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OBJECTIVE AND SUBJECTIVE ACOUSTICAL PARAMETERS IN CATHOLIC 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 (C_{80}, D_{50}, EDT, L, RT and TS) 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 concentrates on the relationships of the subjective parameters with the objective room acoustics measures and with the architectural features of the churches.

1 - INTRODUCTION

This study is part of a research program initiated in 1991 by the author at the U. of Porto and U. 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 (C_{80}, D_{50}, EDT, L, RT, TS, etc.) (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 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 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 in a major survey of 36 Roman Catholic churches in Portugal that were built between the 6th century and the 1960's. The churches are a sample of 14 centuries of church building in Portugal. The oldest church tested was built around the 6-7th century and the most recent 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. 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 1.

Table 1 - 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

A complete objective acoustical analysis of these churches is available in Carvalho 1994. The overall results regarding the subjective acoustic parameters can be seen in Carvalho *et al.* 1996.

2.3 - Measurement Method for Objective Measures

Six objective room acoustics parameters were calculated in each church using the Impulse Response Method. They are: *RT* (or *RT30*) Reverberation Time; *EDT* (or *EDT10*) Early Decay Time; *C80* Early to Late Sound Index or Clarity with a time window of 80 ms; *D* (or *D50*) Early to Total Energy Ratio or Definition with a time window of 50 ms; *TS* Center Time (point in time where the energy received before and after are equal) and *L* (or *G*) Loudness or Overall Level (measure of the room's ability to amplify sound from the source position).

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). 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. 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 B&K Sound Level Meter 2231 w/ Filter Set 1625, Module BZ7109, Microphone 1/2", Software VP7155 and Sound Source 4224.

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 giving results judged normal for all the members.

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.

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:

. *BAL - Balance* (the relative levels of bass and treble frequencies) from *1* (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);

. *CLA* - *Clarity* (the degree to which notes are distinctly separated in time and clearly heard) from *1* (not clear enough) to *7* (extremely clear);
. *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);
. *ECH* - *Echoes* (long delayed reflections that are clearly audible) from *1* (none detected) to *7* (clearly heard);
. *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);
. *INTM* - *Intimacy* (the auditory impression of the apparent closeness of the orchestra) from *1* (absence of intimacy) to *7* (extremely intimate);
. *LOU* - *Loudness* (the overall loudness or strength of the sound) from *1* (extremely weak) to *7* (extremely strong);
. *OIMP* - *Overall Impression* (the overall impression of the acoustical quality of the room) from *1* (very bad) to *7* (very good).
. *REV* - *Reverberance* (the persistence of sound in space) from *1* (totally dry) to *7* (too reverberant);

2.5 - Architectural Parameters

Table 2 - The thirteen Architectural Parameters used.

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

TOTAL - entire church incl. lateral chapels and main altar; *NAVE* - entire church excl. 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. All relationships are done with the averaged subjective acoustic parameter data for each church (36 data points = 36 churches).

Table 3 presents the best and more suitable simple models, linear or non linear, of nearly 400 tested between subjective acoustical parameters and architectural features. Table 3 presents the best suitable models ordered by architectural feature (above) and sorted by subjective acoustic parameter (below).

The best simple relationship between subjective acoustic parameters and the thirteen architectural features exists between *Intimacy* and *Total Volume* (R^2= 0.76) presenting the clear importance that the church volume has regarding the feeling of intimacy.

Table 3 - Some of the best simple models between subjective acoustical parameters and architectural features ordered by architectural feature (above) and by subjective acoustical parameter (below). $R^2 > 0.75$ are bold faced.

SIMPLE MODELS	**R^2 (variance explained)**
INTM = 5.908 - 0.013 **ABST** + 1.4 x 10^{-5} **ABST**^{2}	0.718
INTM = 5.845 - 4.8 x 10^{-3} **ANV** + 2 x 10^{-6} **ANV**^{2}	0.679
INTM = 5.751 - 2.9 x 10^{-3} **ATOT**	**0.756**
BAL = 7.152 - 0.138 **HMAX** + 1.5 x 10^{-3} **HMAX**^{2}	0.577
BAL = 6.693 - 0.075 **HNV** - 1.5 x 10^{-3} **HNV**^{2}	0.627
INTM = 6.666 - 0.064 **LMAX**	0.742
INTM = 6.235 - 0.055 **LNV** - 5.5 x 10^{-4} **LNV**^{2}	0.716
INTM = 10.447 - 0.747 log **VNV**	0.732
BAL = 6.717 - 0.079 **VTAT** - 2.1 x 10^{-3} **VTAT**^{2}	0.601
INTM = 5.410 - 1.6 x 10^{-4} **VTOT**	**0.763**
BAL = 6.693 - 0.075 HNV - 1.5 x 10^{-3} HNV^2	0.627
CLA = 11.538 - 0.841 log VNV	0.575
DIR = 9.258 - 0.5725 log VNV	0.571
ECH = 0.719 + 0.101 HMAX	0.559
INTM = 5.410 - 1.6 x 10^{-4} VTOT	**0.763**
LOU = 5.377 - 3.8 x 10^{-3} ABST	0.613
OIMP = 5.622 - 0.23 x 10^{-3} VTOT + 0.45 x 10^{-8} VTOT^2	0.578

To find a better model to explain the relationships between subjective acoustical parameters and architectural features, general linear models were calculated (see Table 4).

Table 4 - Best relationships between subjective acoustic parameters and architectural parameters (general linear models). $R^2 > 0.75$ are bold faced.

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

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 parameter with the worst adjustment model is the *Background Noise* ($R^2 = 0.35$). This can be 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.

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 5.

Regression analyses were performed with all these seven averaging options to check for their influence in the results. 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.

Table 5 - Seven methods of frequency averaging options.

CODE	DEFINITION	RANGE
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

3.2.2 - Simple models

Using the frequency averaging option M7 (avg of 500 and 1k Hz octave band data), 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 6 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 ($R^2 = 0.83$). The relationship *Loudness*/L with a $R^2 = 0.60$ does not fulfill the reasonable expectations regarding their connection.

Table 6 - Same of the 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.

SIMPLE MODELS	R^2 (variance explained)
CLA = 6.330 + 0.265 C80 - 0.015 $C80^2$	0.724
CLA = 8.108 - 1.162 RT + 0.055 RT^2	**0.834**
DIR = 6.798 - 0.761 EDT + 0.035 EDT^2	**0.760**
DIR = 6.714 - 0.693 RT + 0.028 RT^2	**0.762**
ECH = 0.023 + 0.682 RT - 0.014 RT^2	**0.872**
ECH = - 0.044 + 0.744 EDT - 0.020 EDT^2	**0.864**
LOU = 2.100 + 0.196 L	0.597
OIMP = 6.991 - 0.826 EDT + 0.029 EDT^2	0.735
OIMP = 6.890 - 0.744 RT - 0.020 RT^2	0.742
REV = 1.709 + 2.417 log RT	**0.845**
REV = 1.741 + 2.451 log EDT	**0.854**

3.2.3 - General linear models

To find better models to explain the relationships between subjective and objective acoustical parameters, general linear models were calculated (see Table 7).

Table 7 - Best 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 MODELS	St. Error of Estimate	R^2	Avg option
BAL = 6.050 - 2.342 RT + 2.077 EDT + 0.049 L	0.36	**0.78**	M3
BGN (no suitable model)	-	-	-
CLA = 6.336 - 0.629 RT + 0.052 L	0.52	**0.83**	M7
DIR = 4.858 - 1.067 RT + 0.010 TS + 0.071 L	0.39	**0.80**	M1
ECH = 0.987 + 1.615 RT - 1.161 EDT - 2.071 D	0.34	**0.89**	M6
ENV = 4.276 - 1.719 RT + 1.798 EDT - 3.237 D + 0.069 L	0.36	0.51	M1
INTM = 3.387 - 2.433 RT + 2.243 EDT + 0.150 L	0.46	**0.79**	M1
LOU = 3.630 - 1.620 RT + 1.640 EDT - 0.099 L	0.30	0.70	M1
OIMP = 5.379 - 3.175 RT + 2.776 EDT + 0.066 L	0.49	**0.81**	M1
REV = 5.118 + 2.169 EDT - 7.666 D - 0.025 TS	0.48	**0.85**	M7
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
EDT = - 4.342 + 0.122 BGN + 0.692 REV + 0.890 ECH + 0.954 DIR - 0.513 OIMP	0.47 s	**0.91**	M6
L = - 14.06 + 3.949 LOU + 2.465 INTM + 3.200 DIR - 3.778 OIMP	1.80 dB	**0.77**	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
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

The general linear models are presented in Table 7 together with the indication of which frequency averaging option (Mi) gives the best model. Almost all subjective parameters have suitable models except *Background Noise* and *Envelopment* (R^2 < 0.5). 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.

4 - CONCLUSIONS

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.

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* also confirms the suitability of *C80* to objectively represent the sense of clarity. Nevertheless the *RT* is even better in performing that role. The relationship *Overall Impression/RT* also confirms a similar idea concerning this pair of parameters. The relationship *Loudness/L* does not fulfill the reasonable expectations regarding their connection.

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