ON THE MEASUREMENT OF BINAURAL ACOUSTIC PARAMETERS IN SOME ROMANESQUE CHURCHES

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ABSTRACT

This paper reports the results of the binaural measurements carried out during an acoustic survey which took into account eight Romanesque churches built in Apulia (Italy). In each church, an average of nine receiver positions and at least two source positions were used. The source was omni-directional and the receivers were binaural microphones worn by one of the authors. The results showed that, in spite of the great volume differences, the IACC values were concentrated in a narrow interval. In addition, a dependence on the room volume and on the room width was found.

INTRODUCTION

The research on the acoustic characteristics of churches has been mostly focussed on reverberation time, speech intelligibility and, recently, on other monaural acoustic parameters [1-9]. Binaural parameters have been rarely measured in churches, probably because the intelligibility of speech was considered the most important feature. However, the behaviour of the churches with reference to music performance is gaining more and more importance, and the measurement of the spatial characteristics is a necessary complement to have a thorough description of the acoustics of a room. Since today, only Carvalho measured binaural characteristics in his study on Portuguese churches, but, unfortunately, he used a non-standard parameter [7,10].

The spatial characteristics of sound can be described subjectively in terms of “apparent source width” and “listener envelopment”. Objective measurements of these aspects can be obtained using both parameters based on the inter aural cross-correlation (*IACC*) and on the lateral energy fraction (*LF*). The debate is still open as to which objective parameter is the best to describe one or the other aspect. However, this is not the subject of this paper which is based, owing to instrumentation limitations, only on binaural measurement carried out during an acoustic survey of eight Romanesque churches built in Apulia, in the south of Italy [11,12].

THE ANALYSED CHURCHES

The churches analysed in this survey were built in the Romanesque period and share many architectural features such as the basilican plan, with a main nave and side aisles, the wooden roof with trusses, the marble floor with wooden pews, and hard limestone walls and columns.

Nevertheless, they have different dimensions, with volumes ranging from 32000 to 1500 m^3 (see Table 1), and specific features (see Fig. 1) briefly described below. St. Nicholas Basilica has a wooden ceiling with painted canvases and two columns which separate the nave from the transept. Bari Cathedral has false women's galleries (i.e. the side aisles are higher and roofed), and on the crossing there is a dome. Bitonto Cathedral has a wooden roof with densely spaced trusses and a pulpit on the right pillar of the triumphal arch. Barletta Cathedral is partly Romanesque and partly Gothic; the first part has wooden roof, the latter has ribbed cross-vaults and a choir with radial chapels. Bisceglie Cathedral has only one big apse on the main nave, on the presbytery area there are carpets and a wooden choir. Ruvo Cathedral has no women's galleries and the aisles are cross vaulted. Bovino Cathedral has no women's galleries but both the nave, and the aisles are roofed; the walls are plastered. Ognissanti church has a domed nave, while the aisles are barrel-vaulted. The effects of the architectural differences on monaural acoustic parameters have been discussed elsewhere [11].

Table 1. Geometric details of the 9 churches surveyed.

Id	*Church*	*Volume (m^3)*	*Floor area (m^2)*	*Total area (m^2)*	*Length (m)*	*Max height (m)*	*Width (m)*
A	St. Nicholas Basilica, Bari	32000	1530	10500	54	24.5	26.0
B	Bari Cathedral	30100	1274	9500	46	27.5	25.0
C	Bitonto Cathedral	16000	858	6500	42	22.0	18.2
D	Barletta Cathedral	15800	912	5500	46	21.0	18.4
E	Bisceglie Cathedral	10150	534	4660	29	21.8	17.6
F	Ruvo Cathedral	6400	445	3000	29	18.5	13.3
G	Bovino Cathedral	3840	452	2420	22	11.0	18.5
H	Ognissanti church, Valenzano	1800	258	1300	19	9.6	12.8

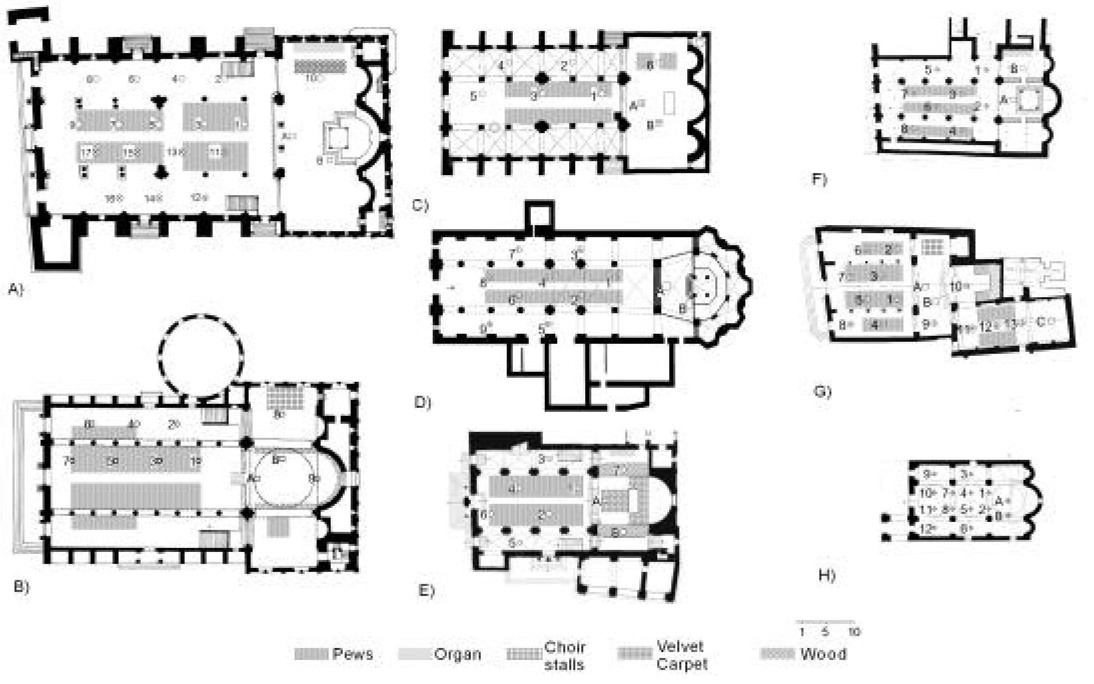

Figure 1. Plans of the eight churches surveyed.

MEASUREMENT TECHNIQUE

The measurements were carried out using an omni-directional sound source made of twelve 100 mm loudspeakers mounted on a dodecahedron driven by a 300 W amplifier. A couple of Core Sound binaural microphones taped to the ears of one of the authors were used to record on a Sony TCD-10 DAT recorder the room responses to a logarithmic sine sweep. The sweep length was of six seconds, followed by a silence long enough to avoid time-aliasing problems.

In each church at least two source positions were used, one on the symmetry axis and one off the axis, both in the presbytery area. The source was placed 1.5 m from the floor. Nine receiver positions were used on average. In very large but symmetrical churches the receivers were only placed in one half of the floor, otherwise they were spread to cover the whole floor area uniformly. St. Nicholas Basilica is an exception because the receivers were placed on both sides of the church. The microphone was placed 1.2 m from the floor surface.

All the measurements and the calculations of the indices were carried out according to ISO 3382 standard [12]. Annex B of the quoted standard suggests to use a dummy head in order to have comparable measurements. However, a human head is accepted provided that the characteristic measure given by the head breadth plus two times the difference between the head length and the distance from the ear entrance point to the occipital wall stays in a range of values such that the measured *IACC* for the real head correlate with those of the dummy head within r = 0.85 or better. Idaka *et al.* [13] found that if this measure for a real person or a dummy head ranges from 318 to 355 mm, it fall into the same range as a Kemar head within 10%, with negligible differences on the measured *IACC* values. In this study the characteristic measure was 335 mm.

The binaural impulse responses, were used to determine both $(1 - IACC_{E3})$ and $(1 - IACC_{L3})$, defined as the average of *IACC* for the three octave bands with centre frequencies 500, 1000, and 2000 Hz integrated, respectively, from 0 to 80 ms, and from 80 to 1000 ms [13]. In addition the inter-aural difference (*IAD*) proposed by Griesinger [14] was calculated as well. The formulation adopted in this study is slightly different and provides a normalized parameter, ranging from 0 (totally correlated signals) to 1 (signals in opposition of phase):

$$IAD = \frac{\int_{t1}^{t2} [p_L(t) - p_R(t)]_{eq}^2 \, dt}{2\int_{t1}^{t2} [p_L^2(t) + p_R^2(t)] dt},$$

where p_L and p_R are the sound pressures at the two binaural microphones. The difference between the signals is equalized with a 6 dB per octave boost below 300 Hz in order to compensate the reduction in inter-aural difference. In this way the parameter is an equivalent of the *LF* so it is possible to express the single number parameters IAD_{E4} and IAD_{L4} as the averages over the octave bands from 250 to 2000 Hz using the same integration limits given for *IACC*.

RESULTS ANALYSIS

The mean values of the aforesaid binaural parameters are summarized in Table 2. It can be observed that the range of the $IACC_{E3}$ values is about 0.08, from 0.616 of Bari Cathedral to 0.694 of Ognissanti church. It is significant that this range coincides with that of the A+ class auditoria defined by Beranek, even though the room dimensions vary considerably. A possible explanation for this behaviour may be the effect of the columns which, as shown by Suzumura and Ando [15], reduce the *IACC*. Figure 2 shows the plot of $(1 - IACC_{E3})$ and IAD_{E4} against the church volume and the total width (including both nave and aisles). It appears that the higher parameter values are measured inside the smaller rooms, and vice versa. St. Nicholas Basilica makes exception to this behaviour, in fact both $(1 - IACC_{E3})$ and IAD_{E4} are high compared to the church dimensions. A comparison with Bari Cathedral, which has similar dimensions, shows this clearly. In the Cathedral the parameters assume the smallest values of the relative ranges, according to the room geometry which provides few early lateral reflections. In the Basilica the parameter values are higher, near the upper limit of the range. This difference may be due to the columns which separate the nave from the transept of the Basilica (iconostasis). They interfere with the propagation of the direct sound (especially at medium and high frequencies), reducing the correlation between the signals arriving at the two ears. The frequency dependence is visible in Figure 3, where measurements made in both churches, at equivalent source-receiver combinations, are shown to support this argument, comparing wide band values with three-band average values.

Table 2. Summary of the mean values of the binaural indices measured inside each church

Id	*Church*	$1\text{-}IACC_{E3}$	$1\text{-}IACC_{E3}$*	IAD_{E4}	$1\text{-}IACC_{L3}$	IAD_{L4}
A	St. Nicholas Basilica, Bari	0.676	0.752	0.408	0.909	0.485
B	Bari Cathedral	0.616	0.774	0.341	0.895	0.475
C	Bitonto Cathedral	0.645	0.737	0.416	0.911	0.485
D	Barletta Cathedral	0.692	0.738	0.391	0.920	0.475
E	Bisceglie Cathedral	0.666	0.774	0.408	0.893	0.468
F	Ruvo Cathedral	0.681	0.757	0.417	0.891	0.487
G	Bovino Cathedral	0.692	0.787	0.405	0.894	0.490
H	Ognissanti church, Valenzano	0.694	0.789	0.444	0.932	0.491
	min	0.616	0.737	0.341	0.891	0.468
	max	0.694	0.789	0.444	0.932	0.491
	range	0.078	0.053	0.103	0.041	0.023

* Values calculated excluding the direct sound contribution

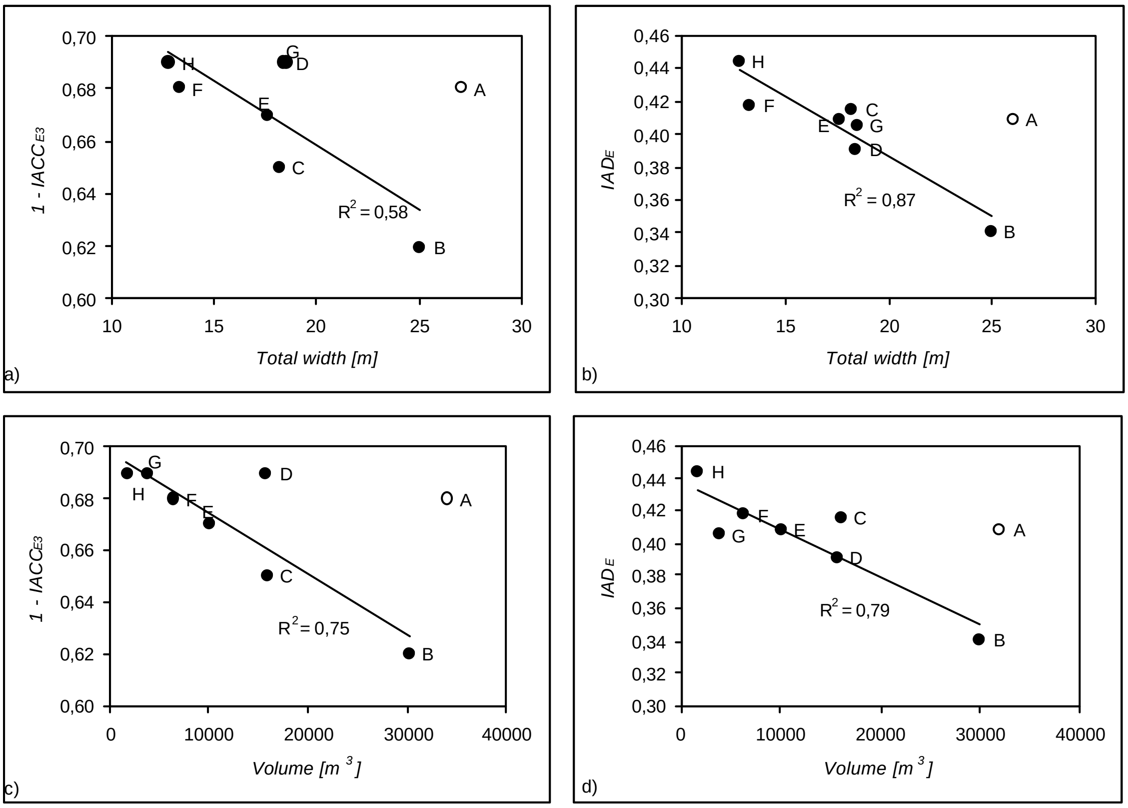

Figure 2. Plot of (1 – $IACC_{E3}$) and IAD_{E4} as a function of the total width and of the volume of the analysed churches. Church identifiers are the same reported in table 2.

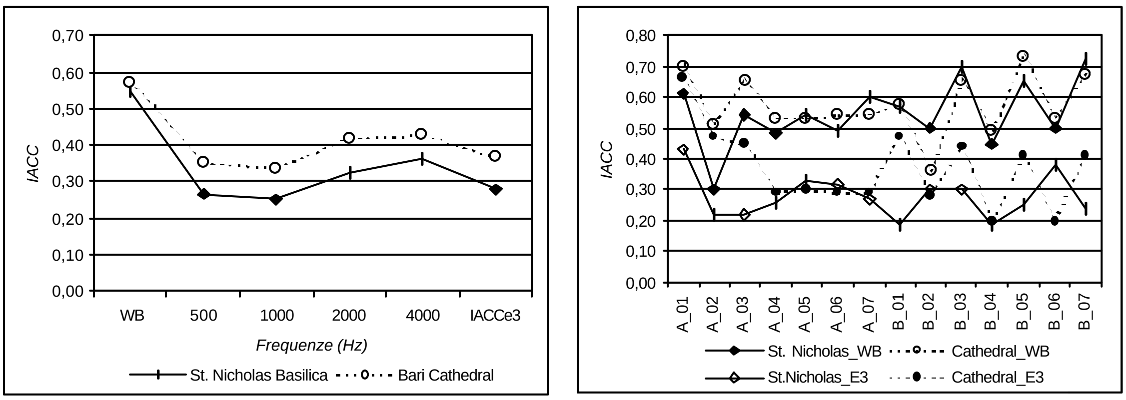

Figure 3. Comparison of *IACC* measurements in St. Nicholas Basilica and in Bari Cathedral.

The analysis of the $IACC_E$ values calculated excluding the direct sound (Table 2), that is assuming 5 ms as the lower integration limit, shows that the mean values are higher, but the range becomes narrower, being only 0.05. This is in agreement with the results found by Idaka *et al*. [13] in many auditoria. A comparison between the mean values calculated with and without the direct sound shows that in St. Nicholas Basilica $(1 - IACC_{E3})$ is 0.752, lower than in Bari Cathedral where it is 0.774. This means that excluding the direct sound, the effect of the columns which separate the nave from the transept becomes negligible, while the narrower span (and consequently the higher number) of the columns of the nave in Bari Cathedral can account for the higher $(1 - IACC_{E3})$ value.

Figure 2 shows that, excluding St. Nicholas Basilica from the analysis, both $(1 - IACC_{E3})$ and IAD_{E4} are correlated with the church width, but only IAD_{E4} has a significant coefficient of determination equal to 0.87. Similarly, both parameters are significantly correlated with the church volume, and IAD_{E4} has, again, a slightly better coefficient of determination. This correlation is an obvious consequence of the dependence of both parameters on the early lateral reflections, which tend to become fewer as the room dimension grows.

Figure 4 shows that the influence of the room dimension disappears or, however, becomes negligible when $(1 - IACC_{L3})$ and IAD_{L4} are taken into account. In this case the mean values of the parameters are higher than their "early" equivalent and are concentrated in a narrow range: respectively from 0.89 to 0.93 and from 0.47 to 0.49. This result means that in the analysed churches the diffusion of the sound, due to surface irregularities, columns, and trusses is high.

In order to analyse whether *IACC* and *IAD* describe different aspects of the sound field or, being calculated from the same measurement, they are correlated, the individual position values of $(1 - IACC_3)$ were plotted as a function of IAD_4 (Figure 5) with reference to the "early" and "late" parts. It appears that the "early" parameters are significantly correlated, even though the points are considerably scattered, while the "late" parameters are not equally well correlated.

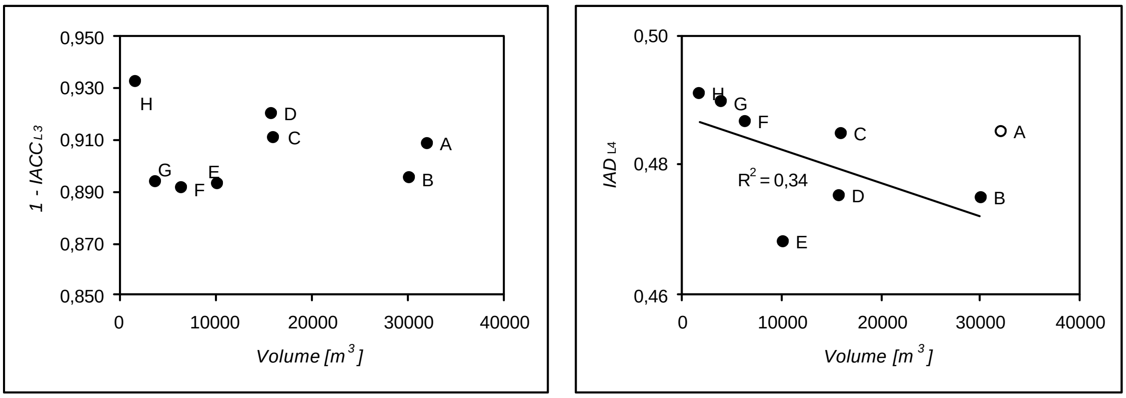

Figure 4. Plot of $(1 - IACC_{L3})$ and IAD_{L4} as a function of the volume of the analysed churches.

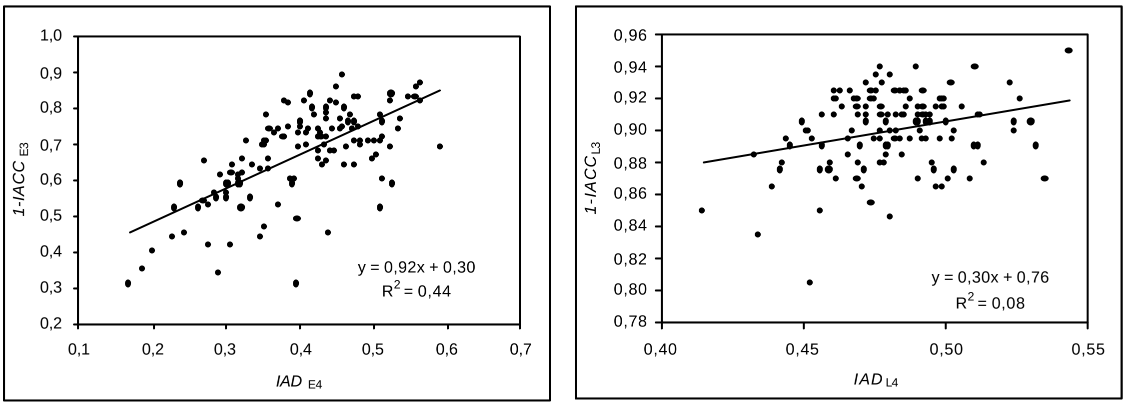

Figure 5. Plot of the correlations between individual position values of the "early" (left) and "late" (right) parameters.

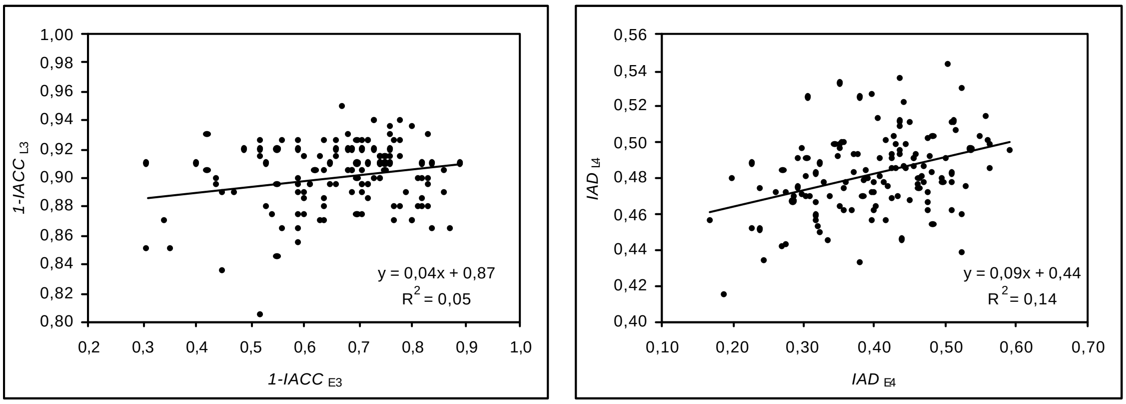

Figure 6. Plot of the correlations between *IACC* based parameters (left) and *IAD* based parameters (right).

Finally, the correlation between the early and late parts of the same parameters was investigated. Figure 6 shows that *IACC* values are not correlated, while a very weak correlation is observed between *IAD* values.

CONCLUSIONS

The measurements of the binaural acoustic parameters in eight Romanesque churches showed that $(1 - IACC_{E3})$ assumes very good values, comparable with those measured in some of the best concert halls. The room-average values of the "early" parameters are well correlated with the church dimensions, while the "late" parameters do not show any proving that the sound is highly diffuse inside all the analysed church. The correlations between the acoustic parameters where finally investigated, showing that most of the measurements are independent of each other, while $(1 - IACC_{E3})$ and IAD_{E4} are correlated.

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