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BACH, A NEW BINAURAL ROOM ACOUSTICAL MEASURE

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ABSTRACT

This study reports on acoustical field measurements made in a major survey of 41 Catholic churches in Portugal built in the last fourteen centuries. Binaural measurements were taken in each church using a dual channel real time frequency analyzer to calculate the *coherence* values between the signals at both ears in 1/3 octave frequency bands. From the *coherence* values a new binaural acoustical measure was developed and called *BACH* (*Binaural Acoustical CoHerence)*. Monaural acoustical measurements were also taken at several source/receiver locations using the impulse response method. *BACH* was shown to be an orthogonal parameter in statistical tests with nine other monaural acoustical measures (RT, EDT, C80, D, TS, L, BR_RT, BR_L and RASTI) and fifteen architectural parameters. Information was collected regarding the quality of music in each church. ANOVA tests were performed to examine the significance of the differences among the groups of equal subjective quality ratings. The author wanted to test the hypothesis that this new binaural acoustical measure can be useful in estimating the general subjective quality of churches regarding music. A linear correlation coefficient near 0.7 was found between the *BACH* and the subjective quality ratings that supported the stated hypothesis. This is exploratory research and developments are being tested to improve the model.

1 - INTRODUCTION

The purpose of this document is to study the interaction between personal feelings regarding musical performances in churches and a new physical quantity to measure it.

The main investigation is focused on the Roman Catholic churches of Portugal. Portugal is one of the oldest European countries and played a prominent role in some of the most significant events in world history. It presents an almost perfect location to trace the history of Catholic church buildings in the world. Portuguese churches can be considered a representative example of Catholic churches in the world (Gil 1992; DGEMN 1936/64; Azevedo 1985).

This study reports on acoustical field measurements in a major survey of 41 Roman Catholic churches in Portugal that were built between the 6th century and 1993. Table 1 presents an alphabetical list of the churches tested in the survey. The churches are a sample of 14 centuries of church building in Portugal. The oldest church tested was number 26 (*S. Frutuoso de Montélios*), which was built around the 6th century. The most recent was church number 35 (*Seroa*), which was completed in 1993. A complete analysis is available as a Ph.D. dissertation and an internal report in the University of Florida's College of Architecture (Carvalho 1994a,b).

The churches were selected to represent the main architectural styles found throughout Portugal and to represent the evolution of church construction in Portugal. The architectural styles of the churches are presented in Table 2. For more uniformity of the sample and due to the sound power limits of the sound source, only churches with a maximum volume of less than 19000 m^3 were selected for the study.

Acoustical measurements were taken in similar numbers of churches grouped by large periods of history: 12 *Visigothic* or *Romanesque* churches (6th-13th centuries), 16 *Gothic* or *Manueline* churches (13th-16th centuries), 13 *Renaissance, Baroque* or *Neoclassic* churches (16th-19th centuries) and 4 *Contemporary* churches (20th century). The main architectural features of these churches are displayed in Table 3.

TABLE 1 - List of 41 churches tested.

N.	CHURCH NAME	VOLUME (m^3)	N.	CHURCH NAME	VOLUME (m^3)
1	ALMANSIL	578	22	SANTA CLARA (PORTO)	2491
2	ARMAMAR	2487	23	S. B. CASTRIS (ÉVORA)	1314
3	BAS. ESTRELA(LISBOA)	18674	24	S. FRANCISCO (ÉVORA)	18631
4	BRAVÃES	946	25	S. FRANCISCO (PORTO)	12045
5	BUSTELO	6476	26	S. FRUTUOSO	320
6	CABEÇA SANTA	751	27	S. GENS (BOELHE)	299
7	CAMINHA	5899	28	S. PEDRO DE FERREIRA	2912
8	CEDOFEITA-NEW (PORTO)	8470	29	S. PEDRO DE RATES	3918
9	CEDOFEITA-OLD (PORTO)	1117	30	S. PEDRO DE RORIZ	2198
10	CETE	1515	31	S. ROQUE (LISBOA)	14207
11	CLÉRIGOS (PORTO)	5130	32	SÉ (LAMEGO)	13424
12	GOLEGÃ	5563	33	SÉ (PORTO)	15260
13	LAPA (PORTO)	11423	34	SÉ (SILVES)	10057
14	LEÇA DO BAILIO	9795	35	SEROA	4225
15	LOUROSA	1163	36	SERRA DO PILAR (GAIA)	11566
16	MÉRTOLA	1950	37	TIBÃES	8608
17	MISERICÓRDIA (ÉVORA)	3338	38	VIANA DO ALENTEJO	3358
18	MOURA	6300	39	VILA DO BISPO	1290
19	N. S. BOAVISTA (PORTO)	3740	40	V. N. AZEITÄO	1239
20	PAÇO DE SOUSA	6028	41	VOUZELA	1148
21	SANT. SACRAM. (PORTO)	6816			

TABLE 2 - Architectural styles of churches tested.

1 - VISIGOTHIC	(6th-11th centuries)	*5 - RENAISSANCE*	(16th-17th centuries)
2 - ROMANESQUE	(12th-13th centuries)	*6 - BAROQUE*	(17th-18th centuries)
3 - GOTHIC	(13th-15th centuries)	*7 - NEOCLASSIC*	(18th-19th centuries)
4 - MANUELINE	(15th-16th centuries)	*8 - CONTEMPORARY*	(20th century)

TABLE 3 - Simple statistics for all churches tested.

ARCH. FEATURE	Min.	Max.	Mean	Median
VOLUME (m^3)	299	18674	5772	3918
AREA (m^2)	56	1031	450	427
MAX. HEIGHT (m)	7	39	15	13
MAX. LENGTH (m)	12	62	33	31
WIDTH NAVE (m)	4	38	13	11

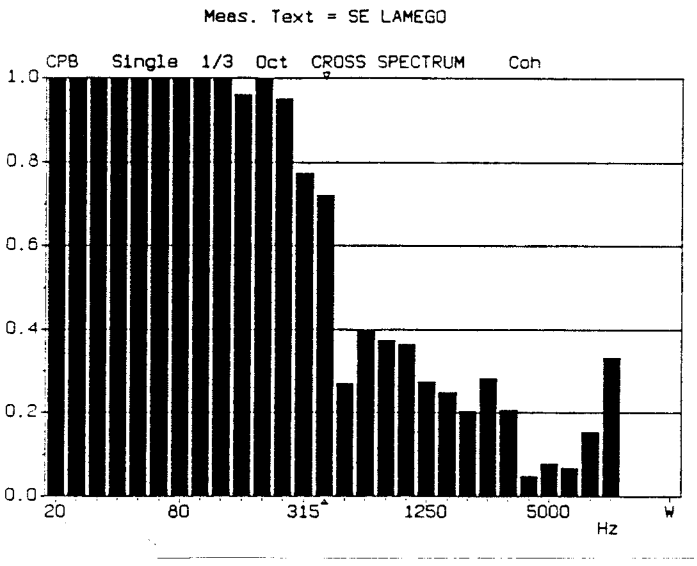
2 - PROCEDURE

Binaural measurements (that refer to the use of microphones located at the two ears of a manikin or human subject) were taken in each church using a dual channel real time frequency analyzer. In the simultaneous analysis of signals it is no longer the signals themselves that are of primary interest, but rather the properties of the physical system responsible for the differences between them.

The idea was to use both instant spectra (channel A and channel B inputs) and their cross spectrum to find the *coherence* values. Channels A and B are microphones held outside both ears of a person in the center of the longitudinal axis of the church. A *pink noise* source was used with the loudspeaker in front of the altar at a height of 0.8 m and with sound pressure levels of 88-104 dB measured at the receiver.

The *coherence* gives a measure of the degree of linear dependence between the two signals as a function of frequency. It is calculated from the two autospectra and the cross spectrum. It can also be interpreted as a squared correlation coefficient expressing the degree of linear relationship between two variables. If the *coherence* is 1 there will be a perfectly linear relationship between the signals at both ears. If it is 0, there is no relationship whatsoever between signals at the two ears (Randall 1987). Figure 1 shows one of the graphical outputs obtained. In each church, three spectra were recorded in the same position (only one position was used - in the middle of the longitudinal axis). The values were then averaged for further analysis (see Table 4).

The churches were measured while unoccupied, as the available state of the art does not allow easy and practical acoustical measurements to be made in an occupied room. The high noise level of the sound source and the long duration of the measurements make the presence of a quiet congregation almost impossible. Furthermore, the use of absorptive materials to simulate the presence of people is also impractical due to the huge amount needed. In addition, most of the available bibliographic data were determined for unoccupied conditions. Therefore consistency of data is useful for possible comparison purposes.



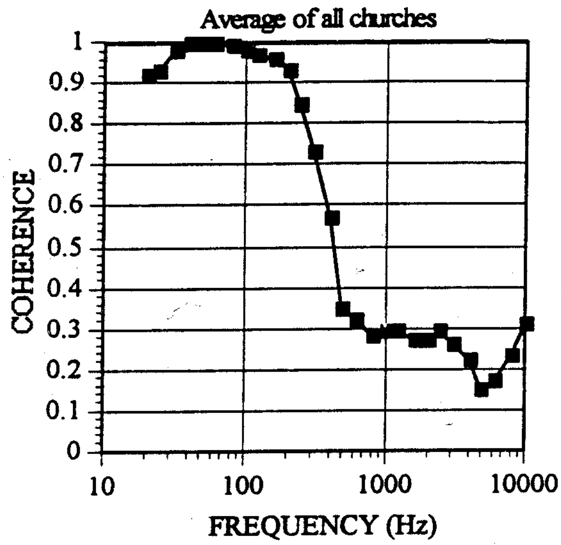


Figure 1 (left) - Specimen of *coherence* data (*y* axis) with 1/3-octave frequency bands (*x* axis).

Figure 2 (right) - Spectrum of averaged *coherence* (*y* axis) for all churches in 1/3-octave frequency bands (*x* axis).

3 - SUBJECTIVE ANALYSIS

Very basic qualitative information was collected in each church by an interview with the local priests and other members of the staff. Answers were requested to simple questions such as if the church had a *good* acoustics or *good* sound, if music sounded *good* in the church, if there were musical performances in the church, which type of musical performances occurred in the church, if the performers like the *sound* of the church, etc. The churches were finally rated on a five level scale: *very bad, bad, normal, good* or *very good* acoustics (Table 5).

4 - BACH

4.1 - Coherence

Using the *coherence* values obtained in twenty-eight 1/3 octave bands (Table 5) a new measure was sought. Figure 2 presents the graphical representation of all bands considering the average of all churches tested. In this graph describing the general behavior of the *coherence* in all the churches tested, four areas can be identified. At very low frequencies the *coherence* is almost constant and equal to 1.0; from 200 to 800 Hz the *coherence* decreases with a roll-off of nearly 0.3/octave; at mid frequencies (1 to 2.5 kHz) there is a constant level for the coherence around 0.28; finally to higher frequencies (3.15 to 10 kHz) a *V* shaped behavior appears with a drop to a *coherence* of 0.15 near 5 kHz.

To analyze which of these characteristics could be related to the subjective quality of the room (Table 5), the Pearson correlation coefficients were calculated between *Subjective* rating and *Coherence* (28 frequency bands) - Table 6. The highest R was found with *Coherence 3150 Hz* (R = 0.552). But this is still a low R and other factors must be involved in the variance of the subjective quality ratings.

TABLE 4 - *Coherence* data by 1/3-octave frequency bands.

	Church	**20**	**25**	**32**	**40**	**50**	**63**	**80**	**100**	**125**	**160**	**200**	**250**	**315**	**400**	**500**
1	Almansil	0.75	0.90	1	1	1	1	0.91	0.96	0.95	0.90	0.91	0.87	0.59	0.31	0.16
2	Armamar	0.99	1	1	1	1	1	1	0.99	0.92	0.94	0.99	0.98	0.73	0.67	0.46
3	Estrela	0.93	0.99	1	1	1	1	0.99	0.99	0.98	0.99	0.94	0.86	0.77	0.73	0.45
4	Bravaes	0.91	0.87	1	1	1	1	1	0.99	0.98	0.97	0.94	0.94	0.70	0.53	0.32
5	Bustelo	0.91	0.99	0.96	1	1	1	1	0.99	1	0.99	0.97	0.97	0.68	0.66	0.37
6	Cab.Santa	0.90	0.68	0.99	1	0.99	1	1	1	0.92	0.79	0.91	0.61	0.49	0.44	0.18
7	Caminha	1	1	1	1	1	1	1	0.96	1	0.90	1	1	0.88	0.53	0.37
8	CED.New	1	0.82	0.99	1	1	1	1	1	0.98	0.99	0.97	0.89	0.80	0.54	0.62
10	Cete	0.99	1	0.97	1	1	1	0.97	0.97	0.99	0.97	0.89	0.90	0.56	0.58	0.25
11	Clerigos	1	1	1	1	1	1	0.97	0.99	0.99	0.88	0.96	0.89	0.59	0.48	0.20
12	Golega	1	1	1	1	1	1	1	1	1	0.93	0.94	0.94	0.85	0.66	0.37
13	Lapa	1	1	1	1	1	1	0.99	1	0.98	0.96	0.99	0.90	0.54	0.35	0.20
14	Leca	1	0.98	0.98	1	1	1	0.99	0.96	1	0.97	0.96	0.71	0.82	0.43	0.21
15	Lourosa	0.92	0.55	0.92	1	1	1	1	1	1	0.99	0.98	0.91	0.85	0.87	0.61
16	Mertola	0.85	0.74	0.99	1	1	0.99	1	1	0.92	0.97	0.87	0.76	0.70	0.67	0.52
17	Miseric	1	1	1	1	1	1	1	0.93	1	1	0.98	0.98	0.95	0.61	0.08
18	Moura	1	1	1	1	1	0.99	0.93	0.96	0.91	0.94	0.90	0.77	0.68	0.35	0.28
19	Boavista	1	1	1	1	1	1	1	0.95	0.98	0.86	0.76	0.63	0.61	0.85	0.52
20	P.Sousa	0.99	0.99	1	1	1	1	1	1	0.94	0.99	0.97	0.74	0.64	0.38	0.21
21	S.Sacr.	0.85	0.93	0.94	0.90	1	1	1	0.99	1	0.98	0.92	0.95	0.88	0.51	0.26
22	S.Clara	0.99	1	1	1	1	1	1	0.99	1	1	0.97	0.79	0.76	0.42	0.25
23	Castris	0.79	0.97	0.99	1	0.98	0.99	1	0.99	0.97	0.83	0.75	0.71	0.63	0.64	0.17
24	S.FRAN.Ev	1	1	1	1	1	1	1	1	0.93	0.95	0.87	0.63	0.75	0.56	0.39
25	S.FRAN.Po	1	1	1	1	1	1	1	1	1	1	1	1	1	0.80	0.55
26	S.Frutu.	1	0.91	0.99	1	1	1	1	1	1	1	0.92	0.83	0.91	0.88	0.86
27	S.Gens	0.70	0.48	0.77	1	1	1	0.99	1	0.96	0.98	0.88	0.88	0.78	0.68	0.25
28	Ferreira	0.69	1	1	1	1	0.99	0.87	0.99	0.98	0.95	0.96	0.87	0.44	0.20	0.12
29	Rates	0.79	1	1	1	1	1	1	1	0.98	0.98	0.91	0.89	0.80	0.59	0.32
30	Roriz	1	1	0.96	1	1	1	1	0.97	0.94	0.99	0.92	0.82	0.93	0.55	0.29
31	S.Roque	0.99	1	1	1	1	1	1	1	1	1	0.94	0.97	0.91	0.71	0.49
32	Lamego	1	1	1	1	1	1	1	1	1	0.96	0.99	0.97	0.78	0.72	0.43
33	Seporto	1	1	1	1	1	1	1	1	1	0.99	0.97	0.91	0.68	0.47	0.16
34	Silves	0.77	1	0.8	1	0.99	1	1	0.98	0.99	0.96	0.85	0.68	0.69	0.56	0.24
35	Seroa	0.65	0.73	1	1	1	1	0.98	0.99	0.92	0.88	0.82	0.70	0.75	0.75	0.52
37	Tibaes	0.99	0.93	1	1	1	1	0.99	1	1	1	0.98	0.88	0.73	0.63	0.47
38	V.Alent.	0.86	1	1	1	1	0.97	1	0.9	0.96	0.98	0.92	0.81	0.61	0.32	0.21
39	V.Bispo	1	1	1	1	1	0.94	1	0.91	0.95	0.97	0.91	0.87	0.68	0.58	0.35
40	Azeitao	1	1	0.99	1	1	0.99	1	1	1	0.98	0.92	0.87	0.78	0.62	0.39
41	Vouzela	0.80	0.65	1	1	1	1	1	1	0.95	1	0.91	0.95	0.75	0.50	0.43
	Average	**0.92**	**0.93**	**0.98**	**1**	**1**	**1**	**0.99**	**0.98**	**0.97**	**0.96**	**0.93**	**0.85**	**0.73**	**0.57**	**0.35**

	Church	**630**	**800**	**1k**	**1250**	**1600**	**2k**	**2500**	**3150**	**4k**	**5k**	**6300**	**8k**	**10k**		**AVG**
1	Almansil	0.19	0.24	0.17	0.14	0.19	0.24	0.40	0.21	0.22	0.27	0.15	0.21	0.21		**0.54**
2	Armamar	0.20	0.35	0.27	0.28	0.28	0.26	0.21	0.17	0.11	0.11	0.08	0.22	0.12		**0.58**
3	Estrela	0.26	0.34	0.34	0.31	0.57	0.60	0.34	0.47	0.33	0.10	0.26	0.08	0.49		**0.65**
4	Bravaes	0.17	0.27	0.16	0.21	0.35	0.25	0.33	0.30	0.14	0.08	0.10	0.13	0.25		**0.57**
5	Bustelo	0.22	0.15	0.30	0.43	0.18	0.22	0.21	0.10	0.13	0.09	0.10	0.18	0.14		**0.57**
6	Cab.Santa	0.52	0.36	0.29	0.51	0.26	0.29	0.27	0.30	0.09	0.15	0.07	0.15	0.25		**0.55**
7	Caminha	0.48	0.21	0.52	0.38	0.28	0.34	0.45	0.46	0.22	0.03	0.14	0.08	0.23		**0.62**
8	CED.New	0.60	0.67	0.55	0.43	0.68	0.68	0.76	0.36	0.42	0.52	0.36	0.26	0.46		**0.73**
10	Cete	0.42	0.26	0.31	0.34	0.15	0.20	0.31	0.22	0.19	0.23	0.15	0.16	0.18		**0.58**
11	Clerigos	0.32	0.14	0.28	0.34	0.19	0.13	0.18	0.16	0.16	0.06	0.11	0.23	0.43		**0.56**
12	Golega	0.23	0.27	0.27	0.39	0.22	0.24	0.12	0.09	0.04	0.08	0.06	0.09	0.18		**0.57**
13	Lapa	0.27	0.12	0.21	0.21	0.13	0.12	0.14	0.06	0.13	0.09	0.13	0.23	0.34		**0.54**
14	Leca	0.28	0.20	0.23	0.16	0.34	0.33	0.54	0.54	0.56	0.20	0.27	0.58	0.24		**0.62**
15	Lourosa	0.65	0.42	0.52	0.34	0.27	0.38	0.08	0.09	0.18	0.19	0.12	0.13	0.08		**0.61**
16	Mertola	0.39	0.27	0.16	0.17	0.15	0.41	0.31	0.33	0.24	0.12	0.22	0.44	0.33		**0.59**
17	Miseric	0.22	0.30	0.19	0.33	0.15	0.12	0.16	0.13	0.18	0.06	0.08	0.12	0.08		**0.56**
18	Moura	0.29	0.16	0.14	0.23	0.25	0.19	0.13	0.13	0.12	0.06	0.10	0.21	0.17		**0.53**
19	Boavista	0.58	0.63	0.44	0.45	0.47	0.32	0.42	0.58	0.10	0.15	0.30	0.55	0.76		**0.68**
20	P.Sousa	0.25	0.23	0.37	0.19	0.27	0.15	0.20	0.14	0.21	0.17	0.09	0.12	0.09		**0.55**
21	S.Sacr.	0.18	0.13	0.22	0.07	0.24	0.20	0.27	0.26	0.31	0.09	0.09	0.28	0.09		**0.55**
22	S.Clara	0.14	0.29	0.51	0.43	0.21	0.19	0.47	0.27	0.11	0.16	0.21	0.14	0.19		**0.59**
23	Castris	0.38	0.18	0.20	0.21	0.18	0.15	0.17	0.24	0.12	0.17	0.11	0.13	0.43		**0.54**
24	S.FRAN.Ev	0.37	0.19	0.20	0.24	0.17	0.19	0.21	0.18	0.11	0.12	0.18	0.04	0.09		**0.55**
25	S.FRAN.Po	0.30	0.50	0.48	0.22	0.21	0.47	0.26	0.62	0.93	0.35	0.43	0.41	0.68		**0.72**
26	S.Frutu.	0.53	0.42	0.48	0.19	0.31	0.23	0.48	0.25	0.29	0.21	0.29	0.27	0.30		**0.66**
27	S.Gens	0.22	0.15	0.20	0.25	0.28	0.30	0.28	0.20	0.15	0.08	0.08	0.06	0.24		**0.53**
28	Ferreira	0.24	0.23	0.22	0.20	0.14	0.17	0.24	0.19	0.11	0.08	0.18	0.11	0.19		**0.51**
29	Rates	0.25	0.25	0.32	0.34	0.16	0.13	0.27	0.29	0.13	0.10	0.12	0.04	0.15		**0.56**
30	Roriz	0.17	0.28	0.19	0.47	0.32	0.29	0.20	0.21	0.22	0.16	0.20	0.09	0.44		**0.59**
31	S.Roque	0.55	0.31	0.22	0.23	0.31	0.26	0.20	0.39	0.11	0.05	0.25	0.14	0.32		**0.62**
32	Lamego	0.41	0.32	0.41	0.28	0.27	0.23	0.24	0.13	0.09	0.07	0.07	0.20	0.30		**0.60**
33	Seporto	0.12	0.13	0.12	0.27	0.45	0.27	0.21	0.36	0.36	0.12	0.16	0.37	0.46		**0.59**
34	Silves	0.27	0.14	0.28	0.16	0.09	0.21	0.14	0.25	0.08	0.09	0.10	0.26	0.14		**0.53**
35	Seroa	0.24	0.43	0.45	0.47	0.31	0.21	0.49	0.35	0.52	0.16	0.43	0.57	0.37		**0.63**
37	Tibaes	0.41	0.52	0.30	0.28	0.41	0.39	0.25	0.15	0.26	0.22	0.12	0.17	0.64		**0.63**
38	V.Alent.	0.27	0.18	0.15	0.21	0.16	0.26	0.16	0.13	0.25	0.32	0.21	0.84	0.67		**0.58**
39	V.Bispo	0.16	0.16	0.19	0.32	0.32	0.32	0.74	0.44	0.13	0.10	0.11	0.29	0.19		**0.59**
40	Azeitao	0.22	0.24	0.25	0.12	0.19	0.35	0.25	0.22	0.11	0.13	0.09	0.06	0.17		**0.57**
41	Vouzela	0.38	0.25	0.37	0.44	0.27	0.07	0.09	0.12	0.56	0.18	0.30	0.31	0.85		**0.61**
	Average	**0.32**	**0.28**	**0.29**	**0.29**	**0.27**	**0.27**	**0.29**	**0.26**	**0.22**	**0.15**	**0.17**	**0.23**	**0.31**		**0.59**

TABLE 5 - List of 41 churches tested with subjective quality ratings.

	CHURCH	Subj. Qual.		CHURCH	Subj. Qual.
1	ALMANSIL	4	22	SANTA CLARA porto	4
2	ARMAMAR	2	23	S. B. CASTRIS évora	3
3	BAS. ESTRELA lisboa	4	24	S. FRANCISCO évora	3
4	BRAVÃES	4	25	S. FRANCISCO porto	5
5	BUSTELO	1	26	S. FRUTUOSO	4
6	CABEÇA SANTA	4	27	S. GENS boelhe	3
7	CAMINHA	4	28	S. P. FERREIRA	2
8	CEDOFEITA.new porto	5	29	S. P. RATES	4
9	CEDOFEITA.old porto	2	30	S. P. RORIZ	4
10	CETE	4	31	S. ROQUE lisboa	5
11	CLÉRIGOS porto	2	32	SÉ lamego	1
12	GOLEGÃ	2	33	SÉ porto	4
13	LAPA porto	4	34	SÉ silves	4
14	LEÇA DO BAILIO	5	35	SERÔA	2
15	LOUROSA	3	36	SERRA PILAR gaia	1
16	MÉRTOLA	4	37	TIBÃES	5
17	MISERICÓRDIA évora	4	38	VIANA DO ALENTEJO	4
18	MOURA	1	39	VILA DO BISPO	5
19	N. S. BOAVISTA porto	5	40	V. N. AZEITÃO	3
20	PAÇO SOUSA	3	41	VOUZELA	5
21	SANT. SACRAM. porto	4			

Subjective Quality: 1 *VERY BAD*, 2 *BAD*, 3 *NORMAL,* 4 *GOOD*, 5 *VERY GOOD*

TABLE 6 - Pearson correlation coefficient between *subjective* quality rating and *coherence*

Coherence	R	Coherence	R	Coherence	R	Coherence	R
20	0.145	100	-0.192	500	0.126	2500	0.380
25	-0.049	125	0.204	630	0.212	**3150**	**0.552**
32	0.040	160	0.218	800	0.305	4000	0.392
40	-0.029	200	-0.039	1000	0.093	5000	0.412
50	0.033	250	-0.047	1250	-0.200	6300	0.410
63	-0.128	315	0.212	1600	0.327	8000	0.238
80	0.317	400	0.044	2000	0.337	10000	0.425

4.2 - BACH Equations

The new binaural acoustical measure, was called BACH, *Binaural Acoustic CoHerence*. Studying the general behavior of the *coherence* values in churches (Figure 2), 22 ratios or combinations of coherence were tested to find the best suited to represent or explain the variance in the subjective quality scores. The formulas are presented in Table 7. To test the fitness of all those 22 formulas, Table 8 displays the R coefficients regarding the linear smoothing between the *Subjective* rating and $BACH_N$. The highest R was found using BACH11's formula (R = - 0.684). The plot of this relationship is shown in Figure 3. This is the measure sought.

TABLE 7 - The 22 BACH formulas tested.

BACH1 = (Coh80 + Coh400) / 2	BACH12 = (Coh250 - Coh400) / Coh400
BACH2 = (Coh80 + Coh400) / (Coh800 + Coh1000)	BACH13 = (Coh250 - Coh400) / Coh250
BACH3 = (Coh125 + Coh250) / (Coh500 + Coh1k)	BACH14 = (Coh200 - Coh400) / Coh400
BACH4 =(Coh80 + Coh125 + Coh400 + Coh.8k+ Coh1k) / 5	BACH15 = (Coh200 - Coh400) / Coh200
BACH5=(Coh80+Coh125+Coh.4k+Coh.8k+Coh1k)/(5.Coh.4k)	BACH16=(Coh250+Coh.5k)/(Coh1k+Coh2k)
BACH6 = (Coh200 + Coh630)	BACH17=(Coh500+Coh1k)/(Coh2k+Coh4k)
BACH7 = (Coh200 + Coh630) / 2	BACH18 = (Coh250x2 - Coh500) / Coh500
BACH8 = (Coh250 - Coh630) / Coh630	BACH19 = Average (all Coh)
BACH9 = (Coh120 + Coh200) / (Coh630 + Coh800)	BACH20 = (Coh250 - Coh500) / Coh500
BACH10=(Coh.1k+Coh125+Coh160)/(Coh.4k+Coh.5k+Coh630)	BACH21 = Coh3150 + Coh4k + Coh5k
BACH11= (Coh50+Coh63+Coh80)/(Coh3150+Coh4k+Coh5k)	BACH22 = Coh3150 + Coh4k

TABLE 8 - Pearson correlation coefficients between *subjective quality* rating and $BACH_N$.

BACHn	R	BACHn	R	BACHn	R	BACHn	R
BACH1	0.093	BACH7	-0.219	BACH13	-0.079	BACH19	0.466
BACH2	-0.142	BACH8	-0.079	BACH14	-0.133	BACH20	-0.049
BACH3	-0.056	BACH9	-0.146	BACH15	-0.057	BACH21	0.573
BACH4	0.203	BACH10	-0.115	BACH16	-0.215	BACH22	0.538
BACH5	-0.104	**BACH11**	**-0.684**	BACH17	-0.339		
BACH6	-0.202	BACH12	-0.136	BACH18	-0.047		

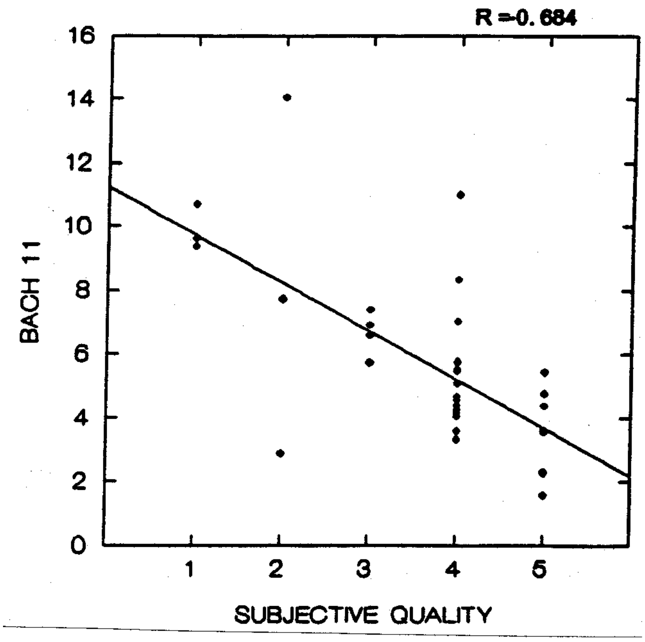


Figure 3 - Plot of subjective quality ratings (1-*V. Bad*, 2-*Bad*, 3-*Norma*l, 4-*Good*, 5-*V. Goo*d) vs. the best BACH formula with linear regression model and correlation coefficient.

4.3 - BACH Analysis

4.3.1 - The formula

Considering the ratings of acoustical quality by the priests of the churches, this R = - 0.684 seems very reasonable to accept as a good relationship and supports the idea that subjective quality in churches regarding music can be assessed by the use of this new binaural measure. Therefore it seems that the overall subjective quality of churches for music can be inversely proportional to the following formula.

BACH = (Coh 50 + Coh 63 + Coh 80) / (Coh 3150 + Coh 4000 + Coh 5000)

by the next relation:

SUBJECTIVE = 5.374 - 0.310 BACH (Standard error of estimate = 0.88);

or

BACH = 11.229 - 1.511 SUBJECTIVE (Standard error of estimate = 1.9).

That is, the greater the difference between the *coherence* at the high and very low frequencies, the lower the church was rated regarding the overall subjective impression of music quality. The explanation for this result is hypothesized to be in the combination of several factors. Considering that not many musical instruments use those high frequencies (4 and 5 kHz), it is perhaps the effect of overtones or upper partials that it is present. It may also be the effects in the perception of treble and timbre or tone color that are also been weighted. In fact only a few instruments such as the xylophone, glockenspiel, harp, piccolo and naturally the organ can give such high notes. Or it may be that a similarity of sounds at both ears, over a wide range of frequencies, are considered to be preferable in live performances as opposed to the enjoyment of a musical piece when listened to using stereo headphones or loudspeakers. It does not appear that this effect can be very important in explaining speech reception because those frequencies (3 to 6 kHz) are above the frequencies most significant to the understanding of speech. For most speech communication the critical frequency range is 300-3000 Hz although some speech cues occur as high as 8 kHz.

Some of these facts describe subtle details of listening to music. It is questionable if the subjective ratings obtained could discriminate. More data is necessary to validate a more positive explanation.

4.3.2 Individual church analysis

Figure 4 presents the analyses of individual churches in two comparison examples of the *coherence* spectra found. In these Figures the dark and clear symbols represent respectively the churches rated *5* (*Very Good*) and *1* (*Very Bad*). Table 9 complements these two Figures. In both of the churches rated *Very Bad* there is a drop in the *coherence* values around 5 kHz. By comparison, both churches rated *Very Good* present a peak in the coherence values between 2.5 and 4 kHz.

TABLE 9 - BACH results for a 4 church example.

CHURCH	SUBJECTIVE QUALITY	BACH
8 - Cedofeita new/Porto	*5 - Very Good*	2.3
18 - Moura	*1 - Very Bad*	9.6
25 - S. Francisco/Porto	*5 - Very Good*	1.6
32 - Sé Lamego	*1 - Very Bad*	10.7

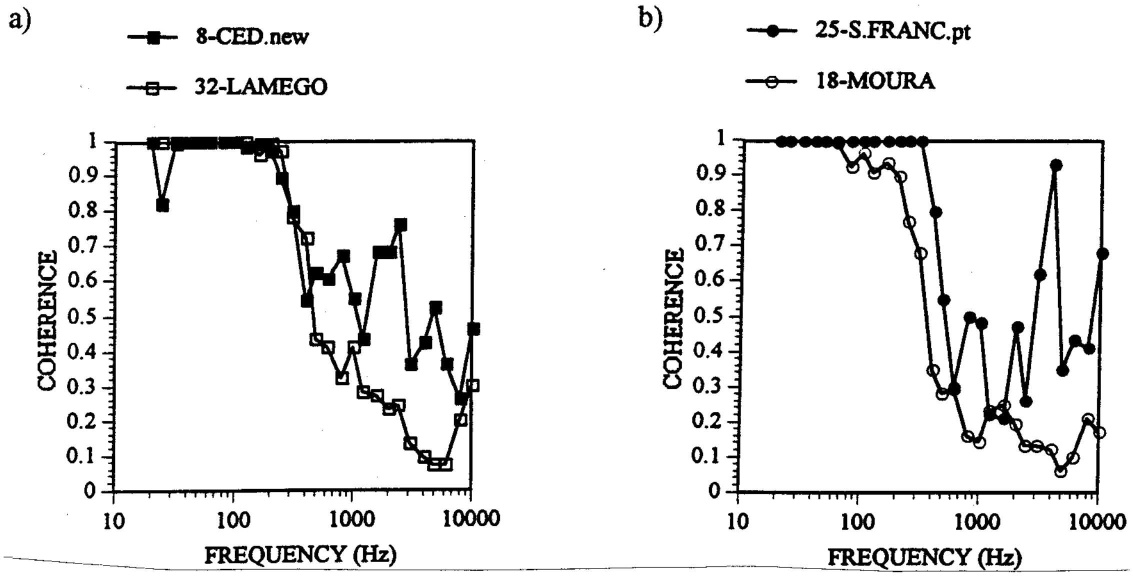


Figure 4 - Two pairwise comparisons of *coherence* spectra (dark/clear symbols relate to *Very Good/Very Bad* subjective quality ratings).
a) Church 8 - *Cedofeita New* (Contemporary) vs. Church 32 - *Sé Lamego* (Romanesque);
b) Church 25 - *S. Francisco,* Porto (Baroque) vs. Church 18 - *Moura* (Manueline).

4.3.3 ANOVA tests

ANOVA tests were performed to examine the significance of the differences among the groups of equal subjective quality ratings. The three options are plotted in Figure 5 and the ANOVA results are expressed in Table 10. The three options were:

OPTION A - 5 groups of equal subjective quality (*1* to *5* in Table 1);
OPTION B - 3 groups of equal subjective quality, labeled:
1 - BAD (= *1* + *2* of option A)
3 - NORMAL (= *3* of option A)
5 - GOOD (= *4* + *5* of option A);
OPTION C - 2 groups equal of subjective quality, labeled:
2 - BAD (= *1* + *2* + *3* of option A)
4 - GOOD (= *4* + *5* of option A).

TABLE 10 - Summary of ANOVA results for 3 options of grouping regarding the subjective quality. Number of pairwise comparisons found statistically different at various p-value levels.

		Number of Pairwise Comparisons				
OPTION	GROUPS	p-value< 0.05	p-value< 0.10	p-value< 0.15	p-value< 0.20	Max.
A	5	3	5	6	6	10
B	3	1	1	2	**3**	3
C	2	**1**	1	1	1	1

Using Table 10, the conclusion is that the five groups system of rating (*1* to *5*) is too narrow to give statistically significant differences (with a p-value < 0.20). The use of a three group rating method (Figure 5b) gives statistically differences in all possible pairwise comparisons (for a p-value < 0.20). The use of a two group rating method (Figure 5c) gives a statistically difference in the only possible pairwise comparison (but now for a p-value < 0.05). Therefore it can be stated that a three group rating of subjective quality in churches in the method used in this study is an acceptable choice.

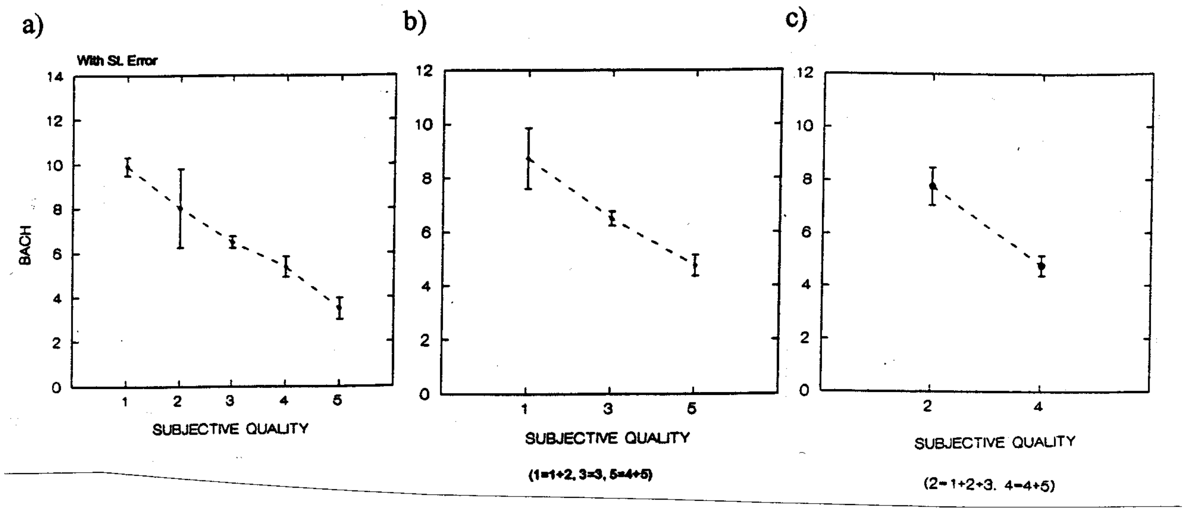


Figure 5 - Plot of BACH vs. three different methods of grouping subjective quality ratings with standard error confidence interval.
a) 5 level scale (1-*V. Bad*, 2-*Bad*, 3-*Normal*, 4-*Good*, 5-*V. Good*);
b) 3 level scale (1-*Bad*, 2-*Normal*, 3-*Good*; c) 2 level scale (1-*Bad*, 2-*Good*).

4.3.4 - General linear model

In order to verify the importance of all the parameters in the subjective ratings, a general linear model was performed. The goal was to relate the *SUBJECTIVE* rating to some of the other parameters used throughout this study. Therefore the model was done with the 28 coherence bands, the 39 acoustical measures (all frequency bands), the 15 architectural parameters and the 22 BACH formulas for a total of 104 parameters. With an α-to-enter/remove equal to 0.05 the final model using a forward stepwise procedure only presented BACH11 as a predictor of the *SUBJECTIVE* rating (with R^2 = 0.47 and a standard error of the estimate = 0.88). Using an α-to-enter/remove equal to 0.10 the final predictors will now include $BACH_{11}$ and COH80 but the R^2 only improved to 0.52 with a standard error of the estimate = 0.84. Consequently, no other parameter tested in this study could be used as a substitute for BACH to give the same type of information. This increases the validity and interest of this new measure and its individuality.

5 - BACH AND THE ACOUSTICAL MEASURES

5.1 - Acoustical Measures

To check the relationship between BACH and the acoustical measures, six well established monaural acoustical measures were taken. The six acoustical measures are defined below.

- Reverberation Time (RT) is the time it takes for sound to decay 60 dB. It was proposed by W. C. Sabine in 1900 (Sabine 1992). It is usually measured from a decay of 30 dB (from -5 to -35 dB or also RT30) and then multiplied by a factor of 2 as expressed in the following formula:

$RT = 2 [SD^{-1} (35) - SD^{-1} (5)]$

where $SD(t)$ = Sound decay as a function of time and $SD^{-1}(t)$ = Inverse function of SD(t).

In this study RT was calculated from reverse integration of the logarithmic decay curve obtained from an impulse response (Schroeder 1965).

- Early Decay Time (EDT) is the time it takes for sound to decay 60 dB. It was proposed by Jordan based on research made by Atal et al. in 1965 (Jordan 1970). It is an adaptation of the reverberation time now measured from a decay of 10 dB (from 0 to -10 dB or also EDT10) and then multiplied by a factor of 6 as expressed in the following formula:

$$EDT = 6 [SD^{-1} (10) - SD^{-1} (0)].$$

In this study EDT was calculated as described above for RT.

- Early to Late Sound Index or Clarity with a time window of 80 ms (C80) is one ratio of early-to-late sound energy or early-to-reverberant sound energy ratio C*t* or EL*t* (typically C80, but C30, C50 or C100 are also used). It is the ratio in dB between the energy received in the first *t* seconds of the received signal and the energy received afterwards. Reichardt et al. proposed it in 1975 where the limit of 80 ms was proposed as the limit of perceptibility for music. It is calculated by using 10 log of the ratio of the integrated squared pressure, arriving before the time *t*, to that arriving after time *t*.

$$C80 = 10 \log \frac{\int_0^{80} p^2(t)dt}{\int_{80}^{\infty} p^2(t)dt}$$

where $p(t)$ is the time function of the impulse response of the enclosure measured using a microphone at a particular location in the room.

- Early to Total Energy Ratio, Early Energy Fraction, Definition or *Deutlichkeit* with a time window of 50 ms (D) is the ratio between the energy received in the first 50 ms and the total energy received. It lies between 0 and 1. D was proposed by Thiele in 1953. The duration of 50 ms was called the limit of perceptibility regarding speech.

$$D = \frac{\int_0^{50} p^2(t)dt}{\int_0^{\infty} p^2(t)dt}.$$

- Center Time (TS, where the S stands for the German *Schwerpunkt*, center of gravity) is the point in time where the energy received before this point is equal to the energy received after this point. It was proposed by Cremer and Muller in 1978.

$$TS = 10 \log \frac{\int_0^{\infty} t.p^2(t)dt}{\int_0^{\infty} p^2(t)dt}$$

- Loudness, Total Sound Level, Overall Level or Strength of arriving energy (L) is the ratio, in dB, of the total energy received at a particular position in the enclosure and the energy received due to the direct sound alone (measured at a distance of 10 m from the source in an anechoic environment). It was first used by Gade and Rindel in 1984 following ideas introduced in earlier studies (Yamagushi 1972; Lehmann 1976;

$$L = 10 \log \frac{\int_0^{\infty} p^2(t)dt}{\int_0^{\infty} p_{10}^2(t)dt}$$

Cremer and Müller 1978). This measure is also denoted as G in the literature:

where $p_{10}(t)$ is the time function of the impulse response in free field conditions at a distance of 10 m.

Two bass ratios were calculated: BR_RT and BR_L proposed by Beranek (Beranek 1962) and Gade (Gade 1989). They are defined by the following equations:

BR_RT - Bass Ratio based on Reverberation Time

BR_RT = [RT(125) + RT(250)] / [RT(500) + RT(1k)]

BR_L - Bass Ratio based on Loudness

BR_L = [L(125) + L(250) - L(500) - L(1k)] / 2 where RT is the reverberation time for the specified octave bands and L is the overall level for the specified octave bands.

The method used to calculate the acoustical measures is based on the integrated impulse-response method described by Schroeder in 1965. A limited-bandwidth noise-burst is generated and transmitted into the church by a loudspeaker via an amplifier. The room's response to the noise-burst (called the impulse response) is then sampled from the RMS detector output of the sound level meter (Brüel & Kjær 1990).

Rather than a pistol, a loudspeaker emitting noise (short noise pulse bursts) in 3/2 octave frequency bands (to ensure that the received noise-burst is of 1/1 octave bandwidth) was used as sound source. For a specific power amplifier this system allows more energy to be transmitted into the room than with a pistol. This advantage is especially important when background noise is present. The pistol is a very powerful and practical sound source. However, its shots usually lack energy in the lower frequency bands and reproducibility (Brüel & Kjær 1988). Moreover, a pistol shot may be of too short duration to allow the noise to attain a steady level in the room (Brüel & Kjær 1980).

The receiving section consisted of one 1/2" diameter microphone (which changed position throughout the room) and a sound level meter with a 1/1-octave filter set. A filter centered on the same frequency as the filter in the transmitting section reduces the influence of background noise.

The procedure was commanded by specific control software (*Room Acoustics*) using a notebook computer *in loco*. The loudspeaker was placed at two sound source locations in each church: one in front of the altar to standardize the measurements and to be able to compare results among churches and another in the center of the main floor to simulate the sound of the congregation. The sound source was positioned at 0.8 m above the floor and at a 45^{o} angle with the horizontal plane. That angle was chosen to transmit more energy into the room volume, to try to better excite the reverberant field of the church. This loudspeaker position also gave more omnidirectionality to the sound source by locating the sides of the loudspeaker with less directivity such as in the back, facing the floor. A *diffuser*, a conical piece snap-locked onto the front of the cabinet, was used to render the measured results less dependent on the position and angle of inclination of the cabinet and to lower the directivity coefficient values.

Each measurement was calculated from an ensemble of three and four pulse responses in each position. This number of samples was chosen considering the high quality of the reproducibility of the sound source used, the number of samples used in the recent past of room acoustics as seen in the available literature, and the experience acquired by previous measurements made by the Acoustic Laboratory of the University of Florida College of Architecture. Five receiver positions were, on average, used, depending on the width of the church. The microphone at each location was placed at 1.30 m above the floor. In total, nearly 8000 values were determined (all combinations of frequency bands and source/receiver locations).

5.2 - Relationships between BACH and Monaural Acoustical Measures

To check the relationship between BACH and the acoustical measures, the Pearson correlation coefficients were calculated for all the octave bands involved. Table 11 shows the values found. Figure 6a presents the plot of the highest correlation found (with TS 4 kHz). With the results displayed in Table 11 (and Figure 6a) there are no strong and evident relations between any of the 39 acoustical measures and the new binaural measure. This increases its individuality.

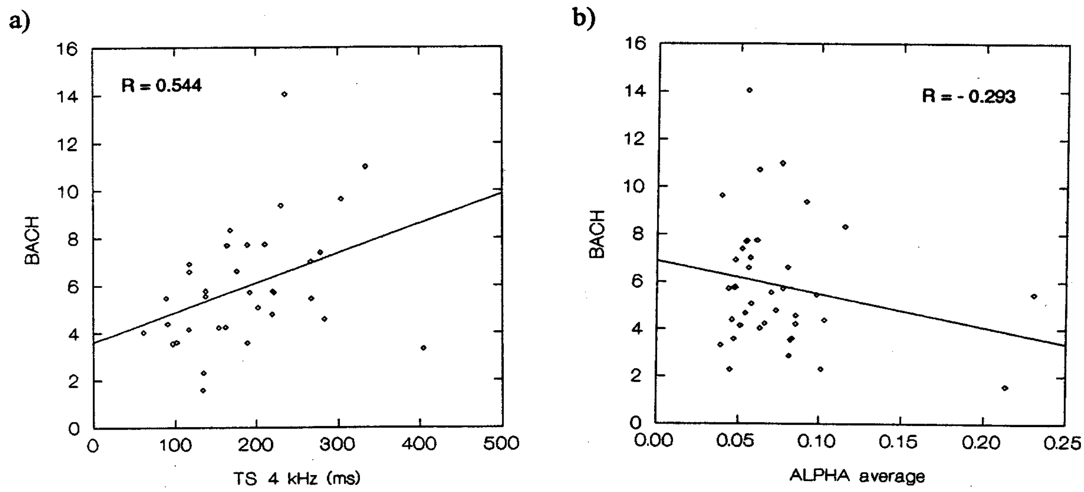


Figure 6 - Plots of BACH vs. the two quantities with the highest correlation coefficient found.
a) Vs. TS_4 kHz, the highest correlation among the acoustical measures; b) Vs. Average absorption coefficient, the highest correlation among the architectural parameters.

TABLE 11 - Pearson correlation coefficients for the relationship between BACH and the acoustical measures.

Measure	*R*	Measure	*R*	Measure	*R*	Measure	*R*
RT 125	0.315	EDT 2k	0.513	D 500	-0.364	L 125	0.033
RT 250	0.299	EDT 4k	0.524	D 1k	-0.443	L 250	0.040
RT 500	0.396	C80 125	-0.296	D 2k	-0.456	L 500	0.035
RT 1k	0.436	C80 250	-0.163	D 4k	-0.440	L 1k	0.052
RT 2k	0.494	C80 500	-0.391	TS 125	0.332	L 2k	0.021
RT 4k	0.517	C80 1k	-0.504	TS 250	0.305	L 4k	-0.105
EDT 125	0.280	C80 2k	-0.543	TS 500	0.433	BR_RT	-0.162
EDT 250	0.284	C80 4k	-0.485	TS 1k	0.507	BR_L	-0.006
EDT 500	0.410	D 125	-0.206	TS 2k	0.538	RASTI	-0.481
EDT 1k	0.473	D 250	-0.006	**TS 4k**	**0.544**		

6 - BACH AND THE ARCHITECTURAL PARAMETERS

6.1 - Architectural Parameters

To check the relationship between BACH and the architectural features of the churches, fifteen architectural parameters were used as seen in Table 12. Table 13 presents the results of the relationship analyses and a summary with simple statistics regarding the fifteen architectural parameters for the churches tested.

TABLE 12 - Description of the architectural parameters used.

TERM	DEFINITION
VOL_TOT	Volume Total (m^3)
VOL_NAVE	Volume Nave (m^3)
AREA_TOT	Area Total (m^2)
AREA_NAV	Area Nave (m^2)
L_MAX	Length Maximum (m)
L_NAVE	Length Nave (m)
H_MAX	Height Maximum (m)
H_NAVE	Height Nave (m)
VTO_ATO	Height Total average(m) [= Volume total / Area total]
W_NAVE	Width Nave (m)
W_AVG	Width average (m)
SEATS	Number of Seats
ALPHA	Absorption Coefficient [α average value for all surfaces]
ABSO_TOT	Total Absorption (m^2)
R_LOCAL	Constant of the room [$R = A / (1 - \alpha_{avg.})$]

Note: *NAVE* stands for the entire church excluding lateral chapels and main altar (apse)
TOTAL stands for the entire church including lateral chapels and main altar (apse)

TABLE 13 - Summary table for the 15 architectural parameters with simple statistics

Architectural Parameters	MIN.	MEDIAN	MEAN	MAX.
VOLUME total (m^3)	299	3918	5772	18674
VOLUME nave (m^3)	250	3386	4747	15936
AREA total (m^2)	56	427	450	1031
AREA nave (m^2)	42	333	353	781
LENGTH maximum (m)	11.5	30.8	33.1	62.2
LENGTH nave (m)	8.3	22.7	24.4	42.3
HEIGHT maximum (m)	6.5	13.4	14.8	39.0
HEIGHT nave (m)	5.8	10.9	12.0	26.0
HEIGHT total avg.* (m)	5.3	10.2	11.2	22.7
WIDTH nave (m)	3.6	11.0	13.0	37.5
WIDTH average (m)	5.0	13.0	13.6	36.8
SEATS	0	210	240	623
ALPHA average	0.030	0.062	0.073	0.230
ABSORPTION total (m^3)	13.7	130.5	170	962
R_LOCAL (m^2) **	14.4	136	189	1222

NOTES: * VOLUME total / AREA total , ** ABS. total / (1 - ALPHA.avg), SKEWNESS - Measure of asymmetry - Positive: long right tail, Negative: long left tail, KURTOSIS - Measure of normality - Signif. greater than zero: the variable is longer tailed than a normal distribution

6.2 - Relationships between BACH and Architectural Parameters

To check the relationship between BACH and the architectural parameters, the Pearson correlation coefficients were calculated for all the fifteen architectural parameters. Table 14 shows the values found. Figure 6b presents the plot of the highest correlation found (with *ALPHA AVERAGE*). With the results displayed in Table 14 (and Figure 6b) there are no evident relationship between any of the fifteen architectural parameters and the new binaural measure. This again, augments its uniqueness.

TABLE 14 - Pearson correlation coefficients for the relationships between BACH and the fifteen architectural parameters.

PARAMETER	R	PARAMETER	R	PARAMETER	R
VOLUME TOTAL	-0.016	LENGTH NAVE	0.084	WIDTH AVG.	-0.111
VOLUME NAVE	-0.004	HEIGHT MAXIMUM	0.075	SEATS	-0.009
AREA TOTAL	-0.046	HEIGHT NAVE avg.	0.183	ABSORPTION TOTAL	-0.253
AREA NAVE	-0.037	HEIGHT AVG. TOTAL	0.158	R LOCAL	-0.271
LENGTH MAXIMUM	0.148	WIDTH NAVE	-0.080	**ALPHA AVG.**	**-0.293**

7 - EQUIPMENT

For the acoustical measures the equipment used was sound level meter *Brüel & Kjær* type 2231; 1/3-1/1 octave filter set *Brüel & Kjær* type 1625; module Room Acoustics *Brüel & Kjær* type BZ7109; sound source *Brüel & Kjær* type 4224; microphone 1/2" diameter *Brüel & Kjær*; notebook computer *Compaq* LTE 386-25 MHz; and application software Room Acoustics *Brüel & Kjær* VP7155. For the RASTI measurements the equipment used was speech transmission meter *Brüel & Kjær* type 3361 consisting of transmitter type 4225 and receiver type 4419; and microphone 1/2" diameter *Brüel & Kjær* type 4129. For the other measurements the equipment used was dual channel real-time frequency analyzer *Brüel & Kjær* type 2144; two 1/2" diameter microphones *Brüel & Kjær* type 4165; two microphone preamplifiers *Brüel & Kjær* type 2639; and application software *Brüel & Kjær ty*pe 5306.

8 - CONCLUSIONS

The definition of a new binaural measure is believed to be an important step in studying the interaction between personal feelings regarding musical performances in churches and a physical quantity to measure it. Using binaural measurements and subjective information collected in 41 churches, Binaural Acoustical CoHerence (BACH), a new binaural measure was presented as a ratio of coherence values (1/3 octave bands) between low (50, 63 and 80 Hz) and high (3.15, 4 and 5 kHz) frequencies. It was found to be orthogonal among the other 104 acoustical measures and architectural parameters ($R^2_i < 0.3$). A linear correlation coefficient near 0.7 was found between the BACH measure and a five point subjective quality rating regarding music in churches (*V. Bad, Bad, Normal, Good*, and *V. Good*), supporting the hypothesis that this measure can be useful in predicting the subjective quality of music heard in churches. A three point (*Bad, Normal*, and *Good*) method of rating the subjective quality of music in churches was found to be more acceptable than the five point scale used.

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