UNIVERSITY OF PORTO
COLLEGE OF ENGINEERING
Department of Civil Engineering
Acoustical Laboratory

SPEECH INTELLIGIBILITY IN CHURCHES. HOW IT RELATES WITH OBJECTIVE ACOUSTICAL PARAMETERS AND ARCHITECTURAL FEATURES

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António P. O. Carvalho, Ph.D. (1)
António E. J. Morgado (1)
Luís Henrique (2)

(1) Acoustical Laboratory, Department of Civil Engineering, College of Engineering, University of Porto, R. Bragas, P-4099 Porto Codex, Portugal (tel.: 351.2.2041931, fax: 351.2.2041940, email: carvalho@fe.up.pt)
(2) School of Music and Performing Arts (*ESMAE*), Polytechnic Institute of Porto (*IPP*), R. Alegria, 503, P-4000 Porto, Portugal (tel.: 351.2.575699/569691, fax: 351.2.580774)

ABSTRACT

This study reports on subjective and objective acoustical field measurements made in a major survey of 36 Roman Catholic churches in Portugal built in the last 14 centuries. Monaural acoustical measurements (*RT*, *EDT*, *C80*, *D50*, *TS*, *L*, and *RASTI*) were taken at several source/receiver locations in each church. A group of college students was asked to judge the intelligibility of speech by evaluating live speech at similar locations in each room. This paper complements those presented at the 1996 Indianapolis and Honolulu ASA Meetings and concentrates exclusively on the relationships of the speech intelligibility church averaged values with the objective room acoustics measures and with some architectural features of the churches. The averaged results by church are graphed and analyzed by comparisons. Correlation analyses and statistical modeling identified some relationships among the measures. For instance, squared correlation coefficients (R^2) of 0.67 were found for the relationships: *SPEECH-RT* and *SPEECH-TS*. Between *SPEECH* and *RASTI* only a maximum R^2 of 0.50 was found. Regarding the churches' architectural features, the maximum R^2 found was 0.52 between *SPEECH* and *NAVE HEIGHT*. A general linear model including several architectural features increased the R^2 to 0.72.

1 - INTRODUCTION

This study is part of a research program initiated in 1991 by the author at the University of Porto (Portugal) and University of Florida (USA). 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, and 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 report concerning relationships between speech intelligibility 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 speech intelligibility of people who attend services in churches could be measured and then related with objective room acoustics measures and architectural features. The among-room variations of speech intelligibility 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 speech, of the qualities of the churches concerning speech intelligibility 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 sound heard during a religious service 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. Five of the churches tested in the first part of this research program (objective measures) were excluded in 1996 for the second part (subjective measures) due to architectural changes done in those churches. Table 1 presents an alphabetical list of the churches that were tested in both parts of 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. AZEITÄO	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).

Speech intelligibility was objectively quantified by the calculation of the Rapid Speech Transmission Index (*RASTI*) which may was hypothesized that can be related to the scores of people taking standard live speech intelligibility tests. This method is based on the measurement of the reduction in signal modulation between the speaker and listener positions. A transmitter generates a special test signal (pink noise in the 500 Hz and 2000 Hz octave bands) to mimic the long-term speech spectrum. An omnidirectional 1/2" diameter microphone receives the signal. The signal is transmitted to the *RASTI* receiver unit, which analyzes the signal and calculates the *RASTI* value that is immediately displayed in the display screen. The receiver and transmitter are independent units (not synchronized) because the signal is repetitive. In each church the transmitter location was in front of the altar, 1.65 m above the floor. Several positions (from 4 to 17) were used for the receiver depending on the length of the church (on average, eight positions were in fact used). In each receiver position three or four measurements were taken and then averaged together to give the *RASTI* value at that location.

Equipment from the Acoustical Laboratory of the University of Porto College of Engineering was used. For the acoustical measures the equipment used was 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" diameter B&K; notebook computer Compaq LTE; and application software Room Acoustics B&K-VP7155. For the RASTI measurements the equipment used was speech transmission meter B&K-3361 consisting of transmitter type 4225 and receiver type 4419; and microphone 1/2" diameter B&K-4129.

2.4 - Measurement Method for Speech Intelligibility

2.4.1 - Listeners and Sound Source

A group of 15 listeners was chosen to judge the quality of speech throughout the churches. 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. A young theater student from the same school, was used as a speaker. In each church he read a different list of 100 words within the same sentence: “This is ... (word)...” (in Portuguese). The sentences were said with similar loudness and rhythm. The list of 100 words used in each church was chosen from an innovative global 400-word list that represents the Portuguese language.

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). Then they listed the words understood on a questionnaire sheet. A total of near 500 questionnaires were scored in the rooms. The scores from the questionnaires were entered into a computer spreadsheet and analyzed using the *SYSTAT*® computer software package.

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 and ANSI S3.6 were performed giving results judged normal for all the members of the listeners’ group.

The Table 4 shows the number and percentage of words used beginning by each of the alphabet letters (*k*, *w* and *y* do not exist in the Portuguese alphabet and *j*, *x* and *z* are very rare). As seen in Table 5, only words with 1 to 4 syllables (according to Portuguese grammar) were used, but the 2 and 3-syllable words were predominant. This was a chosen proceeding in order not to allow listeners to decipher the word by understanding only the sound of some syllables.
The analyses concerning speech intelligibility are displayed in the following Figures and Tables under the criterion named *speech*.

Table 4 - Description of words used in the speech intelligibility tests.

WORDS BEGINNING BY	NUMBER OF WORDS	PERCENTAGE OF WORDS	WORDS BEGINNING BY	NUMBER OF WORDS	PERCENTAGE OF WORDS
A	48	12	***M***	40	10
B	16	4	***N***	8	2
C	28	7	***O***	12	3
D	20	5	***P***	40	10
E	25	6	***Q***	8	2
F	12	3	***R***	28	7
G	8	2	***S***	28	7
H	8	2	***T***	28	7
I	12	3	***U***	8	2
J *or* ***K***	0	0	***V***	15	4
L	8	2	***W, X, Y*** *or* ***Z***	0	0

Table 5 - Description of syllables and words used in the speech intelligibility tests.

NUMBER OF SYLLABLES BY WORD	NUMBER OF WORDS	PERCENTAGE OF WORDS
1	9	2
2	254	64
3	127	32
4	10	2
Total	400	100

2.5 - Architectural Parameters

The thirteen Architectural Parameters used are shown in Table 6.

Table 6 - 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 Speech Intelligibility and Architectural Features

This chapter presents the results concerning the relationships between *Speech Intelligibility* and the architectural features of the churches. In this chapter all relationships are done with the averaged *Speech Intelligibility* data for each church (36 data points = 36 churches).

Table 7 presents the best simple models with the squared values for the correlation coefficients between *Speech Intelligibility* and each of the thirteen architectural parameters. The best relationship exists between *Speech Intelligibility* and *Height Nave* (R^2 = 0.52) presenting the importance that the nave height has regarding the *Speech Intelligibility*. However, other important relationship was found between *Speech Intelligibility* and *Height total average* (R^2 = 0.50). The Figure 1 shows the graphical presentation of the 12 best simple models, presented in Table 7.

With the goal of trying to find a better model that can explain the relationships between speech intelligibility and architectural features a general linear model was 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 model was judged primarily by its 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 model is presented in Table 8 where it is seen that the speech intelligibility seem to be reasonably connected to the architectural features of the churches.

Table 7. Best simple models between *Speech Intelligibility* (in %) and the 13 Architectural Parameters.

EQUATIONS	**R^2 (variance explained)**
Speech = 150.347 - 8.410 log VTOT	0.494
Speech = 147.674 - 8.295 log VNV	0.493
Speech = 93.989 - 0.028 ATOT	0.405
Speech = 135.574 - 9.747 log ANV	0.371
Speech = 106.285 - 0.822 LMAX + 0.002 $LMAX^2$	0.419
Speech = 102.532 - 0.853 LNV	0.406
Speech = 110.453 - 2.563 HMAX + 0.034 $HMAX^2$	0.463
Speech = 104.587 - 1.893 HNV	**0.523**
Speech = 115.774 - 14.235 log WNV	0.237
Speech = 118.641 - 15.165 log WAVG	0.277
Speech = 110.154 - 2.914 VTAT + 0.031 $VTAT^2$	0.501
Speech = 91.729 - 0.070 ABST	0.329
Speech = 73.214 + 129.767 CABS	0.039

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

Table 8. Relationship between *speech intelligibility* (in %) and architectural parameters (general linear model).

GENERAL LINEAR MODEL EQUATION	**St. Error of Estimate**	**R^2**
Speech = 104.5 - 8.9x10^{-3} VTOT + 6.4x10^{-3} VNV + 0.091 ATOT - 1.192 LNV + 1.441 HMAX- 1.915 HNV - 1.830 WNV + 188.7 CABS	7.8	0.72

ATOT-Area Total (m^2); CABS-Absorption Coef. α (avg value for all surfaces); HMAX-Height Maximum (m); HNV-Height Nave (m); LNV-Length Nave (m); VNV-Volume Nave (m^3); VTOT-Volume Total (m^3); WNV-Width Nave (m).

3.2 - Relationships between Speech Intelligibility and Objective Acoustical Parameters

3.2.1 - Averaging Method

The following analyses were done with averaged data for each church. Seven frequency 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.

Regression analyses were performed with each of 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.

Table 9 - Seven options of frequency averaging methods (*Mi*).

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 each of the frequency averaging options *Mi* shown in Table 9, linear and non linear models were used for the *speech intelligibility* regarding their relationships with the six objective room acoustic parameters. Table 10 presents the equations for the best models found and for each objective acoustical parameter. The Figure 2 presents the best relationships found between speech intelligibility and objective acoustic parameters and stated in Table 10.

It is shown that the variance of the *Speech Intelligibility* can be fairly explained with just one of the six objective room acoustic parameters ($R^2 \approx 0.67$). For *D* and *L* the percentage of variance explained by just one objective room acoustic parameter is not very significant ($R^2 < 0.50$).

The relationship *Speech*/RT with a $R^2 = 0.674$ confirms that RT has influence in the *speech intelligibility*. However, using TS the R^2 is very similar (0.665) making this objective room acoustic measure almost as suited as RT to fairly estimate speech intelligibility. The relationship *Speech*/L with a $R^2 = 0.33$ does not fulfill the reasonable expectations regarding their connection.

Table 10. Most significant relationships between *speech intelligibility* (in %) and each of the six objective acoustical parameters (with the frequency averaging method).

METHOD *Mi*	EQUATIONS (simple models)	R^2 (variance explained)
M6	*Speech* = $118.104 - 14.519\ \text{RT} + 0.907\ \text{RT}^2$	**0.674**
M7	*Speech* = $117.157 - 13.966\ \text{EDT} + 0.860\ \text{EDT}^2$	0.660
M4	*Speech* = $95.162 + 2.255\ \text{C80} - 0.331\ \text{C80}^2$	0.644
M7	*Speech* = $53.381 + 197.581\ \text{D} - 215.340\ \text{D}^2$	0.465
M7	*Speech* = $116.937 - 0.181\ \text{TS} + 1.4 \times 10^{-4}\ \text{TS}^2$	0.665
M2	*Speech* = $38.653 + 5.051\ \text{L} - 0.116\ \text{L}^2$	0.328

3.2.3 - General Linear Models

With the goal of trying to find better models that can explain the relationships between *speech intelligibility* 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 is 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 for each frequency averaging option (Mi) are presented in Table 11.

As seen in Table 11 the objective parameter C80 appears as variable in all general linear models indicating that this measure can be very important in predicting the speech intelligibility of churches. D performs almost as well as C80 in that function. L however, does not appear in the models, perhaps revealing that it is not a significant measure in predicting speech intelligibility in churches.

Table 11. Best relationships between *speech intelligibility* (in %) and objective acoustical parameters (general linear models with the frequency averaging method Mi used).

METHOD Mi	EQUATIONS (general linear models)	St. Error of Estimate	R^2 (variance explained)
M1	*Speech* = $140.34 - 40.957\ \text{RT} + 43.354\ \text{EDT} + 8.924\ \text{C80}$	6.9	**0.745**

	- 136.724 D		
M2	*Speech* = 88.83 - 22.017 RT + 4.992 C80 + 0.338 TS	7.9	0.654
M3	*Speech* = 161.41 + 10.190 C80 - 200.874 D	7.2	0.705
M4	*Speech* = 143.66 + 8.960 C80 - 142.471 D	7.3	0.701
M5	*Speech* = 136.67 - 25.058 RT + 25.063 EDT + 7.201 C80 - 120.871 D	7.6	0.696
M6	*Speech* = 141.14 + 8.345 C80 - 134.909 D	7.5	0.686
M7	*Speech* = 129.73 + 6.922 C80 - 100.194 D	7.6	0.675

3.3 - Relationship between Speech Intelligibility and the Objective Parameter RASTI

Similarly as presented above, statistical models were calculated to quantify relationships between *Speech Intelligibility* and RASTI values. To obtain relationships using the RASTI values, there was a need for a corresponding single RASTI value, representative of each church. Three options were tested as described in Table 12.

As shown in Table 13 *RASTI.ndf* appears as the best of the three parameters to predict speech intelligibility ($R^2 = 0.503$). However, this fairly small R^2 reveals that there is no significant relationship between church averaged *RASTI* and speech intelligibility values. It is presumed that the results would be better if there were a direct spatial comparison (relating measure point by measure point) and not just church averaged values to compare. Figures 3 and 4 present the regression models between *RASTI* and *Speech Intelligibility.*

Figure 5 shows, for each church, the ratios between averaged *Speech Intelligibility* and *RASTI* values where it is seen that the *speech intelligibility* values are, in general, the double of the corresponding mean *RASTI* (from x1.3 to x2.5). Table 14 proposes a simple new scale to tie *RASTI* values to subjective speech intelligibility.

Table 12. Three options to calculate averaged RASTI for each church.

CODE	**DEFINITION**
RASTI.001	Using only 1 point in each church (the one in the middle of the longitudinal axis)
RASTI.avg	Average of all positions in each church
RASTI.ndf	Average of all positions Not in the Direct Field of the sound source (excluding positions < 5 m from sound source or not in the main volume of the church)

Table 13. Best models and squared correlation coefficients between *Speech Intelligibility* (in %) and the objective parameter *RASTI* (in %).

Objective Parameter	**EQUATION**	**R^2 (variance explained)**
RASTI.001	-	0.458
RASTI.avg	*Speech* = -52.54 + 4.951 RASTI.avg - 0.041 RASTI.avg^2	0.480
RASTI.ndf	*Speech* = -50.55 + 5.315 RASTI.ndf - 0.048 RASTI.ndf^2	**0.503**

RASTI.001-using only 1 point in each church, the one in the middle of the longitudinal axis; *RASTI.AVG*-avg of all positions in each church; *RASTI.NDF-avg* of all positions Not in the Direct Field of the sound source (excluding positions < 5 m from sound source or not in the main volume of the church).

Table 14. Proposed table to convert from RASTI values to a subjective intelligibility scale (* proposed).

RASTI (in %)	**Speech (in %)***	**Subjective speech intelligibility scale**
0 - 30	0 - 60	*bad*
30 - 45	60 - 75	*poor*
45 - 60	75 - 85	*fair*
60 - 75	85 - 95	*good*
75 - 100	95 - 100	*excellent*

4 - SUMMARY

The scope of this work is to investigate the subjective acoustical behavior of churches regarding speech intelligibility, how it relates with other parameters and to determine simple formulas to predict that acoustical parameter 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 *speech intelligibility* were done by listeners, to reveal through statistical procedures the relationships between the *speech intelligibility* and the architectural parameters of churches (*Volume, Area, Length, Width*, etc.), as well as between the *speech intelligibility* and important acoustical objective measures (*RT*, *EDT*, *C80, D, TS, L* and *RASTI*). The aim is to provide basic information about *speech intelligibility* to predict it in churches at early stages of design or without the need of evaluations 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 *speech intelligibility* and objective criteria can be found in churches.

Architectural features that are important to defining the speech intelligibility in churches were identified. *Nave Height* was found as the most important of these, giving the best fit. In general, eight of the thirteen architectural parameters tested can be used in a general linear model to explain 72% of the variance of the speech intelligibility.

The best fit between speech intelligibility and objective acoustical parameters was for *Speech / RT* (R^2 = 0.67) stating that *RT* can be a reasonable predictor of the speech intelligibility. The relationship *Speech*/*TS* (R^2 = 0.67) also confirms the suitability of *TS* to fairly and objectively represent the speech intelligibility. The relationship *Speech* / *L* with a R^2 = 0.33 does not fulfill the expectations regarding their connection.

In general, some of the six objective acoustical parameters tested can be used in a general linear model to explain 75% of the variance of the *speech intelligibility*. The best general model was found to be with the frequency averaging option M1 (average of all 6 frequency bands from 125 to 4000 Hz). C80 is the only objective acoustical parameter that appears in all the general linear models found to predict speech intelligibility. This indicates that this is also an meaningful measure to predict speech intelligibility.

The relationships between Speech Intelligibility and the *RASTI* was tested using three methods to find a representative single number: *RASTI.001 (*using only 1 point in each church, the one in the middle of the longitudinal axis); *RASTI.avg (*average of all positions in each church) and *RASTI.ndf* (average of all positions Not in the Direct Field of the sound source, that is, excluding positions < 5 m from sound source or not in the main volume of the church).

RASTI.ndf appeared as the best of the three parameters to predict speech intelligibility (R^2 = 0.503). However, this fairly small R^2 reveals that there is no significant relationship between church averaged *RASTI* and speech intelligibility values. It is presumed that the results would be better if there were a direct spatial comparison (relating measure point by measure point) and not just church averaged values to compare.

It was also found that the *speech intelligibility* values were, in general, the double of the corresponding mean *RASTI* (from x1.3 to x2.5). A simple new table was proposed to tie *RASTI* values to subjective speech intelligibility.

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 *speech intelligibility* for each church (36 points=36 churches) plotted vs. the architectural parameters with regression models.

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

Figure 2 - Mean values of *speech intelligibility* for each church plotted vs. the mean value of the objective acoustical parameter with regression models (36 points = 36 churches).

Figure 3 - Mean values of *speech intelligibility* for each church plotted vs. the mean RASTI.ndf (Not in the Direct Field) values with regression model (36 points = 36 churches).

Figure 4 - Mean values of *speech intelligibility* for each church plotted vs. the mean *RASTI.avg* (Avg of all RASTI values in each church) values with regression model (36 points = 36 churches).

Figure 5 - Ratios between church averaged *speech intelligibility* and *RASTI* values.