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RELATIONSHIPS BETWEEN OBJECTIVE ACOUSTICAL MEASURES AND ARCHITECTURAL FEATURES IN CHURCHES

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INTRODUCTION

This study reports on acoustical field measurements in a major survey of Roman Catholic churches in Portugal that were built in the last 14 centuries. Series of monaural acoustical measurements were taken at several source and receiver locations in each church. The measurements included Reverberation Time, Early Decay Time, Early to Late Sound Index, Early to Total Energy Ration, Center Time, Loudness and two Bass Ratios. This paper concentrates on the relationships of these 8 Room Acoustic Parameters with 13 Architectural Features of the churches.

PROCEDURE

1) Churches Description. This paper reports on acoustical field measurements in a major survey of 41 Roman Catholic churches in Portugal that were built from the sixth century until 1993. The churches were chosen to represent the evolution of the architectural styles in church construction in Portugal. Therefore, we measured 12 Visigothic or Romanesque churches (6th-13th centuries), 16 Gothic or Manueline churches (13th-16th centuries), 13 Renaissance, Baroque or Neoclassic churches (16th-19th centuries) and 4 Contemporary churches (20th century). The main architectural features of these churches are displayed in the following table:

ARCHITEC. FEATURE	Minimum	Maximum	Mean	Median
VOLUME (m^3)	299	18674	5772	3918
AREA (m^2)	56	1031	450	427
MAX. HEIGHT (m)	6.5	39.0	14.8	13.4
MAX. LENGTH (m)	11.5	62.2	33.1	30.8

2) Measurement Method. Eight 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 (measure of the room's ability to amplify sound from the source position);

BR_RT - Bass Ratio based on Reverberation Time. BR_RT = [RT(125) + RT(250)] / [RT(500) + RT(1k)];
BR_L - Bass Ratio based on Loudness. BR_L = [L(125) + L(250) - L(500) - L(1k)] / 2 .

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° 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.

3) Architectural Parameters. Thirteen Architectural Parameters were used:

TERM	DEFINITION	TERM	DEFINITION
ALPHA	Absorption Coefficient (average value for all surfaces)	SEATS	Number of Seats
		VOL_TOT	Volume Total (m^3)
AREA_TOT	Area Total (m^2)	VOL_NAVE	Volume Nave (m^3)
AREA_NAV	Area Nave (m^2)	VTO_ATO	Height Total average (m) (= Volume total / Area total)
H_MAX	Height Maximum (m)		
H_NAVE	Height Nave (m)	W_NAVE	Width Nave (m)
L_MAX	Length Maximum (m)	W_AVG	Width average (m)
L_NAVE	Length Nave (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)

RELATIONSHIPS BETWEEN ROOM ACOUSTIC AND ARCHITECTURAL PARAMETERS

1) Averaging Method. The following analyses were done with averaged data for each church. Seven averaging methods were previously tested using the average of 2, 3, 4 or 6 octave frequency-bands to obtain a single-number for each Room Acoustic Parameters and for each church. These options were:

CODE	DEFINITION
41	Average of all 6 frequencies (125 to 4000 Hz octave bands);
41_W24	Average of the 4 lowest frequencies (125 to 1000 Hz octave bands);
41_4H	Average of the 4 highest frequencies (500 to 4000 Hz octave bands);
41_4M	Average of the 4 middle frequencies (250 to 2000 Hz octave bands);
41_3F	Average of the 3 medium frequencies (500, 1000 and 2000 Hz octave bands);
41_O24	Average of the 2 highest frequencies (2000 and 4000 Hz octave bands);
41_2F	Average of 2 medium frequencies (500 and 1000 Hz octave bands).

Regression analyses were performed with all these 7 averaging options to check for their influence in the Architectural Parameters. The differences among them were found to be small. Nevertheless the option 41_2F appeared as the most suitable for this type of analysis, giving the highest percentage of variance explained for almost all situations. This averaging method was then used in all the following studies below.

2) Simple Linear Models. Using the 41_2F frequency-average option (average of 500 and 1000 Hz octave band data) stated above, linear regression models were used for each of the 8 Room Acoustic Parameters regarding their relationships with the 13 Architectural Parameters. Table 1 present the equations for the best linear regression line found for each of the 8 Room Acoustic Parameters. The variance of the L can be largely explained with just one of the 13 Architectural Parameters ($R^2 \approx 0.80$). For RT, EDT, C80 and TS the percentage of variance explained by just 1 Architectural Parameter is not very significant (R^2 between 0.37 and 0.55). The Bass Ratios, with $R^2 \leq 0.25$ cannot be explained or predicted significantly with the use of just 1 Architectural Parameter.

TABLE 1. Relationships between Room Acoustic and Architectural Parameters.

EQUATIONS (SIMPLE LINEAR MODELS)	ST Error of Estimate	R^2 (variance explained)
RT = 0.785 + 0.176 H_MAX	1.1 s	0.54
EDT = 0.754 + 0.171 H_MAX	1.1 s	0.54
C80 = 0.365 - 0.287 H_MAX	2.2 dB	0.46 *
D = 0.289 - 0.00020 AREA_TOT	0.078	0.37 *
TS = 60.835 + 12.634 H_MAX	79 ms	0.55
L = 21.405 - 0.317 L_NAVE	1.8 dB	0.75 *
BR_RT = 1.104 - 1.640 ALPHA	0.16	0.14 *
BR_L = 2.663 - 0.047 L_NAVE	0.81	0.25 *

* Better fit available with non linear model (see Table 2)

3) Non Linear Models. Non linear Regression Models (logarithmic and quadratic smooth) were tested. The results generally agree with those presented above. In Table 2 the cases in which a better than linear fit was found between a Room Acoustic Parameter and a Architectural Parameter are shown. Those are: C80, D, L, BR_RT and BR_L. However the differences in the R values between the *linear* and the *non linear* regression lines for each case are not significant (from 0.016 to 0.105, $\Delta R_{average} = 0.05$). There is not a significant improvement in using non linear models (at least the logarithmic or quadratic smooth) in these cases. The equations for those 5 non linear models are presented in Table 2.

TABLE 2. Relationships between Room Acoustic and Architectural Parameters (Non Linear Models).

EQUATIONS (Simple Non Linear Models)	R^2 (variance explained)
C80 = 8.850 - 4.887 Log_n (H_MAX)	0.487
D = 0.685 - 0.083 Log_n (AREA_TOT)	0.504
L = 36.101 - 7.219 Log_n (L_NAVE)	0.781
BR_RT = 1.363 - 0.020 L_MAX + 0.00021 (L_MAX)^2	0.162
BR_L = 5.264 - 1.094 Log_n (L_MAX)	0.274

4) General Linear Models. To find a better linear model to explain the relationships between Room Acoustic and Architectural Parameters, general linear models were calculated using the Forward Stepwise Modeling method with an α-to-enter (or -to-remove) equal to 0.05. The General Linear Models are presented in Table 3.

TABLE 3. Relationships between Room Acoustic and Architectural Parameters (General Linear Models).

GENERAL LINEAR MODEL EQUATIONS	ST Error of Estimate	R^2
RT = 1.148 + 0.149 H_MAX + 0.078 W_NAVE - 13.383 ALPHA	0.91 dB	0.71
EDT = 1.075 + 0.145 H_MAX + 0.077 W_NAVE - 12.756 ALPHA	0.90 dB	0.71
C80 = 0.864 - 0.217 W_NAVE - 0.404 VTO_ATO + 35.121 ALPHA	1.2 dB	0.85
D = 0.452 + 0.000014 VOL_TOT - 0.007 L_NAVE - 0.008 W_NAVE - 0.014 VTO_ATO + 1.364 ALPHA	0.042	0.84
TS = 85.448 + 10.603 H_MAX + 5.941 W_NAVE - 983.356 ALPHA	61 ms	0.74
L = 22.918 - 0.306 L_NAVE - 24.520 ALPHA	1.5 dB	0.82
BR_RT = 1.279 + 0.00045 SEATS - 0.008 L_MAX - 1.867 ALPHA	0.14	0.35
BR_L = 2.663 - 0.047 L_NAVE	0.80	0.25

The R^2 coefficients are improved (the percentage of variance explained is greater) if we include, together with the Architectural Parameters, the *expected values* for some Room Acoustic Parameters calculated by the *diffuse field theory* formulas [$EDT_{exp}=RT$; $TS_{exp}=RT/0.0138$; $C80_{exp}= 10Log_{10}(e^{1.104/RT}-1)$; $L_{exp}=10Log_{10}(RT/V)+45$]. In that case, knowing the real RT (usually easily measured *in loco*), better predictions for EDT, TS, C80 and L can be found (the same 0.05 was used for the α-to-enter/remove - see Table 4).

TABLE 4. Revised predictions for Room Acoustic Parameters (using Arch. Parameters and known real RT).

GENERAL LINEAR MODEL EQUATIONS (Using expected values)	R^2 (variance explained)	Standard Error of Estimate (STD of residuals)
$EDT = - 0.019 + 0.976\ EDT_{exp}$	0.996	0.11 s
$TS = 8.518 + 0.974\ TS_{exp}$	0.985	14 ms
$C80 = 0.0576 + 1.045\ C80_{exp}$ - 0.025 L_MAX	0.944	0.70 dB
$L = - 0.196 + 0.966\ L_{exp}$	0.957	0.76 dB

As seen, the percentage of variance explained by the use of the expected values of the acoustic measures is significantly better than with the models using only the Architectural Parameters. Note that only the parameter C80 shows the inclusion of some Architectural Parameter in the General Linear Models. If a larger α-to-enter/remove was to be chosen, it should be an $\alpha \geq 0.16$ in order to have all 4 of these general linear equations with (at least) one Architectural Parameter. But even then their R^2 would not greatly improve (except in the C80 model where a small increase of 0.03 would be found for its R^2).

CONCLUSIONS

- Simple non linear models gave a slightly better ($\Delta R^2 < 0.14$) prediction line than the linear models in the majority (70%) of the cases studied. Among these, the ***logarithmic*** smooth presents a better fit in many cases, especially those regarding the parameter D. This is due to the logarithmic mathematical characteristic of many of those parameters (by their definition);
- Some of the 13 Architectural Parameters tested can be used in General Linear Models to explain from 71% to 88% of the variance of the six main Room Acoustic Parameters (RAP) studied. The use of the expected values for some of the RAP can improve that agreement to values close to 99.7%.