Relationships between Subjective and Objective Acoustical Measures in Churches

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ABSTRACT

This study reports on subjective and objective acoustical field measurements made in a survey of 36 Catholic churches in Portugal built in the last 14 centuries. Monaural acoustical measurements (RT, EDT. C80, D50. TS and L) were taken at several source/receiver locations in each church and a group of college students was asked to judge the subjective quality of music. The listeners in each church evaluated live music performances at similar locations in each room. Evaluation sheets were used to record the listeners' overall impressions of room acoustic quality and also *Loudness, Reverberance. Intimacy, Envelopment, Directionality, Balance, Clarity Echoes* and *Background Noise*. This paper concentrates on the relationships of the subjective pararneters with the objective room acoustics measures and with the architectural features of the churches. Correlation analyses and statistical modeling identified significant relationships among the measures. For instance, linear correlation coefficients (| R |) of 0.8-0.9 were found for the relationships: *Reverberance*/RT and *Clarity*/C80; the maximum | R | found was 0.93 for *Echoes*/RT. Regarding architectural features the maximum | R | found was 0.87 between *Intimacy* and *Total Volume*.

1. INTRODUCTION

This study is part of a research program initiated in 1991 by Carvalho at the University of Porto and University of Florida[1]. The aim of the project is to explore methods to evaluate, predict and preview the acoustical qualities of churches. The program has included two major components to date:

- *Objective studies of existing churches* – Measurements were taken in 41 Portuguese Catholic churches, at multiple locations in each room. Several objective acoustical parameters were measured (RT, EDT, C80, D50, TS, L, BR_RT, BR_L, RASTI)[1].
- *Subjective studies of existing churches* – This has included both evaluating live musical performances in 36 churches and speech intelligibility testing. This work is characterized by the use of a sample of listeners, evaluation of several locations in each room, assessment of many rooms and comprehensive statistical analysis of the data[2].

This paper presents a report concerning relationships between subjective and objective acoustical parameters and with the architectural features found in this large sample of churches.

2. METHODOLOGY

2.1 Method Summary

The main research hypothesis is that the perceptions of people who attend services or concerts in churches could be measured and then related with objective room acoustics measures and architectural features. The among-room variations of subjective scores can be viewed as differences that result from the architectural and objective acoustical proprieties of the churches that experience shows actually exist. Therefore strategies to measure and predict these variations would be helpful to acoustical consultants and architects.

The study consisted of two parts, both involving analyses in (almost) empty churches. The first part was to gather objective results of the main room acoustics measures. The second part was to gather subjective evaluations from listeners, using live music performances, of the acoustical qualities of the churches using the same sample of churches.

There are certain limitations using this type of methodology for evaluation. The acoustical response of the church changes when it is fully occupied and the character of the music heard during a religious service or during a musical performance is likely different. Nevertheless this methodology gives a normalized acoustic environment that could be easily used for comparison.

2.2 Sample of Churches Used

The 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 and Portuguese churches can be considered representative of Catholic churches in the world.

This study reports on acoustical field measurements conducted between June 1993 and January 1996 in a major survey of 36 Roman Catholic churches in Portugal that were built between the 6th century and the 1960's. Table I presents an alphabetical list of the churches tested in the survey. The churches are a sample of 14 centuries of church building. The oldest church tested was number 14 (*Lourosa*), which was built around the 6-7th century. The most recent was church number 18 (*N.S. Boavista – Porto*), which was completed in the 1960's.

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

The churches were also grouped chronologically: 12 *Visigothic* or *Romanesque* churches (6th-13th centuries), 11 *Gothic* or *Manueline* churches (13th-16th centuries), 9 *Renaissance* or *Baroque* churches (16th-18th centuries) and 4 *Neoclassic* or *Contemporary* churches (18th-20th century). The main architectural features of these churches are displayed in Table 3.

A complete objective acoustical analysis of these churches is available[1] and also the overall results regarding the subjective acoustic parameters[2].

Table 1. List of the 36 churches tested

N.	Church Name	Vol (m^3)	N.	Church Name	Vol (m^3)
1	Almansil	578	19	Paco de Sousa	6028
2	Armamar	2487	20	Sant Sacram (Porto)	6816
3	Bas Estrela (Lisboa)	18674	21	S B Castris (Evora)	1314
4	Bravaes	946	22	S Francisco (Evora)	18631
5	Bustelo	6476	23	S Gens (Boelhe)	299
6	Cabeca Santa	751	24	S Pedrode Ferreira	2912
7	Caminha	5899	25	S Pedro de Rates	3918
8	Cedofeita-old (Porto)	1117	26	S Pedro de Roriz	2198
9	Cete	1515	27	S Roque (Lisboa)	14207
10	Clerigos (Porto)	5130	28	Se (Lamego)	13424
11	Golega	5563	29	Se (Porto)	15260
12	Lapa (Porto)	11423	30	Se (Silves)	10057
13	Lecado Bailio	9795	31	Serrado Pilar (Gaia)	11566
14	Lourosa	1163	32	Tibaes	8608
15	Mertola	1950	33	VianadoAlentejo	3358
16	Misericordia (Évora)	3338	34	Vila do Bispo	1290
17	Moura	6300	35	V N Azeitao	1239
18	N S Boavista (Porto)	3740	36	Vouzela	1148

Table 2. Architectural styles of the 36 churches tested

1	Visigothic	(6th-11th centuries)
2	Romanesque	(12th-13th centuries)
3	Gothic	(13th-15th centuries)
4	Manueline	(15th-16th centuries)
5	Renaissance	(16th-17th centuries)
6	Baroque	(17th-18th centuries)
7	Neoclassic	(18th-19th centuries)
8	Contemporary	(20th century)

Table 3. Simple statistics for architectural features of all 36 churches tested

Architectural Feature		Minimum	Median	Mean	Maximum
Volume	(m^3)	299	3829	5809	18674
Area	(m^2)	56	424	448	1031
Maximum height	(m)	6	14	15	39
Maximumlength	(m)	13	31	34	62
Width nave	(m)	5	11	12	26

2.3 Measurement Method for Objective Measures

Six objective room acoustics parameters were calculated in each church using the Impulse Response Method (a sound source generates sound within the room and a receiving section acquires the sound pressure signal after the sound source ceases emit). They are:

- *RT* Reverberation Time using the integrated impulse-response method. RT30 (from –5 to –35 dB);
- *EDT* Early Decay Time. *EDT10* (from 0 to –10 dB);
- *C80* Early to Late Sound Index or Clarity with a time window of 80 ms.
$$C80 = 10 \log E(0,80)/E(80,\infty);$$
- *D* Early to Total Energy Ratio (Early Energy Fraction, Definition or *Deutlichkeit*) with a time window of 50 ms.
$$D = E(0,50)/E(0,\infty);$$
- *TS* Center Time (point in time where the energy received before this point is equal to the energy received after this point);
- *L* Loudness, Total Sound Level or Overall Level (measure of the room's ability to amplify sound from the source position). This measure is also denoted as G in the literature.

The method used is based on the integrated impulse-response method. A limited-bandwidth noise-burst is generated and transmitted into the church by a loudspeaker via an amplifier. The response of the room to the noise-burst (the *impulse response*) is then sampled from the RMS detector output of the sound level meter (time constant 5 ms). A loudspeaker emitting short pulse noise bursts in 3/2 octave frequency bands (to ensure that the received noise-burst is of 1/1 octave bandwidth) was used as a sound source. The receiving system consisted of one 112" microphone and a sound level meter with a 1/1 octave filter set. The measurement was controlled by software installed on a notebook computer. In each church, two locations were used for the loudspeaker (in front of the altar and in the centre of the main floor).The sound source was positioned 0.8 m above the floor, at a 45° angle with the horizontal plane. Each measurement was calculated from an ensemble of 3 or 4 pulse responses in each position. Five receiver positions were, in average, used depending on the width of the church. The microphone, at each location, was placed 1.30 m above the floor. In total, approximately 8000 values were determined (all combinations of the 6 octave-frequency bands, 125 to 4k Hz, and source-receiver locations).The equipment used consisted of a sound level meter, 1/3-1/1 octave filter set, an analysis module *Room Acoustics* (B&K-BZ7 109), a sound source and a 1/2" microphone. The notebook computer had application software *Room Acoustics* (B&K-VP7 155) installed.

2.4 Measurement Method for Subjective Parameters

2.4.1 Listeners and Music Sound Sources

A group of 15 listeners was chosen to judge the quality of music throughout the churches. It was decided that a group of average and randomly selected listeners was not suitable for this study due to the need to have some acoustical knowledge concerning the parameters being tested. Therefore a group of 12 college students and 3 of their professors from the School of Music and the Performing Arts (Polytechnic Institute of Porto) was chosen.

To qualify their answers, all members of this group of listeners performed audiometric tests to evaluate their hearing capabilities. Audiograms from 125 Hz to 8 kHz and according to ISO R389/1964 and ANSI S3.6/1969 were performed giving results judged normal for all the members of the listeners' group.

In each church the listeners were seated in two similar locations named *Position A* (right hand seats of the centre of the longitudinal axis of the main floor) and *Position B* (central seats at the rear main floor). A total of nearly 500 questionnaires were scored.

They listened to baroque and classic music for approximately ten minutes. The music used was a live performance from oboe and cello played first individually and then in ensemble. The pieces played were 3 or 4-minutes parts of the Bach's *Suite No 3* (for the cello) and Telemann's *Fantasy* or Vivaldi's *Sonata in G minor* (for the oboe). After this, they played together the *Duet for oboe and bassoon* from Johann Gottlieb Naumann. Then they rated the acoustical qualities of the church on a questionnaire sheet. The scores from the questionnaires were entered into a computer spreadsheet and analyzed.

2.4.2 Acoustic Evaluation Sheet

The acoustic evaluation sheet used throughout the tests had ten semantic differential rating scales with seven points. The ten subjective acoustical parameters evaluated were:

- LOU – Loudness (the overall loudness or strength of the sound) from I (extremely weak) to 7 (extremely strong);
- CLA – Clarity (the degree to which notes are distinctly separated in time and clearly heard) from I (not clear enough) to 7 (extremely clear);
- REV – Reverberance (the persistence of sound in space) from l (totally dry) to 7 (too reverberant);
- INTM – Intimacy (the auditory impression of the apparent closeness of the orchestra) from l (absence of intimacy) to 7 (extremely intimate?;
- DIR – Direcotionality (the auditory impression that the sound comes from the axis of the sound source; importance of the direct sound field) from I (very bad) to 7 (excellent);
- ENV – Envelopment (the sense of being immersed in the sound or surrounded by it; importance of the reverberant field) from I (not surrounding at all) to 7 (extremely surrounding);
- BAL – Balarce (the relative levels of bass and treble frequencies) from I (totally unbalanced) to 7 (very well balanced);
- BGN – Background Noise (the sound heard other than from the source in the performance area) from 1 (not audible) to 7 (too loud);
- OIMP – Overall Impression 17 (the overall impression of the acoustical quality of the room) from I (very bad) to 7 (very good).

Remarks about Directionality. After pilot-tests, it was found that a new criterion (*directionality*) should be included together with the *envelopment*. In fact, the parameter envelopment was not easy for some listeners to fully comprehend and assess in churches. In this type of room the usually very large sound envelopment is not judged in the same way as that of many concert halls. Concert halls are usually smaller than churches and are generally considered more pleasant by listeners. However, in churches, the envelopment sensation is far above the maximum for music listening. Therefore, it was decided to include an easier measure to judge spatial aspects.This was named *directionality* and it attempts to evaluate not the spatial impression given by the reverberant field but the importance of the direct sound in the sensory experience. With this parameters the confusion partially disappeared as shown by some of the correlation analyses[2].

2.5 Architectural Parameters

The thirteen Architectural Parameters used are shown in Table 4.

Table 4. Architectural Parameters used

Term	Definition	Term	Definition
ABST	Total Absorption (m^2)	LMAX	Length Maximum (m)
CABS	Absorption Coefficient α (average value for all surfaces)	LNV	Length Nave (m)
		VTOT	Volume Total (m^3)
ATOT	Area Total (m^2)	VNV	Volume Nave (m^3)
ANV	Area Nave (m^2)	VTAT	Height Total average (m) (= Volume total/Area total)
HMAX	Height Maximum (m)	WNV	Width Nave (m)
HNV	Height Nave (m)	WAVG	Width average (m)

TOTAL stands for the entire church including lateral chapels and main altar; *NAVE* stands for the entire church excluding lateral chapels and main altar.

3. RESULTS

3.1 Relationships between Subjective Acoustic Parameters and Architectural Features

This chapter presents the results concerning the relationships between subjective acoustic parameters and the architectural features. In this chapter all relationships are with respect to the averaged subjective data for each church (36 data points = 36 churches).

Table 5 presents the absolute values for the linear correlation coefficients (Pearson coefficients) between subjective acoustic parameters and the thirteen architectural features. The best linear relationship exists between *Intimacy* and *Total Volume* (|R| = 0.87) demonstrating the importance that the church volume has regarding the feeling of intimacy. However, other important linear relationships were found:

Lo Mdness Iotal Absorption	(|R| = 0.78);
Clarity/NaveVolume	(|R| =0-71);
Echoes/Maximum Height	(|R| = 0.75);
Directionality/Nave Volume	(|R| = 0.73);
Balance/Nave Height	(|R| = 0.79);
Overall Impression/Total Volume	(|R| = 0.75).

Tables 6 and 7 present the best simple models (those with $R^2 > 0\ 55$), linear or nonlinear, of nearly 400 tested between subjective acoustical parameters and architectural features. Table 6 presents the models ordered by architectural feature and Table 7 presents them sorted by subjective acoustic parameter.

Table 5. Absolute values for linear correlation coefficients (|R|) between subjective acoustical parameters and architectural features. |R| > 0.85 are bold faced

| R |	BGN	LOU	CLA	REV	ECH	INTM	DIR	ENV	BAL	OIMP
VTOT	0.168	0.769	0.701	0.642	0.690	**0.873**	0.721	0.317	0.697	0.751
VNV	0.188	0.724	0.711	0.661	0.706	**0.854**	0.728	0.271	0.705	0.749
ATOT	0.064	0.741	0.693	0.652	0.620	**0.870**	0.692	0.291	0.621	0.712
ANV	0.094	0.659	0.688	0.669	0.613	0.821	0.681	0.212	0.592	0.683
LMAX	0.175	0.779	0.671	0.618	0.603	**0.861**	0.688	0.241	0.615	0.681
LNV	0.196	0.739	0.686	0.659	0.621	0.844	0.718	0.235	0.618	0.688
HMAX	0.206	0.657	0.670	0.620	0.747	0.737	0.681	0.095	0.743	0.678
HNV	0.269	0.678	0.670	0.590	0.733	0.755	0.673	0.175	0.789	0.681
WNV	0.148	0.353	0.533	0.559	0.495	0.543	0.465	0.000	0.466	0.476
WAVG	0.116	0.461	0.625	0.641	0.570	0.641	0.564	0.043	0.515	0.578
VTAT	0.324	0.694	0.637	0.596	0.725	0.755	0.668	0.172	0.773	0.663
ABST	0.129	0.783	0.589	0.522	0.505	0.827	0.592	0.431	0.581	0.630
CBAS	0.013	0.175	0.198	0.201	0.257	0.051	0.191	0.290	0.158	0.187

Table 6. Best simple models between subjective acoustical parameters and architectural features ordered by architectural feature. R^2 > 0.75 are bold faced

Equations	R^2 (variance explained)
$OIMP = 5.622 - 0.23 \times 10^{-3}\ VTOT + 0.45 \times 10^{-8}\ VTOT^2$	0.518
$LOU = 5.257 - 7.5 \times 10^{-5}\ VTOT$	0.591
$INTM = 5.410 - 1.6 \times 10^{-4}\ VTOT$	**0.763**
$OIMP=5.636-0.29 \times 10^{-3}VNV - 0.74 \times 10^{-8}VNV^2$	0.577
$INTM = 10.447 - 0.747 \log VNV$	0.732
$INTM = 5.751 - 2.9 \times 10^{-3}\ ATOT$	**0.756**
$INTM = 5.845 - 4.8 \times 10^{-3}\ ANV + 2 \times 10^{-6}\ ANV^2$	0.679
$LOU = 5.883-0.031\ LMAX$	0.607
$INTM = 6.666 - 0.064\ LMAX$	0.742
$INTM = 6.235 - 0.055\ LNV - 5.5 \times 10^{-4}\ LNV^2$	0.716
$ECH =0.719 + 0.101\ HMAX$	0.559
$BAL = 7.152 - 0.138\ HMAX + 1.5 \times 10^{-3}\ HMAX^2$	0.577
$INTM = 7.237 - 0.298\ HNV + 5.3 \times 10^{-3}\ HNV^2$	0.597
$BAL = 6.693 - 0.075\ HNV - 1.5 \times 10^{-3}\ HNV^2$	0.627
$INTM = 7.366 - 0.339\ VTAT + 6.7 \times 10^{-3}\ VTAT^2$	0.593
$BAL =6.717 - 0.079\ VTAT - 2.1 \times 10^{-3}\ VTAT^2$	0.601
$LOU = 5.377 - 3.8 \times 10^{-3}\ ABST$	0.613
$INTM=5.908 - 0.013\ ABST+ 1.4 \times 10^{-5}\ ABST^2$	0.718

Table 7. Best simple models between subjective acoustical parameters and architectural features sorted by subjective acoustical parameter. $R^2 > 0.75$ are bold faced

Equations	R^2 (variance explained)
LOU = $5.257 - 7.5 \times 10^{-5}$ VTOT	0.591
LOU =5.883-0.031 LMAX	0.607
LOU =$5.377\text{-}3.8 \times 10^{-3}$ ABST	0.613
ECH = 0.719 + 0.101 HMAX	0.559
INTM = $5.410 - 1.6 \text{ x } 10^{-4}$ VTOT	**0.763**
INTM = 10.447 – 0.747 log VNV	0.732
INTM = $5.751 - 2.9 \times 10^{-3}$ ATOT	**0.756**
INTM = $5.845 - 4.8 \times 10^{-3}$ ANV + 2×10^{-6} ANV^2	0.679
INTM = 6.666 – 0.064 LMAX	0.742
INTM = 6.235 – 0.055 LNV – 5.5×10^{-4} LNV^2	0.716
INTM = 7.237 – 0.298 HNV + 5.3×10^{-3} HNV^2	0 597
INTM = 7.366 – 0.339 VTAT + 6.7×10^{-3} VTAT^2	0.593
INTM= 5.908 – 0.013 ABST + 1.4×10^{-5} ABST^2	0.718
BAL = 7.152 – 0.138 HMAX + 1.5 × 10-3 HMAX^2	0.577
BAL = 6.693 – 0.075 HNV – 1.5 × 10 3 HNV^2	0.627
BAL = 6.717 – 0.079 VTAT – 2.1 × 10 3 VTAT^2	0.601
OIMP = 5.622 – 0.23 x 10-3 VTOT + 0.45 × 10–8 vTOT^2	0.578
OIMP = 5.636 – 0.29 x 10-3 VNV – 0.74 × 10 8 VNV^2	0.577

Figure l shows the graphical representation of the best simple models, presented in Tables 6 and 7. The best models ($R^2 = 0.76$) are those relating *Intimacy/Total Volume* and *Intimacy/Total Area*.

With the goal of trying to find a better model that can explain the relationships between subjective acoustical parameters and architectural features, general linear models were calculated. The operational procedure was to use forward or backward stepwise modeling with an a-to-enter (or to-remove) equal to 0.15.The accuracy of the models was judged primarily by their R2 which represents the percentage of variance explained and secondarily by the standard error of the estimate which represents the magnitude of differences between estimated and observed values. The general linear models are presented in Table 8.

The best general linear models were found for *Intimacy* ($R^2 = 0.87$) and *Loudness* ($R^2 = 0.77$) The auditory impressions of the apparent closeness of the orchestra and the overall loudness of the sound seem to be connected to the architectural features of the churches.

The subjective acoustical parameters with the worst adjustment model is the *Background Noise* (R^2 = 0 35). This can be easily explained because background noise is temporary and depends on the extraneous noise. *Envelopment* also presented a low R^2 (0.43) due to the fact that this parameter was not fully assessed in churches (as seen in 2.4.2).

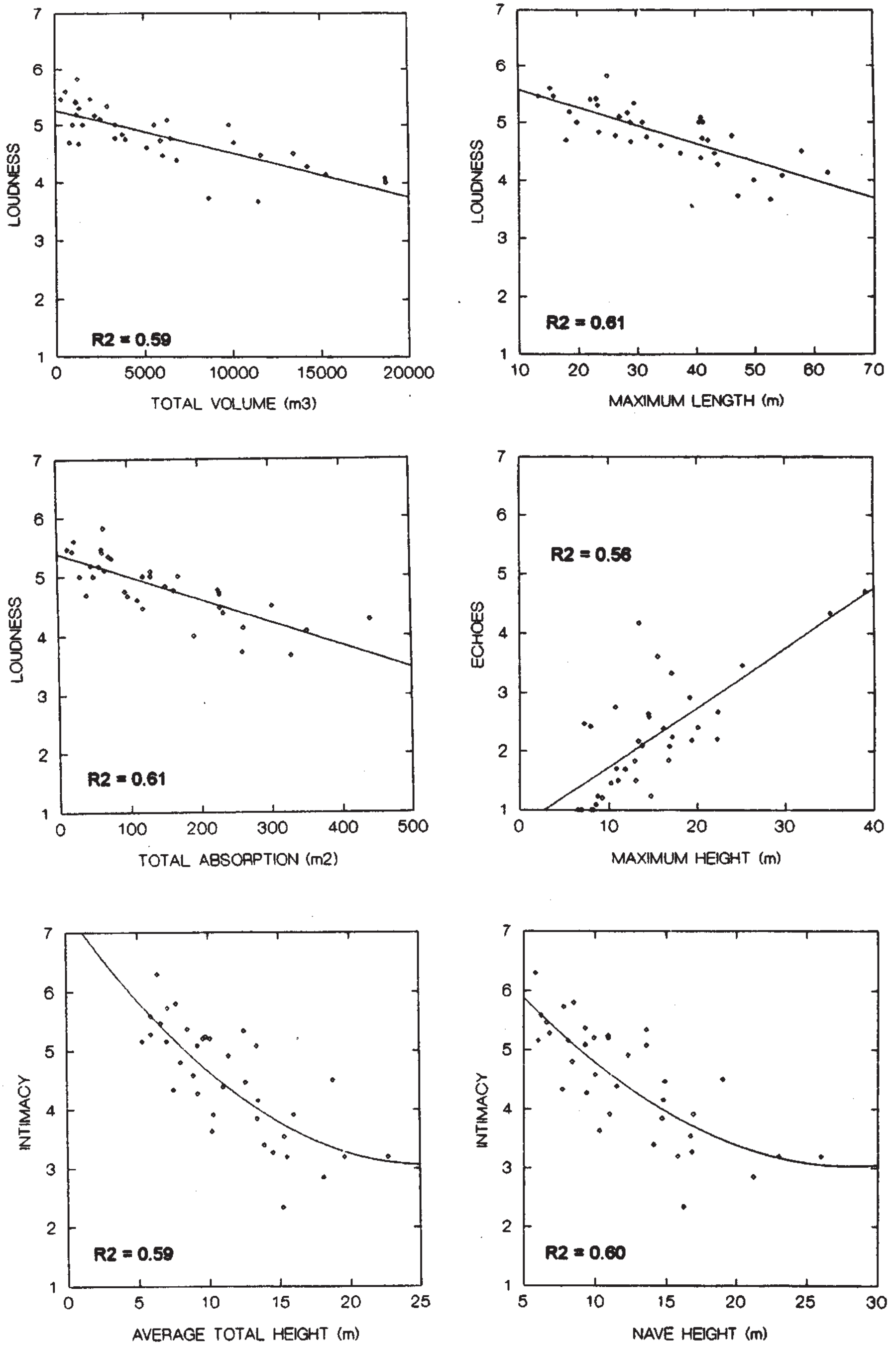

Figure 1. Mean values of subjective acoustic parameters for each church (36 points = 36 churches) plotted vs. the architectural parameters with regression models.

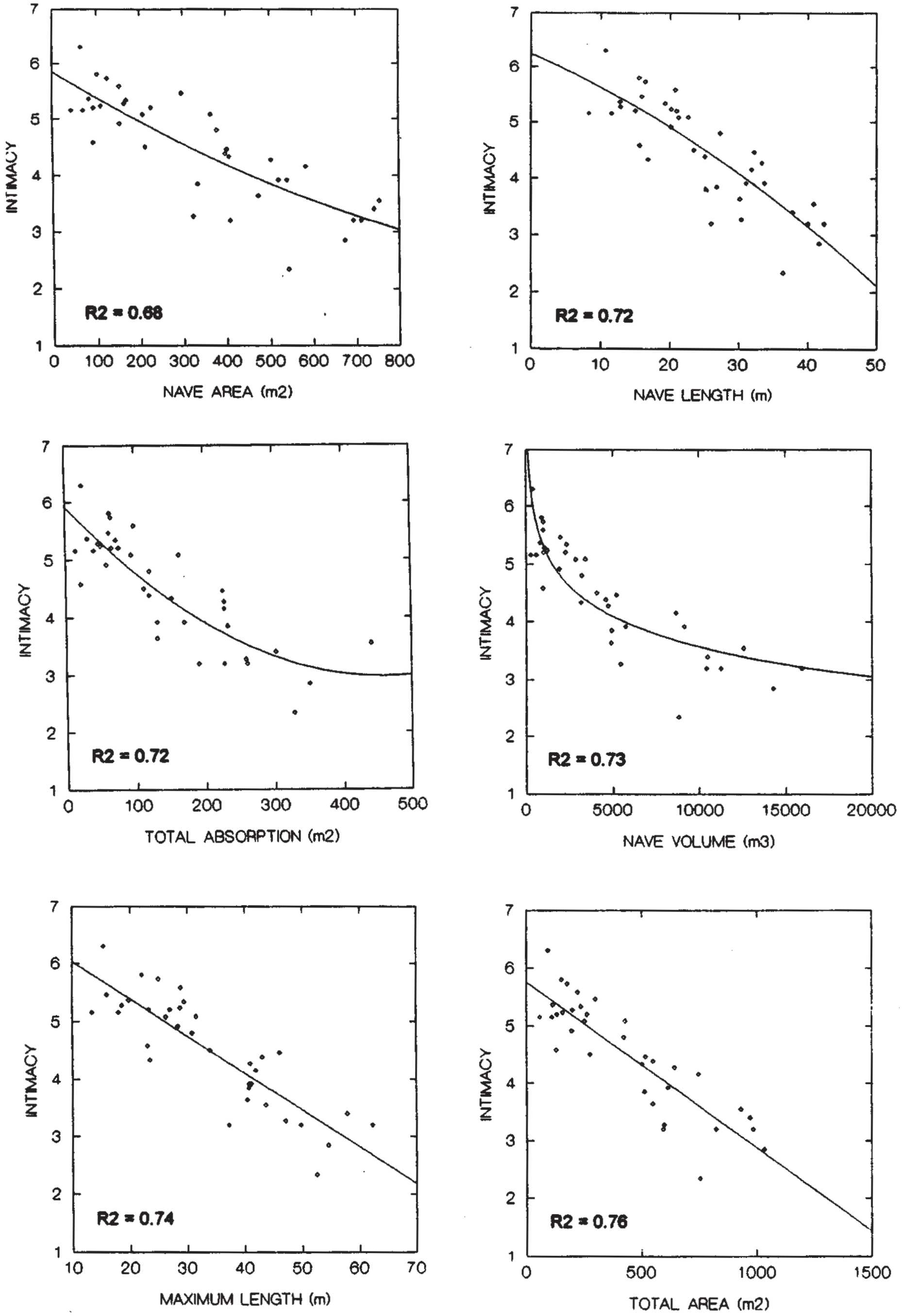

Figure 1 (cont.). Mean values of subjective acoustic parameters for each church (36 points = 36 churches) plotted vs. the architectural parameters with regression models.

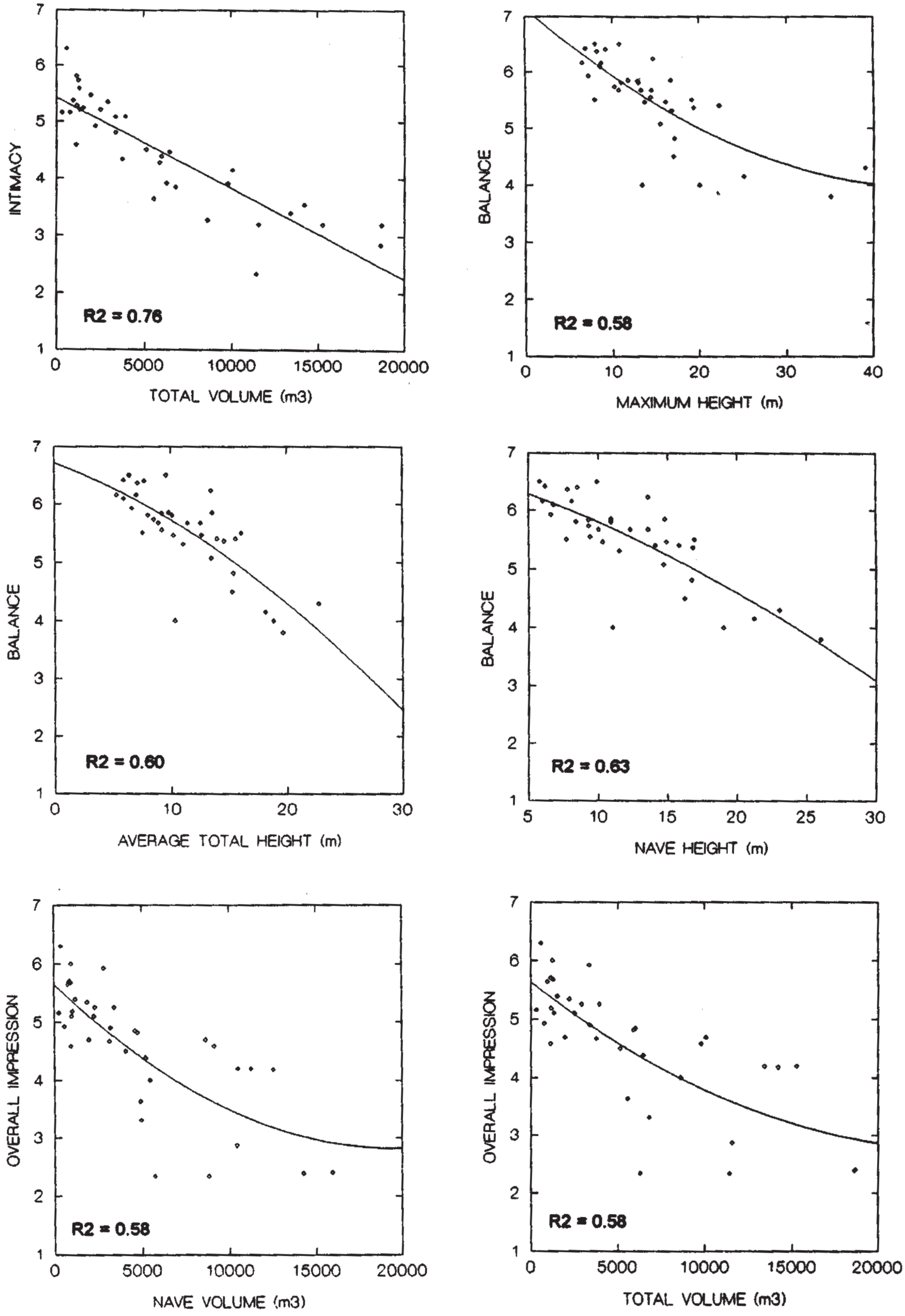

Figure 1 (cont.). Mean values of subjective acoustic parameters for each church (36 points = 36 churches) plotted vs. the architectural parameters with regression models.

The architectural parameter CABS (average absorption coefficient a) appears as variable in almost all the above general linear models indicating that this architectural feature can be important in predicting the subjective acoustic response of churches. The average width of churches (WAVG) performs almost as well as CABS in that function.

Table 8. Relationships between subjective acoustic parameters and architectural parameters (general linear models). R^2 > 0.75 are bold faced

General Linear Model Equations	Standard Error of Estimate	R^2
BGN =1.649 – 0.018 ATOT + 0.012 ANV + 0.084 LMAX + 7.2 × 10^{-3} ABST	0.95	0.35
LOU = 5.933 + 3.9 × 10–3 ANV – 0.028 LMAX + 0.102 HNV – 0.053 WAVG –0.097VTAT – 3.1 × 10–3 ABST	0.28	**0.77**
CLA = 6.833 – 0.116 HNV – 0.100 WAVG + 10.932 CABS	0.80	0.61
REV = 1.179-8.2 × 10^{-3} ANV + 0.179 LNV + 0.220 WAVG – 17.090 CABS	0.75	0.63
ECH = –0.284 – 5.6 × 10^{-3} ANV + 0.100 LNV + 0.062 HMAX + 0.142 WAVG – 12.929 CABS	0.59	0.69
INTM = 5.858 + 3.6 × 10^{-3} ATOT – 0.048 LMAX – 0.060 WNV – 7.3 x 10^{-3} ABST+ 14.86 CABS	0.39	**0.87**
DIR = 6.833 + 4.0 × 10^{-3} ANV – 0.100 LNV – 0.041 HNV – 0.095 WAVG + 10.831 CABS	0.52	0.66
ENV = 4.265 + 0.027 LMAX + 0.030 HMAX – 6.893 CABS	0.39	0.43
BAL = 6.881 – 0.107 HNV – 0.036 WNV + 5.819 CABS	0.43	0.70
OIMP = 5.561 + 6.0 × 10^{-3} ATOT – 0.048 LMAX – 0.114 WAVG – 8.5 × 10^{-3} ABST + 22.672 CABS	0.69	0.65

3.2 Relationships between Subjective and Objective Acoustical Parameters

3.2.1 Averaging Method

The following analyses used averaged data for each church. Seven averaging methods were tested using the average of 2, 3, 4 or 6 octave frequency-bands to obtain a single value for each objective room acoustic parameter and for each church. These options were named M I to M7 and are indicated in Table 9.

Table 9. Seven options of frequency averaging options

Code	Definition	
M1	Average of all 6 frequency bands	(125 to 4000 Hz octave bands)
M2	Average of the 2 highest frequency bands	(2000 and 4000 Hz octave bands)
M3	Average of the 4 lowest frequency bands	(125 to 1000 Hz octave bands)
M4	Average of the 4 highest frequency bands	(500 to 4000 Hz octave bands)
M5	Average of 4 medium frequency hands	(250 to 2000 Hz octave bands)
M6	Average of 3 medium frequency bands	(500, 1000 and 2000 Hz octave bands)
M7	Average of 2 medium frequency bands	(500 and 1000 Hz octave bands)

Regression analyses were performed with all these seven averaging options to check for their influence in the results6 The differences among them were found to be small. Nevertheless the option M7 (500 and 1k Hz) appeared the most suitable for this type of analysis, giving the highest percentage of variance explained for almost all situations. This averaging option was then used in the following studies.

3.2.2 Simple Models

Using the frequency averaging option M7 (average of 500 and 1000 Hz octave band data) stated above, linear and non linear models were used for each of the ten subjective acoustic parameters regarding their relationships with the six objective room acoustic parameters. Table 10 presents the equations for some of the best models found. The variance of the *Echoes* and *Reverberance* can be largely explained with just one of the six objective room acoustic parameters ($R^2 > 0.85$). For *Background Noise, Loudness, Intimacy, Envelopment* and *Balance* the percentage of variance explained by just one objective room acoustic parameter is not very significant ($R^2 < 0.55$).

The relationship *Reverberance*/RT with a $R^2 = 0.845$ confirms that RT is an objective measure of the sense of reverberance. However, using EDT the R^2 increases to 0.854 making this objective room acoustic measure a little more suited to the feeling of reverberance.

The relationship *Clarity*/C80 with a $R^2 = 0.72$ also confirms the suitability of C80 to objectively represent the sense of clarity. Nevertheless the EDT (and RT) are even better in performing that role ($R^2 = 0.83$). This confirms the ideas presented by Chiang[4,5]. The relationship *Overall Impression*/EDT ($R^2 = 0.74$) also confirms a similar consideration of this pair of parameters by Cervone[3].

The relationship *Loudness*/L with a $R^2 = 0.60$ does not fulfill the expectations regarding their relationship.

The Figure 2 presents some of the best or more significant relationships found between subjective and objective acoustic parameters using the frequency averaging option M7 (500 and 1k Hz).

3.2.3 General Linear Models

With the goal of trying to find better models that can explain the relationships between subjective and objective acoustical parameters, general linear models were calculated. Again the operational procedure was to use *forward* or *backward* stepwise modeling with an α-to-enter (or to-remove) equal to 0.15. The accuracy of the models was judged primarily by their R^2 which represents the percentage of variance explained and secondarily by the standard error of the estimate which represents the magnitude of differences between estimated and observed values. The general linear models are presented in Table 11 together with indication of which frequency averaging option (Mi) gtives the best model.

As seen in Table 11 almost all subjective parameters have suitable models except *Background Noise* and *Envelopment* ($R^2 < 0.70$). The objective parameter RT appears as variable in almost all general linear models indicating that this measure can be very important in predicting the subjective acoustic response of churches. EDT and L perform almost as well as RT in that function. C80 however, does not appear in the models, perhaps revealing that it is not a significant measure in predicting subjective acoustic responses in churches.

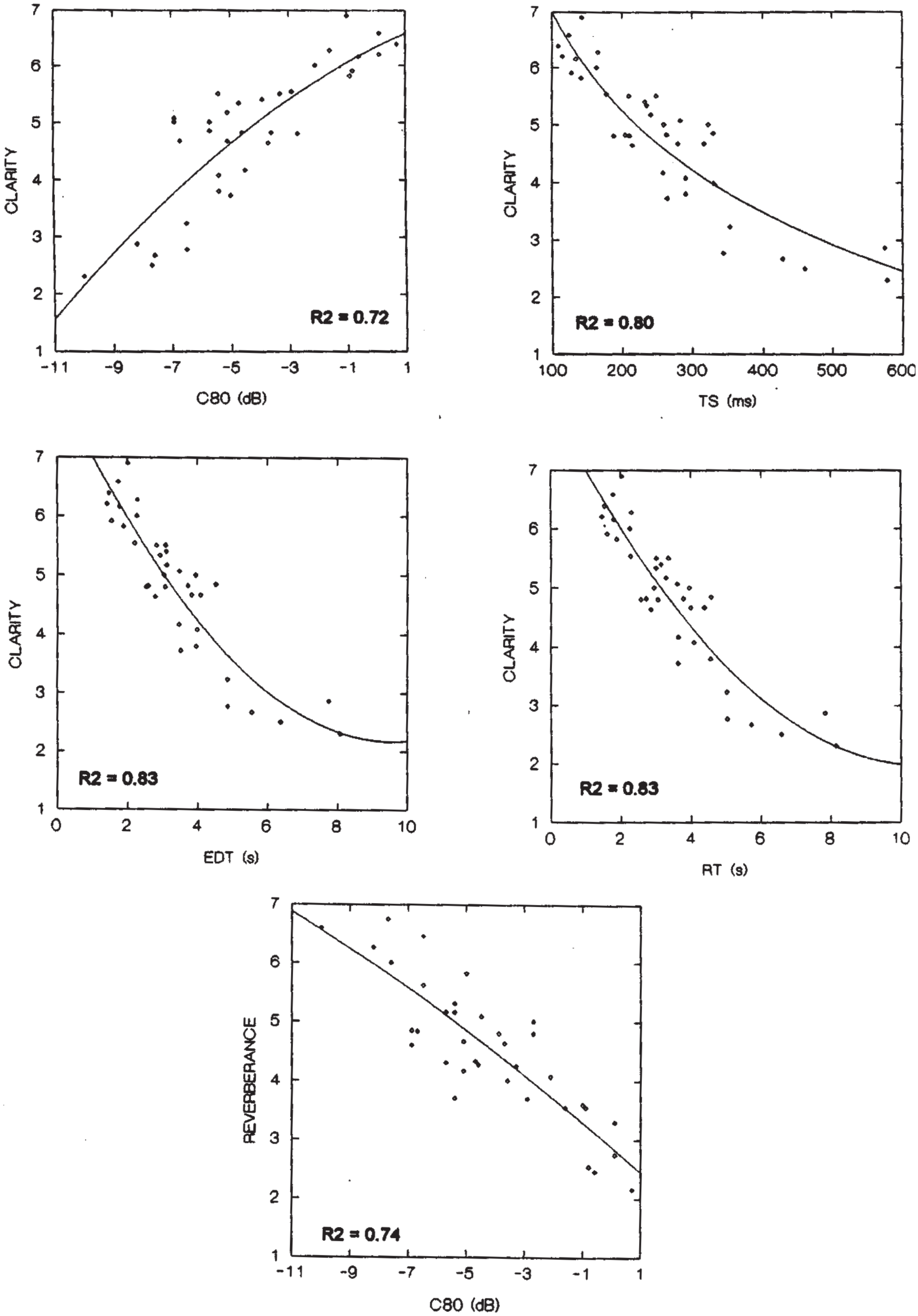

Figure 2. Relationships between subjective and objective acoustic parameters using the frequency averaging option M7 (500 and 1k Hz)

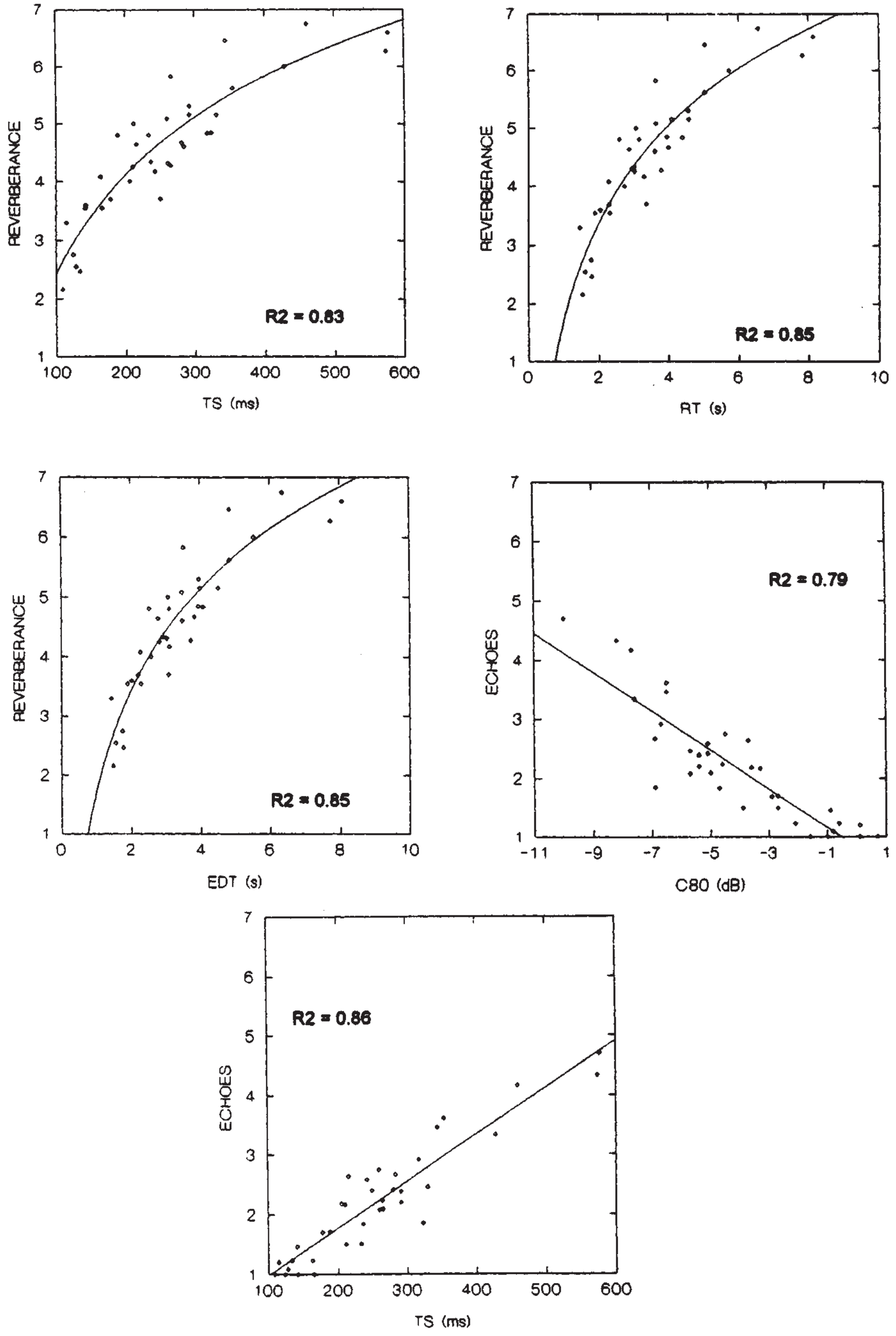

Figure 2 (cont.). Relationships between subjective and objective acoustic parameters using the frequency averaging option M7 (500 and 1k Hz)

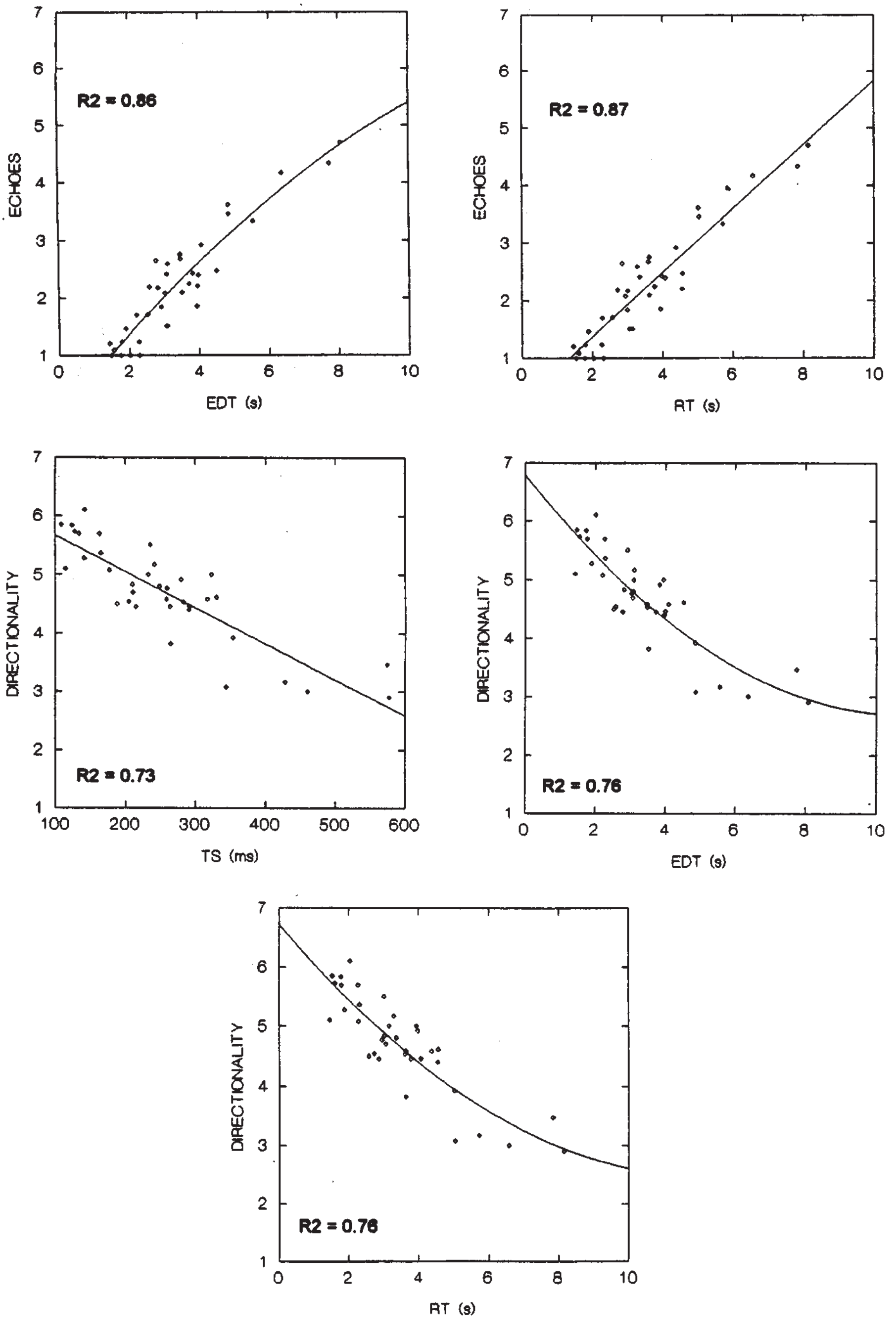

Figure 2 (cont.). Relationships between subjective and objective acoustic parameters using the frequency averaging option M7 (500 and 1 k Hz)

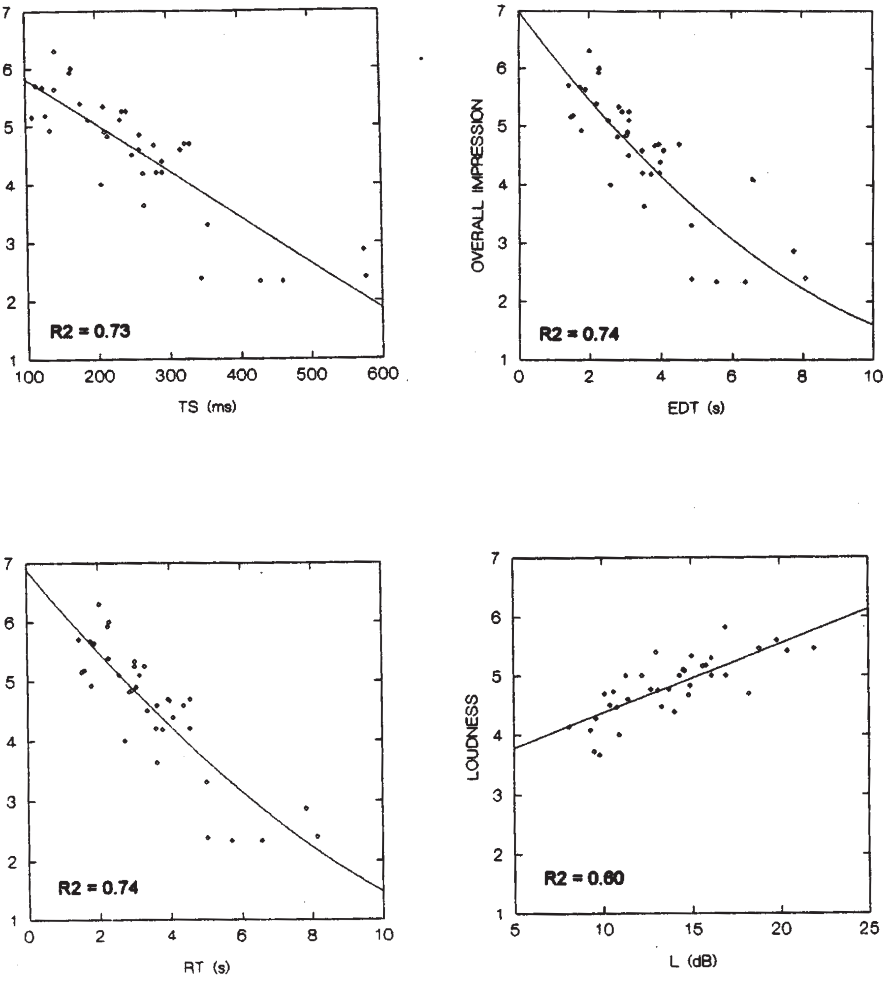

Figure 2 (cont.). Relationships between subjective and objective acoustic parameters using the frequency averaging option M7 (500 and 1 k Hz)

Table 10. Most significant relationships between subjective and objective acoustic parameters (using the frequency averaging method M7 – 500/lk Hz). $R^2 > 0.75$ are bold faced.

Equations (simple methods)	R^2 (variance explained)
$CLA = 6.330 + 0.265\ C80 – 0.015\ C80^2$	0.724
$CLA = 18.717 – 2.542 \log TS$	**0.798**
$CLA = 8.230 – 1.265\ EDT + 0.066\ EDT^2$	**0.829**
CLA =8.108-1.162 RT + 0.055RT2	**0.834**
$REV = 2.876 – 0.421C80 – 5.1 \times 10^{-3}\ C80^2$	0.740
$REV = 8.902 + 2.459 \log TS$	**0.825**
REV = 1.709 + 2.417 1og RT	**0.845**
$REV = 1.741 + 2.451 \log EDT$	**0.854**
$ECH = 0.829 – 0.329\ C80$	**0.788**
$ECH = 0.044 + 0.744\ EDT – 0.020\ EDT^2$	**0.864**
$ECH = 0.192 + 7.9 \times 10^{-3}\ TS$	**0.864**
$ECH = 0.023 + 0.682\ RT – 0.014\ RT^2$	**0.872**
$DIR = 6.281 – 6.1 \times 10^{-3}\ TS$	0.729
$DIR = 6.798 – 0.761\ EDT + 0.035\ EDT^2$	**0.760**
$DIR = 6.714 – 0.693\ RT + 0.028\ RT^2$	**0.762**
$OlMP = 6.606 – 7.9 \times 10^{-3}\ TS$	0.725
$OIMP = 6.991 – 0.826\ LDT + 0.029\ EDT^2$	0.735
$OIMP = 6.890 – 0.744\ RT – 0.020RT^2$	0.742
$LOU = 2.100 + 0.196L$	0.597

4. CONCLUDING REMARKS

The scope of this work is to investigate the subjective acoustical behavior of churches, how it relates with other parameters and to determine simple formulae to predict acoustical parameters by the use of elementary architectural features and objective room acoustic parameters.

This work continues and develops previous studies in this field and has its basis in subjective and objective acoustical analyses done on field measurements in a survey of 36 Catholic churches in Portugal that were built in the last 14 centuries.

This is an interim paper on work in progress, and some results are perceived as a basis for further study. However, there are several conclusions that can be drawn. The results of this research indicate that statistically significant relationships between subjective and objective criteria can be found in churches.

Architectural features that are important in defining the overall acoustical impression in churches were identified. *Total Volume* was found to be the most important of these, and gave the best fit between subjective acoustical parameters and architectural measures for *Intimacy/Total Volume*. *Intimacy* and *Loudness* were the only subjective acoustical parameters where the influence of the architectural parameters was statistically significant in the listeners' response.

Table 11. Relationships between Subjective and Objective Acoustic Parameters (General Linear Models) with the frequency averaging option used. R^2 > 0.75 are bold faced

General Linear Model Equations	Estimate (StD of residuals)	St Error of (variance explained)	R2 option Mi	Averaging
BGN (no suitable model)		–	–	–
LOU	= 3.630 – 1.620 RT + 1.640 EDT – 0.099 L	0.30	0.70	M1
CLA	= 6.336 – 0.629 RT + 0.052 L	0.52	**0.83**	M7
REV	= 5.118 + 2.169 EDT – 7.666 D – 0.025 TS	0.48	**0.85**	M7
ECH	= 0.987 + 1.615 RT- 1.161 EDT – 2.071 D	0.34	**0.89**	M6
INTM	= 3.387 – 2.433 RT + 2.243 EDT + 0.150 L	0.46	**0.79**	M1
DIR	= 4.858 – 1.067 RT + 0.010 TS + 0.071 L	0.39	**0.80**	M1
ENV	= 4.276 – 1.719 RT + 1.798 EDT- 3.237 D + 0.069 L	0.36	0.51	M1
BAL	= 6.050 – 2.342 RT + 2.077 EDT + 0.049 L	0.36	**0.78**	M3
OIMP	= 5.379 – 3.175 RT + 2.776 EDT + 0.066 L	0.49	**0.81**	M1
RT	= 6.192 + 0.140 BGN + 0.733 REV + 1.058 ECH + 0.353 INTM + 1.235 DIR – 0.870 OIMP	0.48s	**0.92**	M1
EDT	= 4.342 + 0.122 BGN + 0.692 REV + 0.890 ECH + 0.954 DIR – 0.513 OIMP	0.47s	**0.91**	M6
C80	= 23.82 – 0.278 BGN – 1.195 CLA – 2.102 REV – 1.853 ECH – 1.120 INTM – 2.734 DIR – 0.804 ENV + 0.913 OIMP	0.84 dB	**0.92**	M5
D	= 1.168 – 0.012 BGN – 0.059 REV – 0.058 ECH + 0.048 INTM – 0.116 DIR – 0.044 ENV	0.04	**0.83**	M5
TS	= 521.9 + 36.46 CLA + 55.45 REV + 70.51 ECH + 72.98 DIR + 26.28 ENV – 64.22 OIMP	32 ms	**0.91**	M1
L	= 14.06 + 3.949 LOU + 2.465 INTM + 3.200 DIR – 3.778 OIMP	1.80 dB	**0.77**	M1

The architectural parameter CABS (average absorption coefficient a) appears as variable in almost all the general linear models indicating that this architectural feature can be important in predicting the subjective acoustic response of churches. The average width of churches (*WAVG*) performs almost as well as *CABS* in that function.

In general, some of the thirteen architectural parameters tested can be used in general linear models to explain from 61% to 87% of the variance of the eight main subjective acoustic parameters studied.

The best fit between subjective acoustical parameters and objective acoustical parameters was for *Echoes/RT*. The relationship found for *Reverberance/RT* confirmed that *RT* can be a reasonable predictor of the subjective feeling of reverberance. *Reverberance* always needed *RT* or *EDT* to be predicted by the objective acoustical parameters however, *EDT* appeared as more suitable to explain the sense of reverberance.

The relationship *Clarity/C80* (R^2 = 0.72) also confirms the suitability of *C80* to objectively represent the sense of clarity. Nevertheless the *EDT* (and the *RT*) are even better in performing that role (R^2 = 0.83). The relationship *Overall Impression/EDT* (R^2 = 0.74) also confirms a similar idea concerning this pair of parameters. The relationship *Loudness/L* with a R^2 = 0.60 does not fulfill the reasonable expectations regarding their relationship.

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