced by how musicians play. Another way [3] is to replace the orchestra by loudspeakers playing the same anechoic motif, record it with binaural microphones, and reproduce it using loudspeakers with cross-talk compensation. Halls are ranked by paired comparison.

The procedure presented in [3] was applied in the present study with some innovations, providing relations between subjective preferences and physical parameters measured in Italian churches. High quality binaural impulse responses (BIRs) were collected in many churches using equalized sweeps radiated by an omni-directional source and recorded with a binaural head and torso. A subset of BIRs was convoluted with an anechoic motif and cross-talk filtered for transaural presentation with a stereo dipole speaker configuration.

THE ON-SITE SURVEY

Measurements complied with the ISO 3382 standard [5] and involved an omni-directional sound source made of twelve 120 mm loudspeakers (with frequency response 100 Hz to 16 kHz) mounted on a dodecahedron, together with an additional sub-woofer to cover frequencies below 100 Hz. A calibrated measurement chain with an omni-directional random incidence microphone (GRAS 40AR) measured the sound pressure levels. An MLS signal was used to get the calibrated impulse responses to obtain the relative sound pressure levels by comparison with the response obtained using the same measurement chain in a reverberant chamber. The length of the MLS sequences was chosen in order to avoid time-aliasing problems. Synchronous averaging over a minimum of 16 sequences reduced the effects of background noise.

High-quality impulse responses for auralization purposes and to calculate state-of-the-art acoustic parameters were collected by a B-format microphone (Soundifield Mk-V) and a binaural head and torso (B&K 4100D). The signal exciting the rooms was a constant envelope equalized sine sweep generated with MATLAB [6]. The sequence was of 21th order, passing from 44 Hz to 20 kHz in 40 s. After equalization the spectrum of the radiated sound was substantially flat from 50 Hz to 16 kHz with a total radiated power level (with pink noise) of 99.8dB. The signal was emitted and recorded using an Echo Layla 24 sound card. Room responses were recorded at a sampling rate of 48 kHz and 24 bit depth, obtaining after deconvolution high quality impulse responses with very low noise (the S/N ratio was generally higher than 60 dB even at the lowest frequencies).

Two sources were located in the chancel area (Fig. 1), one on the symmetry axis, on the edge of the presbytery area at least 2 m in front of the altar, and one off the axis, shifted at least 2 m backwards and 1/3 of the nave width sidewards. The source was 1.5 m above the floor. Nine receivers were used on average. In very large symmetrical churches the receivers were placed in one half, elsewhere they covered the floor uniformly.

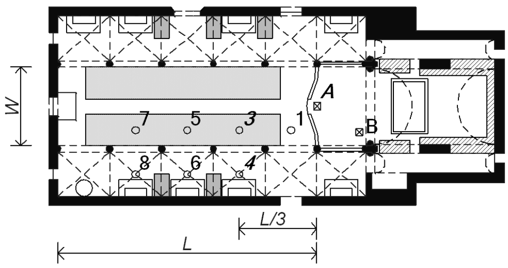

Figure 1 – Typical layout of source and receiver placement in churches

Microphones were placed 1.2 m above the floor. The B-format microphone pointed with the X axis toward the sound source, while the binaural head was placed on the seat facing the chancel area (with no head rotation). The whole set of IRs was used to calculate acoustical parameters according to the ISO 3382 standard [5]. A sample was chosen for the test. For each church one source-receiver combination was chosen, with the source at the center and the receiver in the nave at about 1/3 of the distance *L* between the source and the back wall (receiver 3). In churches with a complex cross-section or considerable width, an additional receiver was placed near the side wall at *L*/3 from the source (receiver 4).

More than twenty churches were surveyed. They differ in style, size, typology and obviously in acoustics (reverberation time varying from 2 s to 12 s). Some churches deviated a lot from the others, and in other cases there were strong similarities. We took into account a set of nine churches. In one of them an additional receiver was thought to be necessary to represent the variations in the lateral reflected energy, so a total of 10 different IRs were finally considered.

THE LISTENING TEST

During the survey both B-format and binaural IRs were collected, so a large variety of auralization techniques were available. Binaural reproduction using headphones or transaural presentation, multichannel presentation of the Ambisonics decoded B-format signal, or a combination of them (Ambiophonics). At this stage only transaural presentation of binaural signals was employed. It allowed realistic reproduction of the sound field by using two channels only. To get the best virtual image of the churches ensuring robustness with respect to head movement, the “stereo dipole” configuration [7] was used. Even though a wider span of about 30° might improve the reproduction of acoustic parameters [8], the classical configuration with two closely spaced loudspeakers, spanning an angle of 10° as seen by the listener, was preferred.

Signals radiated by the loudspeakers had to be cross-talk cancelled to remove the part of the sound that reaches the right ear from the left loudspeaker and vice versa. Thus each listener’s ear receives the corresponding signal recorded by the binaural dummy head. The cross-talk cancellation is done by convolution of the two binaural signals with a set of two (if the loudspeaker setup is perfectly symmetrical) or four (in the general case) inverse filters. The latter may be conveniently obtained by inverting the IRs measured in the listening room using a frequency-domain deconvolution method with regularization to prevent excessive boost at the frequency range extremes [9]. This technique is particularly successful because when the binaural head used to get the listening room IRs is the same used during the on site survey, the inverse filters manage to cancel out a great part of the microphone-dependent spatial effects, leaving each listener to hear with "his own ears" [9]. The auralized materials were adjusted to a normalized level of 70 dB, because the listening level may influence preferences [3].

Three different signals were used during the listening test. The excerpts, lasting for about 30 s, were taken from the first movement of the Symphony N. 4 in E-flat major by Bruckner, the Ouverture from Mozart's *Nozze di Figaro*, and the Gregorian Chant *Pange Lingua* in Frygian mode.

The room was made as dry as to allow reproduction of auralized material, following recommendation ITU-R BS.1116-1 [10] when possible. Walls were finished with a pyramidal melamine resin panel, mounted at a variable distance from the wall to increase low frequency absorption. The perforated gypsum panel ceiling had additional suspended pyramidal panels. The wood floor on joists was covered with a thick carpet. The room had a flat frequency response and a reverberation time of 0.09 s at medium frequencies, decreasing to 0.05 s at 8 kHz. Below 250 Hz the reverberation time grows to 0.35 s at 63 Hz. The room was acoustically isolated. The room was quasi-rectangular with internal dimensions roughly 3.70×2.50 m (Fig. 2). The floor area is about one third of the area suggested by the ITU recommendation for multichannel reproduction, but the room receives one listener at a time, so the dimension is acceptable. The two loudspeakers (Yamaha MSP5) have a flat frequency response from 60 Hz to 30 kHz and are placed on a stand in front of the wall with a span of 10° as seen by the listener. The level of the speakers was aligned at the center of the listener position.

Three listening tests have been performed with respectively 27, 40 and 50 persons. Noone had experience with artificial head recordings, but many of them were critical listeners of music. A majority of subjects played an instrument or studied music. In line with ITU-R 1116-1 [10] listeners were trained before the test. The cross-talk system was checked with pink noise sent at the left, the right and finally both ears (centering the monophonic sound image). Listeners found a comfortable position to localize the sounds and avoided large head movements causing localization changes. Listeners were then exposed to the sound material and the computer interface. They were invited to focus on the effect of the room rather than musical details, to share their sensations and discuss the differences they detected.

Churches were graded by paired comparison of the auralized sounds. Differences often being subtle, the test relied on short-term memory, comparing two churches at a time. We did not adopt the double-blind triple-stimulus technique because no bias-free reference could be selected. To ease comparison and use the short-term memory effectively, a near-instantaneous switching between stimuli was allowed. The subject controlled the test with a graphical interface based on the LISE environment [11], modified to allow switching between signals, interruption, and to

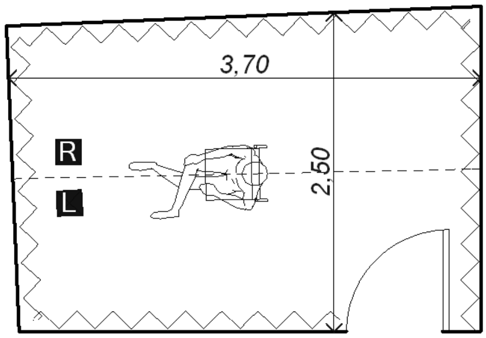

Figure 2 – Schematic plan of the listening room

choose where to listen. Stimuli were given randomly without repetition. Subjects expressed their preference or lack of such. To reduce circular error rates [12], they were not forced to choose. After comparison the preferred signal received a +1 score, the other –1. No preference gave a double zero score. Results were saved in a matrix whose entries indicate how many times a church has been preferred by a listener.

RESULTS

A subject reliability screening was made after the test. To identify unreliable listeners a circular error rate (CER) was considered. A circular error occurs when sound A is preferred to sound B, B to C, and C to A. Circular errors may indicate listener inaccuracy or change of assessment criteria. Since these errors were not eliminated by allowing lack of preference, they were assumed as a reliability measure. Listeners with CER above 25% were considered to be unreliable and their results discarded.

Geometrical parameters include volume, floor area, source-receiver distance, average nave height and width measured at the receiver position. Acoustical parameters include multi-octave band averages of T_{30}, *EDT*, and *Ts*, C_{80}, *LF* and 1–$IACC_{80}$. Spectral balance was taken into account by calculating bass and treble ratios (*BR*, *TR*) using *EDT* values, together with their ratio *BR*/*TR*. Strength related parameters were not included in the analysis because the reproduced signals were normalized. Many parameters were strongly correlated. The number of parameters to be included in the analysis was therefore reduced to avoid redundancy (Table 1).

The preference scores of the tests were subject to linear factor analysis. The analyses yielded a factor of exceptional importance explaining between 45 and 56% of the variance. A second factor explained between 16 and 23%. The remaining factors all explain less than 10% and shall not be considered. Individual factor weights are conveniently represented in two-dimensional *preference spaces* (Fig. 4-6). Each listener is represented by a point. Projected onto one of the axes it indicates the individual weight given to the corresponding factor. No consensus factor appears, but in all three cases it is seen that a clear majority gives a positive weight to the main factor.

It is now interesting to analyze which objective parameters contribute to the factors obtained by the factor analysis. There are not many significant correlations between physical parameters and the second factor, whose importance remains unclear. We observe that the clarity parameter C_{80} has a strong positive correlation with the first factor in all cases. Reverberation parameters are negatively correlated to the main factor and strongly clustered, although the significance varies. In fact, in the first case the correlation is low, indicating a substantial indifference of the listeners towards this parameter, while in the other cases it is strongly correlated. Finally the spatial parameters and the distance from the source are also negatively correlated with the main explaining factor, and somewhat clustered. Other parameters appear to be less important, although *LF* is always positively correlated to both factors. In particular, in the first case it is one of the acoustic parameters which contributes most to the first factor. Taking into account the different kinds of music, this structural similarity is interesting.

Table 1 – Summary of the acoustical parameters measured in the selected sample of IRs. (Rm=Romanesque, Gt=Gothic, Rn=Renaissance; Ba=Baroque, Mo=Modern)

ID	*Style*	*Volume*	*S-R combin.*	*S-R distance*	T_{30} *(500-1k)*	*BR*	C_{80} *(500-2k)*	*LF (125-1k)*	*1-IACC$_E$ (500-2k)*
		m³		m	s		dB	%	%
SC	Rm	10500	A05	11.9	2.1	1.10	0.3	25.1	57.3
ML	Ba	8700	A03	8.7	3.3	1.13	-4.2	33.7	67.0
CC	Mo	9000	A03	12.5	4.4	1.12	-4.4	17.0	48.7
			A04	18	4.4	1.12	-5.4	20.0	82.3
JE	Rn	39000	A04	20.6	5.1	1.07	-7.4	12.6	48.0
MO	Rm	20000	A03	9.5	5.4	1.09	-4.2	26.6	79.0
LU	Gt	33100	A04	18.1	5.7	0.96	-9.2	35.5	76.0
RI	Mo	6000	A03	11.2	6.3	1.07	-5.9	29.8	68.3
MF	Ba	16400	A01	9.9	7.2	1.03	-5.4	12.0	38.3
TD	Rn	19000	A02	10.8	8.9	1.26	-7.6	12.2	66.3

CONCLUSIONS

The analysis of the results for to the three motifs taken into account shows that in all cases only the first factor is actually important, explaining about 50% of the variance, while the second plays a marginal role with about 25% of explained variance. In none of the cases the subjects showed a consensus preference for one of the factors and for a specific direction. However, the majority of the listeners gave a positive weight to the main factor indicating a preference for higher clarity and, for Bruckner’s excerpt, strong lateral reflections, while for the others shorter reverberation times. A second group, quite significant in number for the Gregorian chant, seems to be substantially indifferent to the main factor. A third group, with singular personal taste, gives a negative weight to the main factor.

Form the present research it appears that higher clarity is an important factor to be achieved in churches. However, it is worth observing that the highest clarity value

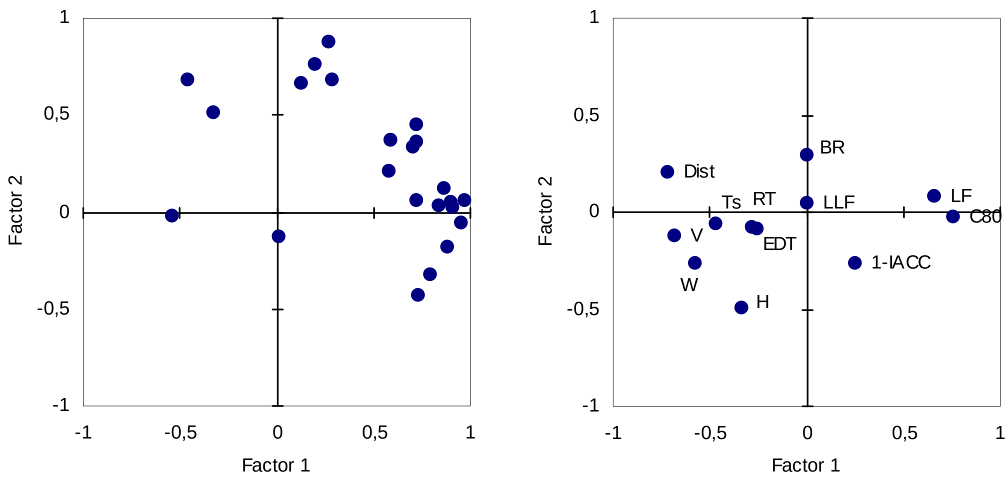

Figure 4 – Preference space and correlations with physical parameters (Bruckner)

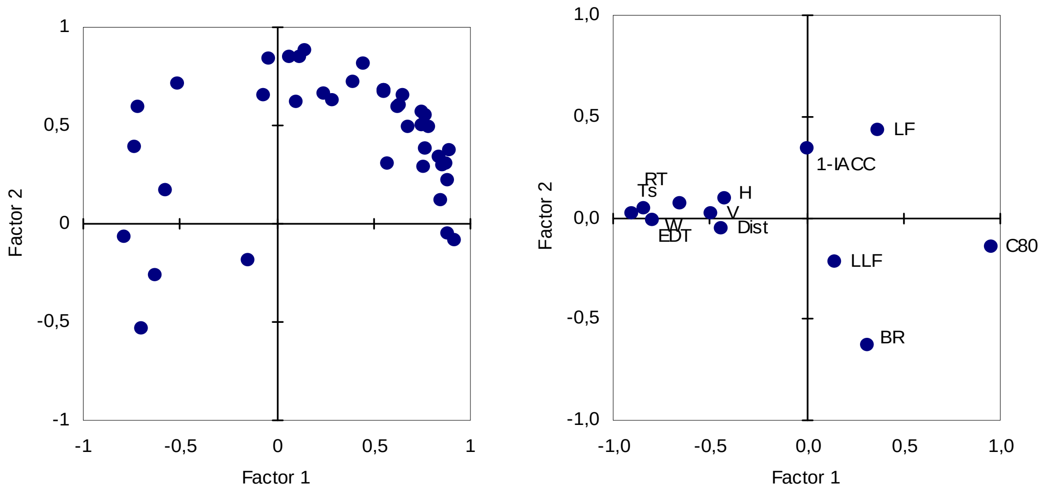

Figure 5 – Preference space and correlations with physical parameters (Mozart)

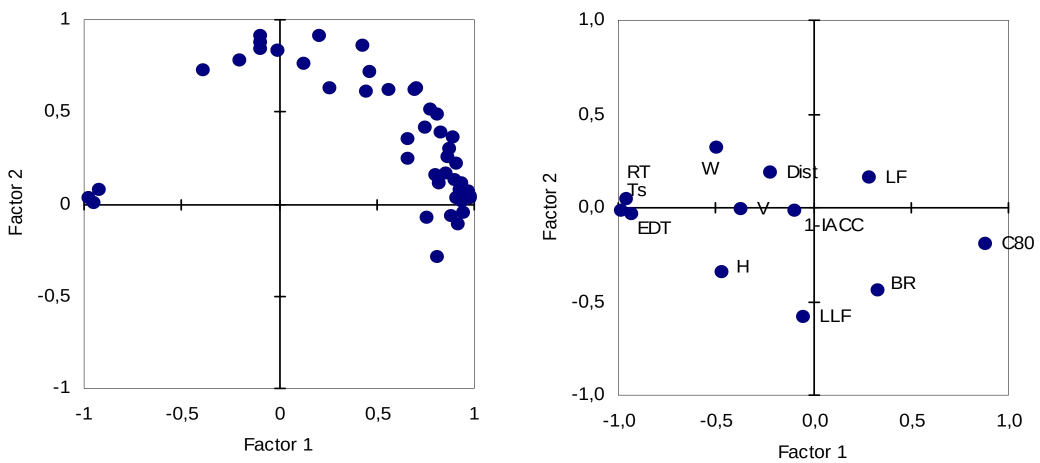

Figure 6 – Preference space and correlations with physical parameters (Gregorian Chant)

used in the research was 0.3 dB and that the corresponding IR did not receive the highest preference, suggesting that according to the listeners it is, probably, too much clear. However further research is under way in order to better understand the complex relations between subjective preference and objective parameters.

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