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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 acoustics qualities and also *Loudness, Reverberance, Intimacy, Envelopment, Directionality, Balance, Clarity, Echoes,* and *Background Noise.* This paper complements the one presented at the Indianapolis ASA Meeting (May 1996) and concentrates on the relationships of the subjective parameters with the objective room acoustics measures and with the architectural features of the churches. The results are graphed and analyzed by comparisons. 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 the author at the University of Porto and University of Florida. 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) (Carvalho 1994).
- *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 (Carvalho *et al.* 1996).

This paper presents a preparatory report concerning relationships between subjective and objective acoustical parameters and with the architectural features found in this large sample of churches. A paper in the continuation of this work is expected to be presented at the 133rd Meeting of the Acoustical Society of America in State College, concerning relationships between speech intelligibility and objective acoustic measures and architectural features.

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 regarding analyses in (almost) non occupied 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 evaluations. 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 an actual musical performance is likely different. Nevertheless this methodology gives a normalized sound environment that could be easily compared among churches.

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 in the world. Portuguese churches can be considered a representative example of Catholic churches in the world.

This study reports on acoustical field measurements done 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 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 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.

Acoustical evaluations were held in churches grouped by large periods of history: 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 as a Ph.D. Dissertation (Carvalho 1994). The overall results regarding the subjective acoustic parameters can be seen in Carvalho *et al.* 1996.

Table 1 - List of the 36 churches tested.

N.	CHURCH NAME	VOLUME (m^3)	N.	CHURCH NAME	VOLUME (m^3)
1	ALMANSIL	578	19	PAÇO DE SOUSA	6028
2	ARMAMAR	2487	20	SANT. SACRAM. (PORTO)	6816
3	BAS. ESTRELA (LISBOA)	18674	21	S. B. CASTRIS (ÉVORA)	1314
4	BRAVÃES	946	22	S. FRANCISCO (ÉVORA)	18631
5	BUSTELO	6476	23	S. GENS (BOELHE)	299
6	CABEÇA SANTA	751	24	S. PEDRO DE 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	CLÉRIGOS (PORTO)	5130	28	SÉ (LAMEGO)	13424
11	GOLEGÃ	5563	29	SÉ (PORTO)	15260
12	LAPA (PORTO)	11423	30	SÉ (SILVES)	10057
13	LEÇA DO BAILIO	9795	31	SERRA DO PILAR (GAIA)	11566
14	LOUROSA	1163	32	TIBÃES	8608
15	MÉRTOLA	1950	33	VIANA DO ALENTEJO	3358
16	MISERICÓRDIA (ÉVORA)	3338	34	VILA DO BISPO	1290
17	MOURA	6300	35	V. N. AZEITÃO	1239
18	N. S. BOAVISTA (PORTO)	3740	36	VOUZELA	1148

Table 2 - Architectural styles of the 36 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 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
MAXIMUM LENGTH (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 pulses-noise 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. The receiving section consisted of one 1/2" microphone and a sound level meter with a 1/1 octave filter set. All the procedure was controlled by a specific software using, *in loco*, a notebook computer. In each church, two sound source locations were used for the loudspeaker (in front of the altar and in the center of the main floor). The sound source was positioned at 0.8 m above the floor and making a 45^{o} 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 at 1.30 m above the floor. In total, near 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 Sound Level Meter "Brüel & Kjær" (B&K) type 2231, 1/3-1/1 Octave Filter Set B&K-1625, Module *Room Acoustics* B&K-BZ7109, Sound Source B&K-4224, Microphone 1/2" B&K, Notebook computer *Compaq* LTE and Application Software *Room Acoustics* B&K-VP7155.

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 of having same 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 center of the longitudinal axis of the main floor) and *Position B* (central seats at the rear main floor). A total of near 500 questionnaires were scored in the rooms.

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-minute 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 using the *SYSTAT®* computer software package.

2.4.2 - Acoustics Evaluation Sheet

The acoustics 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 *1* (extremely weak) to *7* (extremely strong);
- *CLA - Clarity* (the degree to which notes are distinctly separated in time and clearly heard) from *1* (not clear enough) to *7* (extremely clear);
- *REV - Reverberance* (the persistence of sound in space) from *1* (totally dry) to *7* (too reverberant);

- *INTM - Intimacy* (the auditory impression of the apparent closeness of the orchestra) from *1* (absence of intimacy) to *7* (extremely intimate);
- *DIR - Directionality* (the auditory impression that the sound comes from the axis of the sound source; importance of the direct sound field) from *1* (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 *1* (not surrounding at all) to *7* (extremely surrounding);
- *BAL - Balance* (the relative levels of bass and treble frequencies) from *1* (totally unbalanced) to *7* (very well balanced);
- *ECH - Echoes* (long delayed reflections that are clearly audible) from *1* (none detected) to *7* (clearly heard);
- *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* (the overall impression of the acoustical quality of the room) from *1* (very bad) to *7* (very good).

Remarks about *Directionality*. After the pilot-tests, done previously to engage in the full testing program, 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 similarly to that of many concert halls. This is due that the *large* envelopment sensation in concert halls and in churches have different sensory meanings. The one in concert halls is usually smaller than in churches and generally considered pleasant by listeners. However, in churches the *huge* level of envelopment is difficult to assess due to the reverberant conditions. Therefore, due to its usually large reverberant conditions, the envelopment sensation is far above the maximum optimum for music listening in many churches. Therefore, a need was determined to include an easier measure to judge spatial aspects of the experience that was conceptually similar. 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 parameter the confusion partially disappeared as shown by some of the correlation analyses (Carvalho *et al.* 1996).

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 done with the averaged subjective acoustic parameter 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) presenting the clear importance that the church volume has regarding the feeling of intimacy. However, other important linear relationships were found:

Loudness/Total Absorption	($|R|$ = 0.78);
Clarity/Nave Volume	($|R|$ = 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 non linear, 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)**
$OIMP = 5.622 - 0.23 \times 10^{-3}\ VTOT + 0.45 \times 10^{-8}\ VTOT^2$	0.578
$LOU = 5.257 - 7.5 \times 10^{-5}\ VTOT$	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 = $5.377 - 3.8 \times 10^{-3}$ ABST	0.613
ECH = 0.719 + 0.101 HMAX	0.559
INTM = $5.410 - 1.6 \times 10^{-4}$ 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 = $5.622 - 0.23 \times 10^{-3}$ VTOT + 0.45×10^{-8} $VTOT^2$	0.578
OIMP = $5.636 - 0.29 \times 10^{-3}$ VNV - 0.74×10^{-8} VNV^2	0.577

The Figure 1 shows the graphical presentation 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 the *forward* or the *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 8.

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 - 0.097 VTAT - 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 - 7.3×10^{-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

The best general linear models were found for *Intimacy* (R^2 = 0.87) and *Loudness* (R^2 = 0.77). The auditory impression 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 easy to be fully assessed in churches (as seen in 2.4.2).

The architectural parameter CABS (average absorption coefficient α) 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.

3.2 - Relationships between Subjective and Objective Acoustical Parameters

3.2.1 - Averaging Method

The following analyses were done with 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-number for each objective room acoustic parameter and for each church. These options were named M1 to M7 and are explained 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 bands (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 results (Morgado 1996). The differences among them were found to be small. Nevertheless the option M7 (500 and 1k Hz) appeared as 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 below.

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 represent 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 in Chiang 1991 and 1994. The relationship *Overall Impression*/EDT (R^2 = 0.74) also confirms a similar idea concerning this pair of parameters shown in Cervone *et al.* 1991.

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

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).

Table 10. Most significant relationships between subjective and objective acoustic parameters (using the frequency averaging method M7 - 500/1k Hz). R^2 > 0.75 are bold faced.

EQUATIONS (SIMPLE MODELS)	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 = $8.108 - 1.162\ RT + 0.055\ RT^2$	**0.834**
REV = $2.876 - 0.421\ C80 - 5.1 \times 10^{-3}\ C80^2$	0.740
REV = $- 8.902 + 2.459 \log TS$	**0.825**
REV = $1.709 + 2.417 \log RT$	**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**
OIMP = $6.606 - 7.9 \times 10^{-3}\ TS$	0.725
OIMP = $6.991 - 0.826\ EDT + 0.029\ EDT^2$	0.735
OIMP = $6.890 - 0.744\ RT - 0.020\ RT^2$	0.742
LOU = $2.100 + 0.196\ L$	0.597

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. The operational procedure was to use the *forward* or the *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 the indication of which frequency averaging option (Mi) gives the best model. The general linear models for all the frequency averaging options (M1 to M7) can be seen in Morgado 1996.

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.

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	**St. Error of Estimate (StD of residuals)**	**R^2 (variance explained)**	**Avging option Mi**
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	0.48 s	**0.92**	M1
EDT = - 4.342 + 0.122 BGN + 0.692 REV + 0.890 ECH + 0.954 DIR - 0.513 OIMP	0.47 s	**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

4 - SUMMARY

The scope of this work is to investigate the subjective acoustical behavior of churches, how it relates with other parameters and to determine simple formulas 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. Series of *in loco* analyses regarding subjective acoustical parameters (*Background Noise*, *Balance*, *Clarity*, *Directionality*, *Echoes*, *Envelopment*, *Intimacy*, *Loudness*, *Reverberance*, and *Overall Impression)* were done by listeners, to reveal through statistical procedures the relationships between the subjective acoustical parameters and the architectural parameters of churches (*Volume, Area, Length, Width*, etc.), as well as between the subjective acoustical parameters and important acoustical objective measures (*RT*, *EDT*, *C80*, *D*, *TS*, and *L*). The aim is to provide basic information about some subjective acoustical parameters to predict them in churches at early stages of design or without the need of measurements in the real buildings.

This is an interim paper on work in progress. Some of the results are perceived as hypotheses for additional 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 to defining the overall acoustical impression in churches were identified. *Total Volume* was found as the most important of these being 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.

The architectural parameter *CABS* (average absorption coefficient α) 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 connection.

Additional analysis and modeling continues on this large data base to more entirely explore the topics raised in this paper.

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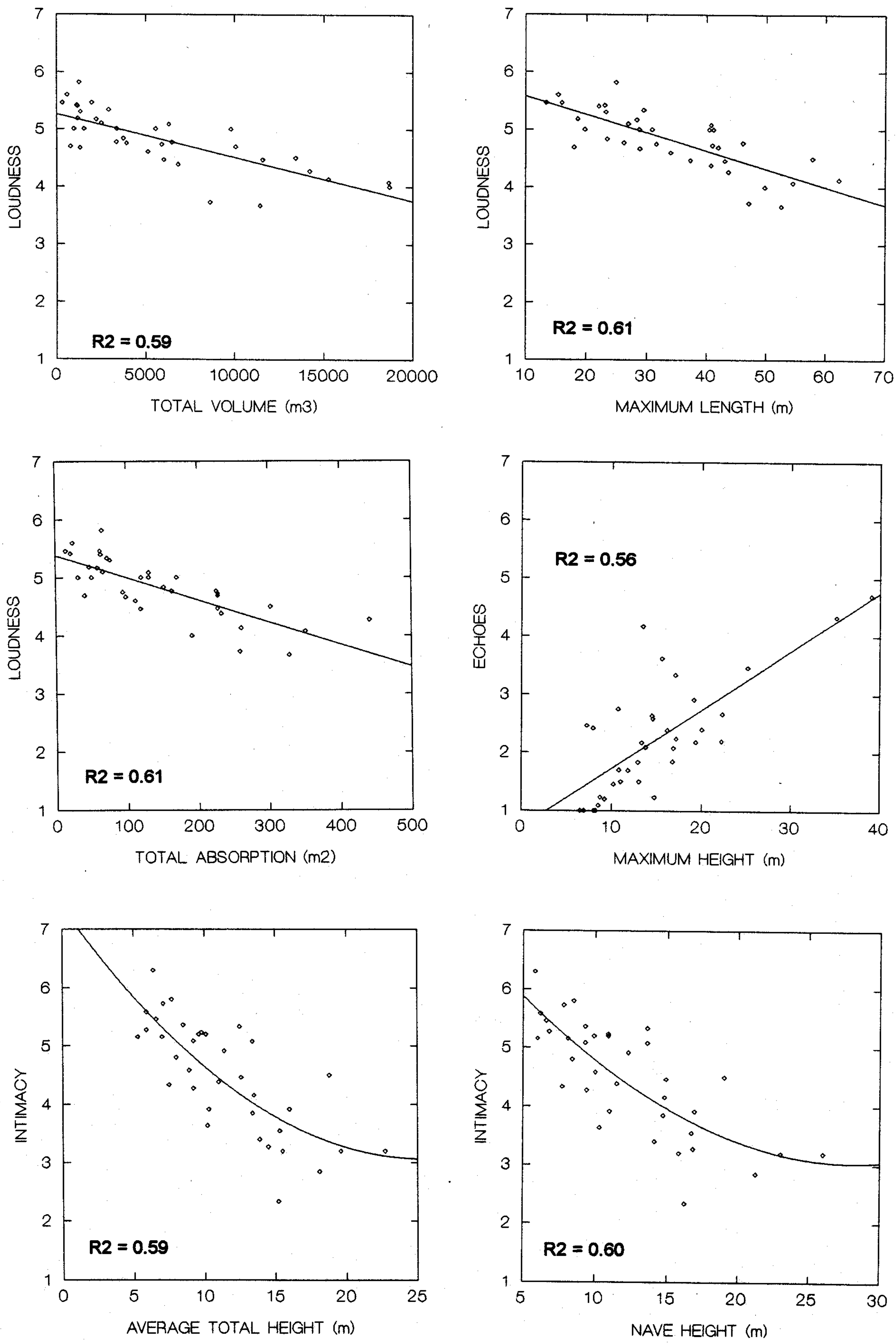

Figure 1 - Mean values of subjective acoustic parameters for each church (36 points=36 churches) plotted vs. the architectural parameters with regression models.

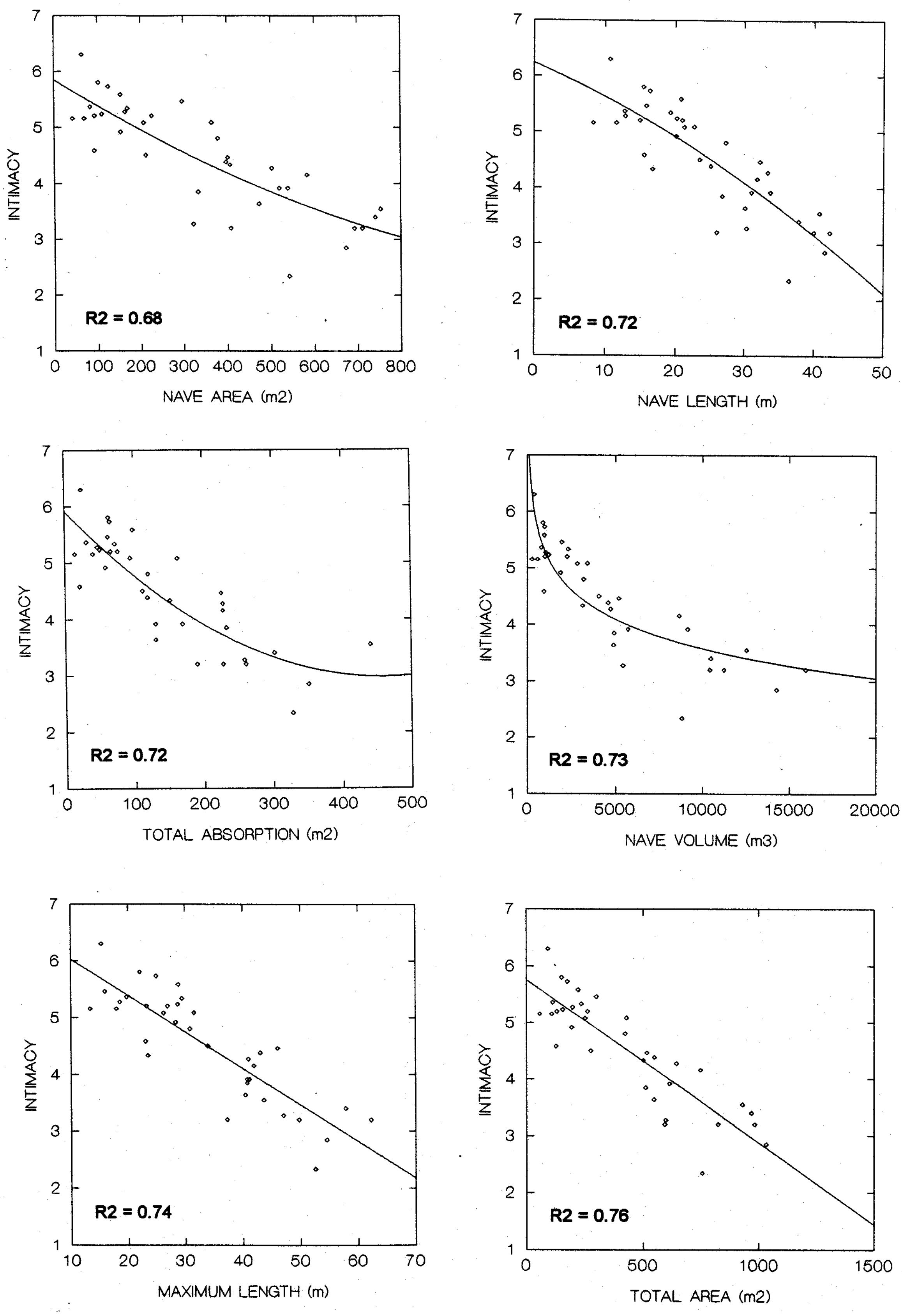

Figure 1 (continued) - Mean values of subjective acoustic parameters for each church (36 points=36 churches) plotted vs. the architectural parameters with regression models.

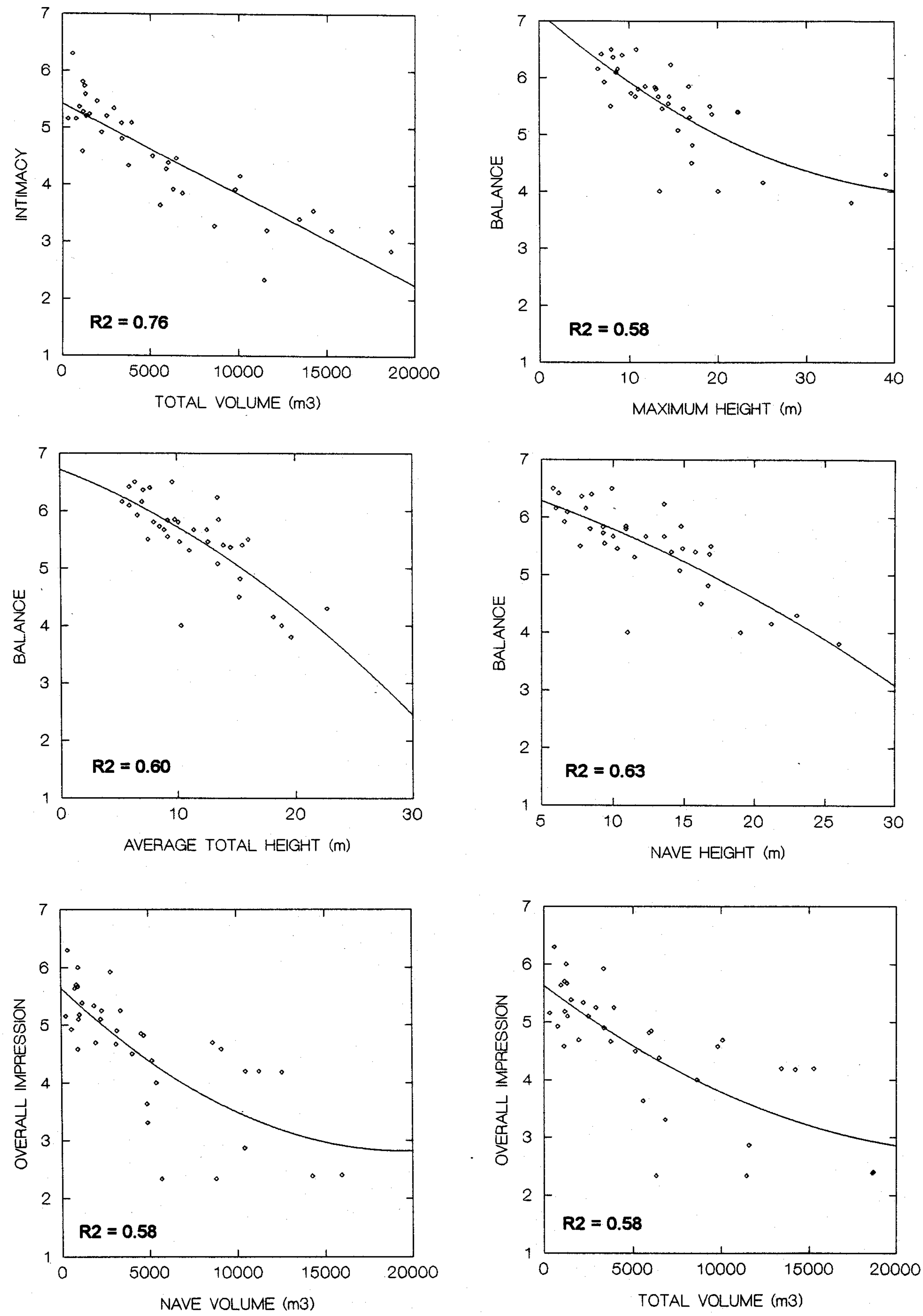

Figure 1 (continued) - Mean values of subjective acoustic parameters for each church (36 points=36 churches) plotted vs. the architectural parameters with regression models.

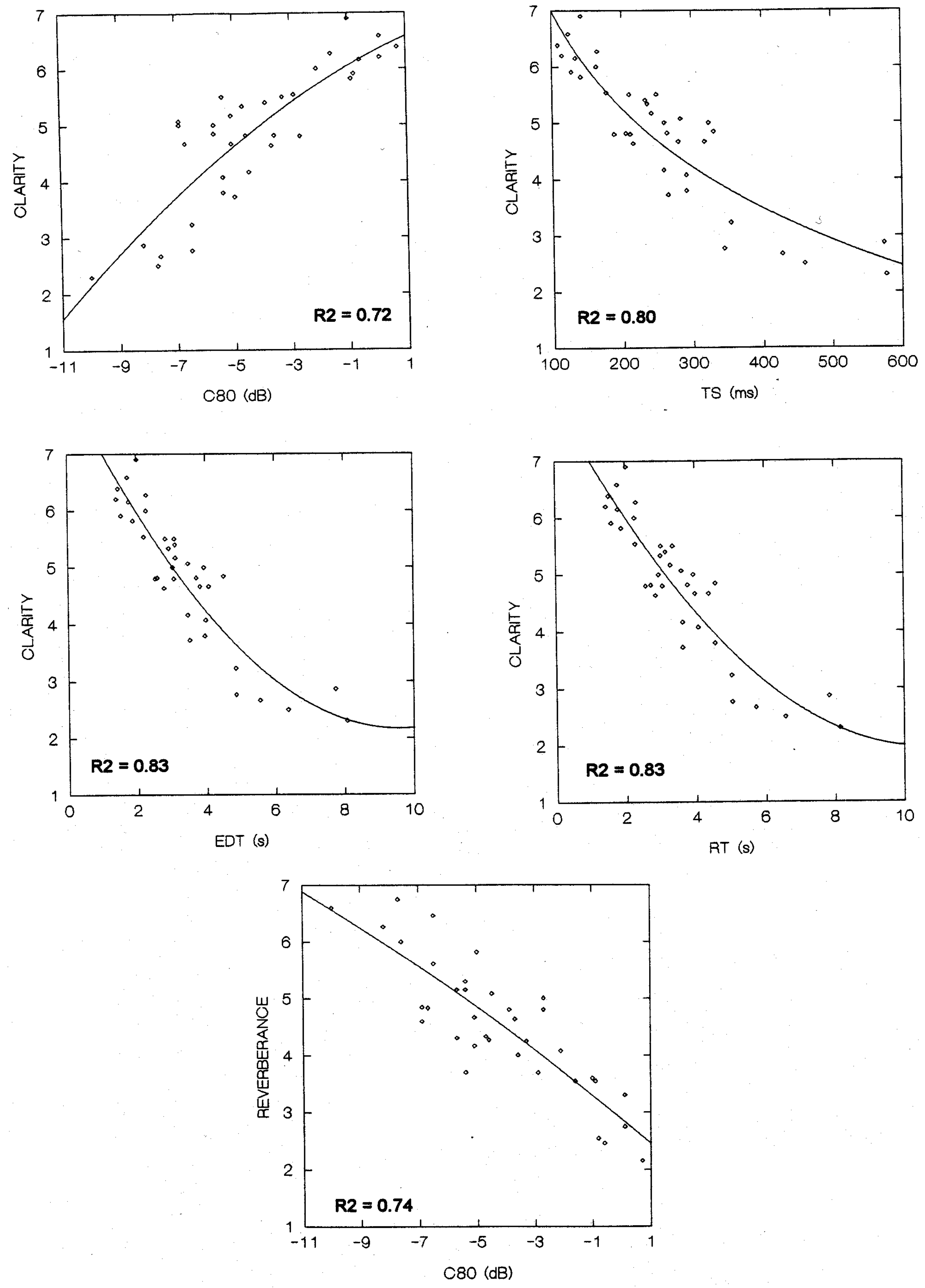

Figure 2 - Mean values of subjective acoustic parameters for each church plotted vs. the mean value of the associated objective acoustical parameter (500 and 1 k Hz) with regression models (36 points = 36 churches).

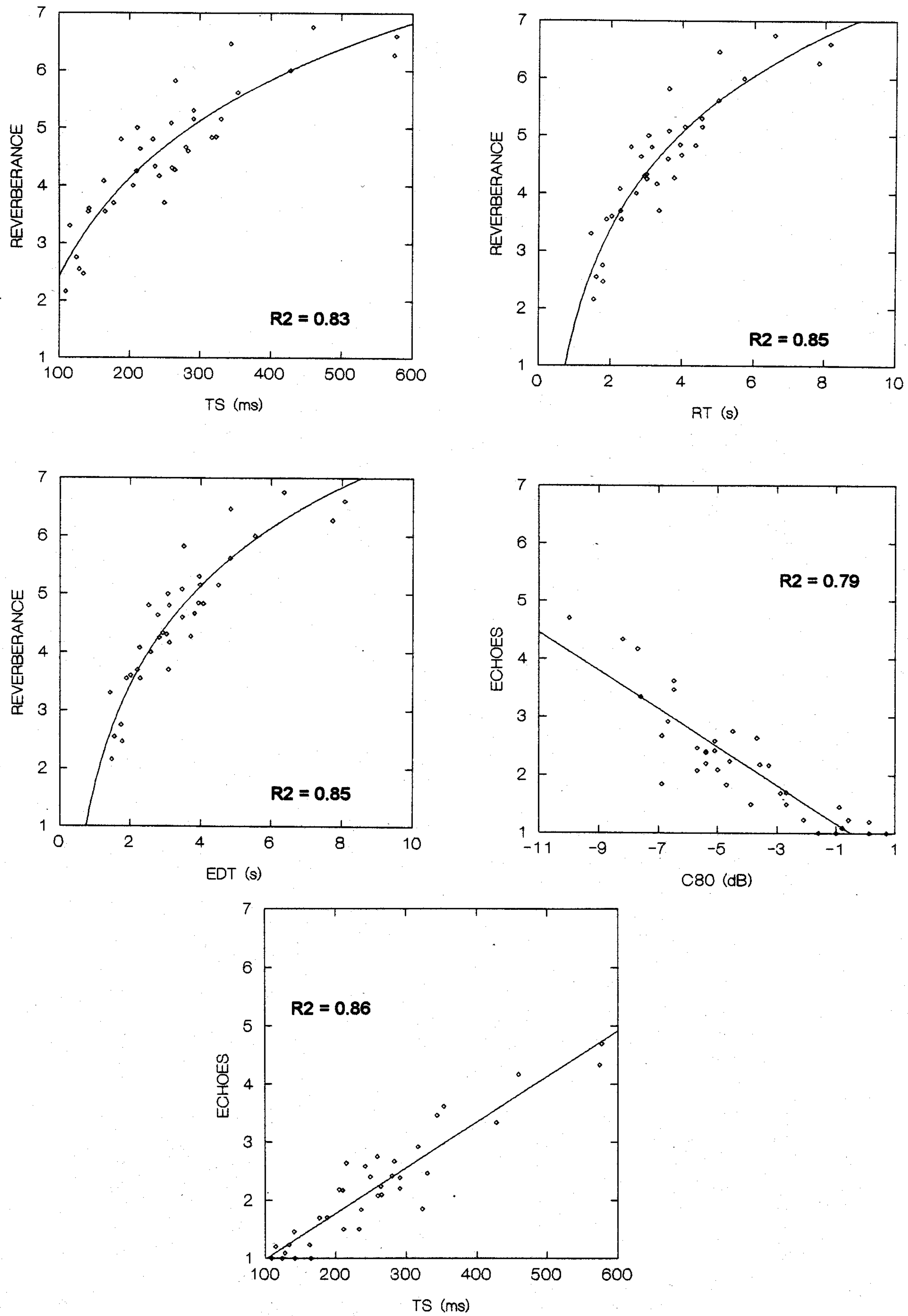

Figure 2 (continued) - Mean values of subjective acoustic parameters for each church plotted vs. the mean value of the associated objective acoustical parameter (500 and 1 k Hz) with regression models (36 points = 36 churches).

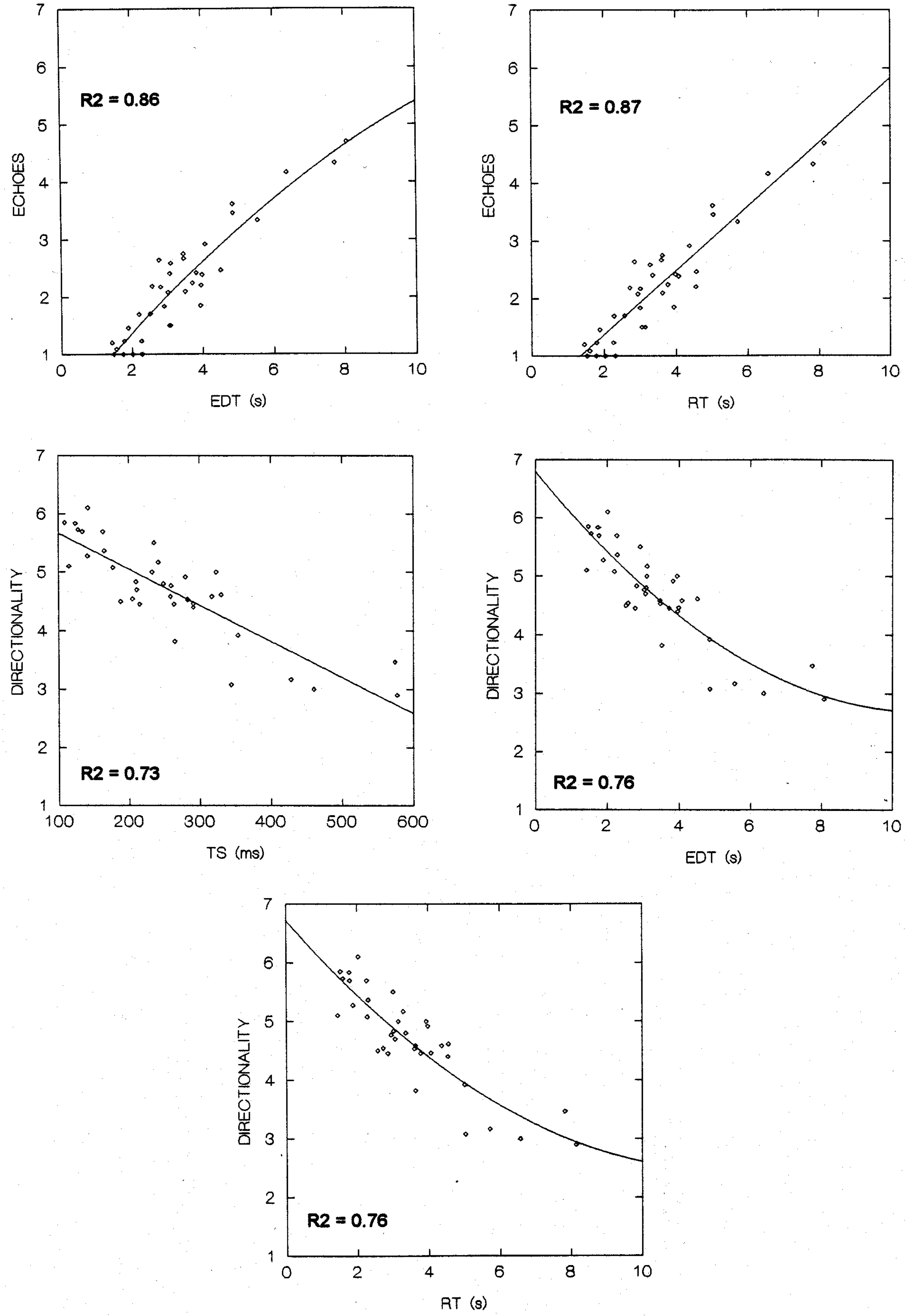

Figure 2 (continued) - Mean values of subjective acoustic parameters for each church plotted vs. the mean value of the associated objective acoustical parameter (500 and 1 k Hz) with regression models (36 points = 36 churches).

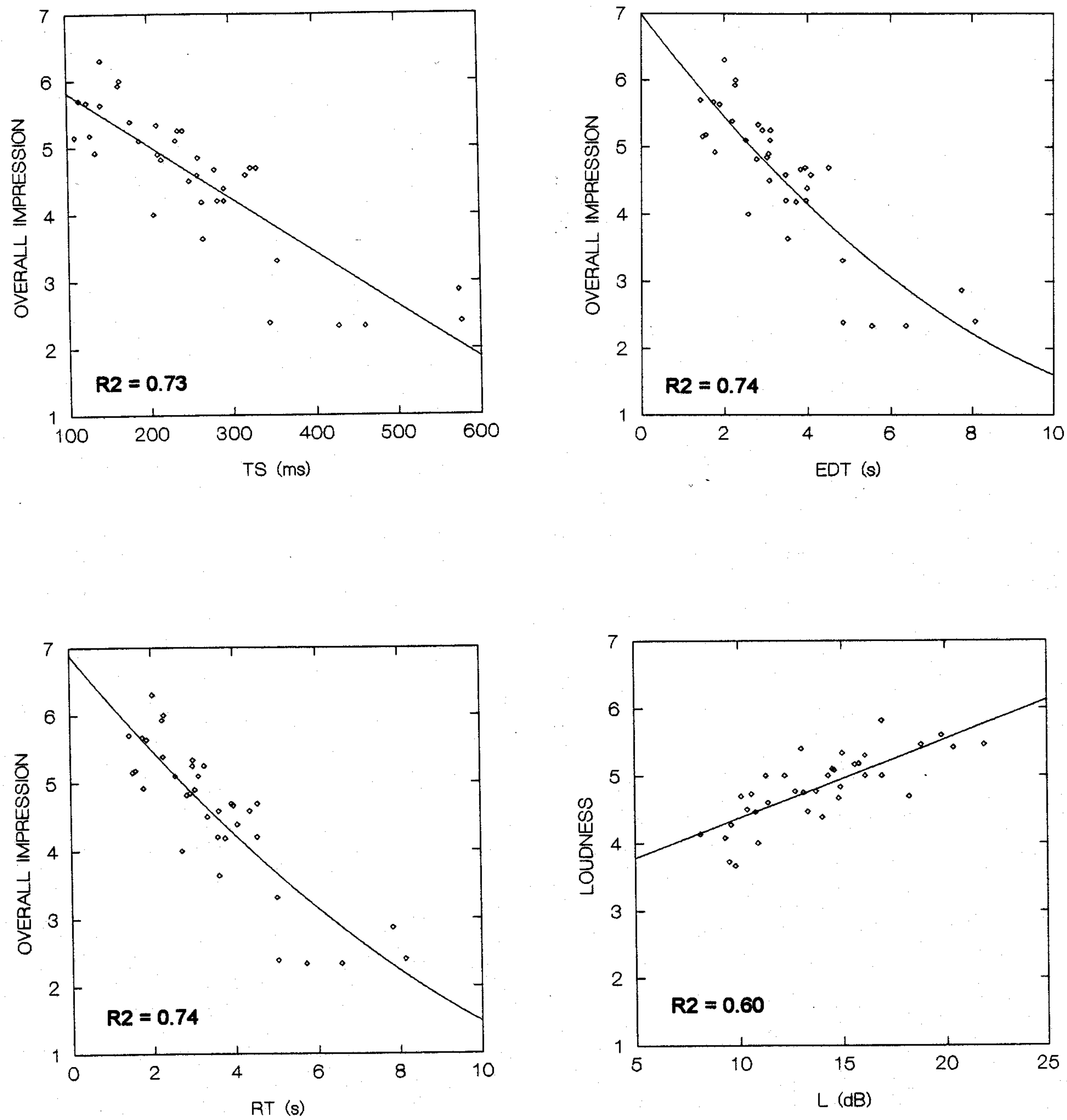

Figure 2 (continued) - Mean values of subjective acoustic parameters for each church plotted vs. the mean value of the associated objective acoustical parameter (500 and 1 k Hz) with regression models (36 points = 36 churches).