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Relations between rapid speech transmission index (RASTI) and other acoustical and architectural measures in churches

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Abstract

The use of rapid speech transmission index (RASTI) in churches is studied and the relationships with acoustical and architectural parameters identified using a major survey of Catholic churches in Portugal. It was found that the vast majority of churches tested have RASTI values below 0.45 giving a poor rating in the quality of speech intelligibility. RASTI values within churches can be reasonably predicted by the use of center time (TS) at 1000 Hz. Loudness (L) does not appear as an important characteristic regarding RASTI values supporting the idea that the intelligibility of speech, under reverberant conditions does not depend on loudness. A prediction equation using three architectural parameters was calculated to estimate the average RASTI in churches. The effect of the architectural styles and the use of pulpits on RASTI values was also studied. © 1998 Elsevier Science Ltd. All rights reserved.

Keywords: RASTI; Churches; Architectural acoustics; Acoustic measures; Speech intelligibility.

1. Introduction

Praying and lecturing, that is, activities mainly related to speech, are an important part of services in Catholic churches. Nevertheless, acoustical problems in the intelligibility of speech are the general rule in this type of building. They are not as important as in other types of rooms where speech is used perhaps because the experience of the mass and related services and its liturgical structure is crucial to our ability to recognize speech. The purpose of this paper is to study speech intelligibility in churches by the use of the rapid speech transmission index (RASTI) and to analyze its relationships with other acoustical measures and architectural parameters calculated in a major survey of Portuguese churches.

The use of the RASTI as an index to predict the intelligibility of speech in churches does not have a large bibliographic data base. Not many studies have been

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published [1–4]. The study of the relationships between RASTI and other acoustical measures appears as an interesting necessity. Therefore, several monaural acoustical measures pertinent to churches were evaluated and their relationships with RASTI calculated. Other studies were done regarding the effect of the sound source location, the effect of architectural styles, etc., on RASTI values measured in churches.

2. Procedure

2.1. Description of sample

This paper reports on acoustical field measurements in a major survey of churches that were built since the sixth century. 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. For more uniformity of the sample, only churches with a room volume of less than 19,000 m^3 were selected for the study. The main architectural features of these churches are displayed in Table 1.

The churches are a sample of 14 centuries of church building in Portugal and were selected to represent the main architectural styles found throughout Portugal and to represent the evolution of church construction in Latin countries. The summary of the architectural styles of the churches are presented in Table 2.

2.2. Measurement method

Speech intelligibility was estimated by the calculation of the RASTI which has been related to subjective intelligibility [5–7] (Table 3). The RASTI method involved measurement (with B&K-3361) of the reduction of a transmitted test signal that has certain characteristics representative of the human voice. The RASTI method, a simplified version of the speech transmission index (STI), was developed by Houtgast and Steeneken [5]. The advantage of RASTI regarding other objective and subjective methods is that it can be quickly evaluated without speakers or listeners. It involves the measurement of the reduction of a transmitted test signal that has

Table 1
Main architectural features of the 41 churches tested

Architectural feature	Minimum	Median	Mean	Maximum
Volume (m^3)	299	3918	5772	18,674
Area (m^2)	56	427	450	1031
Max. height (m)	7	13	15	39
Max. length (m	12	31	33	62

Table 2
Architectural styles of the 41 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
Definition of the RASTI transfer function [7]

RASTI (%)	Subjective intelligibility scale
0–30	Bad
30–45	Poor
45–60	Fair
60–75	Good
75–100	Excellent

certain characteristics such as intensity, modulations or directional proprieties, representative of the human voice. A transmitter generates pink noise at levels of 59 and 50 dB, or + 10 dB, for the 500 and 2000 Hz octave bands, respectively, to mimic the long-term speech spectrum and with similar directional proprieties that would be measured from a human speaker (at 1 m). The low frequency modulations that exist in speech are simulated by nine discrete modulation frequencies between 0.7 and 11.2 Hz. A microphone receives the signal that is analyzed by the receiver unit to calculate the RASTI from the modulation reduction factors. Perfect transmission of speech requires that the received temporal speech envelope replicates the one emitted. This can be quantified in terms of alterations brought in the modulation of the speech envelope as the result of the acoustical characteristics of the room. RASTI is an index between 0 and 1 derived from the measured reduction in signal modulation between the transmitter and receiver positions. RASTI automatically includes the effect of reverberation and background noise because it is derived from the measured signal degradation. RASTI values can be transformed to a speech intelligibility scale as seen in Table 3.

The objective acoustics parameters calculated are:

RT	reverberation time using the integrated impulse-response method. RT30 (from -5 to -35dB)
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.
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 for the calculation of the eight room acoustic parameters 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 room's response to the noise-burst is then sampled from the RMS detector output of the sound level meter. A loudspeaker (B&K-4224) emitting short noise pulse bursts in 3/2 octave frequency bands was used as sound source. The receiving section consisted of one 1/2" diameter microphone (B&K-4155) and a sound level meter (B&K-2231) with a 1/1 octave filter set (B&K-1625). All of the procedures were controlled by software (B&K-BZ7109 and VP7155) from a notebook computer. In each church the loudspeaker was placed at two sound source locations: 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 at a 45° angle with the horizontal plane. Each measurement was calculated by average from an ensemble of three or four consecutive responses in each position. Five receiver positions were used on average in each church. The microphone was placed at 1.30 m above the floor at each location. In total, nearly 8000 values were determined (all combinations of the six octave-frequency bands, 125 to 4000 Hz, and source–receiver locations).

Regarding the RASTI measurement in each church, the transmitter location was in front of the main altar at 1.65 m above the floor to represent a standard speech situation during services (without using the PA system of the church). Eight positions on average in each church were used for the receiver location. In each receiver position three or four measurements were taken and then averaged to give the RASTI value at that location. In total, nearly 1200 data-points were collected. Table 4 presents a simple general statistical analysis concerning all data collected.

Figs. 1–3 present general analyses of the RASTI data collected. Fig. 1 displays the histogram of all the RASTI data measured (nearly 350 points). Fig. 2 shows the mean RASTI value in each church and their confidence interval with one standard

Table 4
RASTI simple statistics for the 41 church sample

Parameters	Rasti (%)
Minimum	21
Median	40
Mean	43
Maximum	79
Standard deviation	12

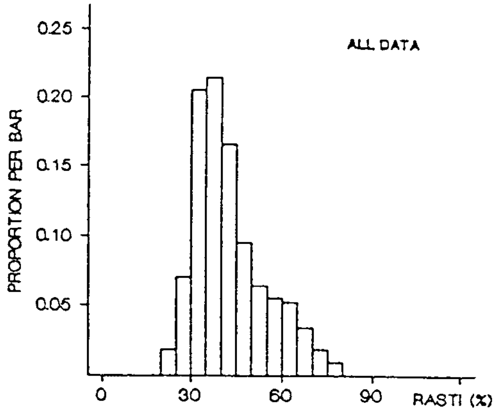

Fig. 1. Histogram of RASTI data collected in the 41 church sample.

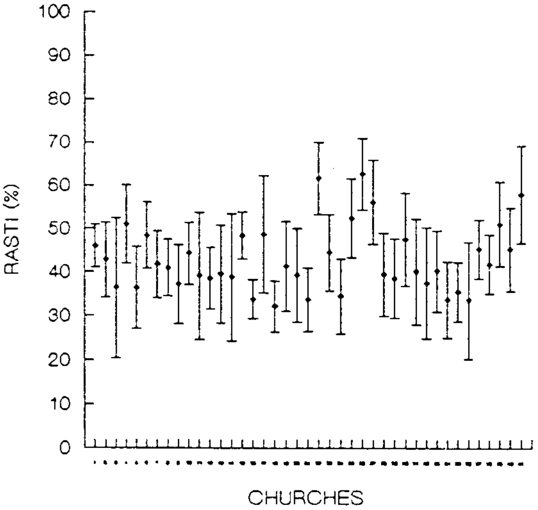

Fig. 2. Mean values of RASTI with one standard deviation confidence interval for each church (numbered 1 to 41 from left to right on the x axis).

deviation. The mean values range from 0.33 to 0.62 where the subjective quality is judged *fair* or *poor*. Only two churches have mean RASTI values above 0.60. The vast majority of churches have RASTI values below 0.45 giving a poor rating in the quality of speech intelligibility. This value is below the minimum performance of 0.50 required in many spaces, for instance when using voice systems [8].

Fig. 3 plots the variation of RASTI with the distance to the sound source with a logarithmic smoothing. In this case, only the positions on the longitudinal axis of each church were used. There is a steep decrease in the positions closer to the sound source where positions are located in the direct field and a reduced slope at larger distances where positions are located in the reverberant field.

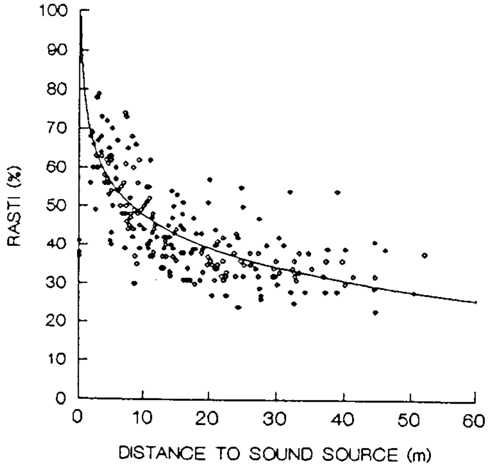

Fig. 3. RASTI values vs. receiver distance to sound source in all churches with logarithmic smooth.

3. RASTI and other acoustical measures

3.1. Procedure

Statistical analysis was used to determine the relationships between those eight room acoustic measures and the RASTI values. Models were calculated using several types of smoothing to determine the best regression line for the correspondence between RASTI and each of the other acoustical measures. The models tested were the linear ($y = a + b \cdot x$), logarithmic ($y = a + b \cdot \log_n x$), power ($y = a \cdot x^b$) and exponential ($y = a \cdot e^{b \cdot x}$). Two approaches were followed:

1. Using *all data* (including points in the transmitter's direct field);
2. Using *data without the direct field* values (that is, excluding the points located at a distance less than 5 m from the transmitter unit or not in the main volume of the church, like in chapels or in the main altar area).

3.2. Statistical models

For each of the eight acoustic measures and for each octave frequency band (38 cases in total) linear and non linear simple models were tested. Table 5 summarizes the results displaying the type of smoothing used, the R^2 for each model and the corresponding equations for the best model for each acoustical measure. Fig. 4 shows the plots for the best models and loudness.

It was found that RASTI values within churches in positions not in the direct field of the sound source can be reasonably predicted by the use of the TS (1 kHz) in the same position, with a $R^2 = 0.80$. Regardless of the receiver position within the church, RASTI can be predicted (with a $R^2 = 0.74$) by the use of the C80 (2 kHz). If the assumption that RASTI is a good predictor of speech intelligibility is valid [5],

Table 5
Statistical analyses for the relations between the RASTI and the 38 acoustic measures with prediction models for RASTI

Acoustical measure	Direct field data	Type of smoothing	R^2	Prediction model (RASTI = ...)	Fig
RT(125)	No	Power	0.629		
RT(250)	No	Power	0.679		
RT(500)	No	Power	0.731		
RT(1k)	No	Power	0.743		
RT(2k)	No	Power	**0.756**	57.149 (RT2k)−0.406)	4(a)
RT(4k)	No	Power	0.753		
EDT(125)	No	Power	0.627		
EDT(250)	No	Power	0.690		
EDT(500)	No	Power	**0.782**	58.335 (EDT500)(−0.386)	4(b)
EDT(1k)	No	Power	0.775		
EDT(2k)	No	Power	0.779		
EDT(4k)	No	Power	0.771		
C80(125)	Yes	Linear	0.516		
C80(250)	Yes	Exponential	0.534		
C80(500)	Yes	Exponential	0.667		
C80(1k)	Yes	Exponential	0.655		
C80(2k)	Yes	Exponential	**0.735**	49.19 exp [0.06659 C80(2k)]	4(c)
C80(4k)	Yes	Linear	0.677		
D(125)	Yes	Linear	0.497		
D(250)	Yes	Linear	0.509		
D(500)	Yes	Linear	0.700		
D(1k)	Yes	Linear	0.680		
D(2k)	Yes	Linear	**0.705**	26.91 + 62.92 *D*(2k)	4(d)
D(4k)	Yes	Linear	0.621		
TS(125)	No	Power	0.645		
TS(250)	No	Power	0.675		
TS(500)	No	Power	0.784		
TS(1k)	No	Power	**0.803**	378.136 TS(1k)(−0.419)	4(e)
TS(2k)	No	Power	0.787		
TS(4k)	No	Power	0.736		
L(125)	Yes	Linear	0.141		
L(250)	Yes	Linear	0.120		
L(500)	Yes	Linear	0.122		
L(1k)	Yes	Linear	0.108		
L(2k)	Yes	Exponential	0.128		
L(4k)	Yes	Exponential	**0.167**	30.45 exp [0.02594 *L*(4k)]	4(f)
BR_RT	No	Linear	0.033	46.28−8.274 BR_RT	
BR_L	Yes	Linear	0.020	39.28 + 1.382 BR_L	

then TS (1 kHz) will also be one. Regardless of the receiver position within a church, RASTI was found to be easily predicted with the use of C80 (2 kHz).

Concerning the two approaches for this study (data with or without the direct field positions) it was found that the exclusion of the direct field data strongly affected only the prediction models for RT and EDT (achieving a 55% higher R^2), because RT and EDT are generally relatively constant within a church and are not strongly affected by the proximity of the sound source. Loudness (*L*) does not appear as an important characteristic regarding the RASTI values (R^2maximum = 0.17) because

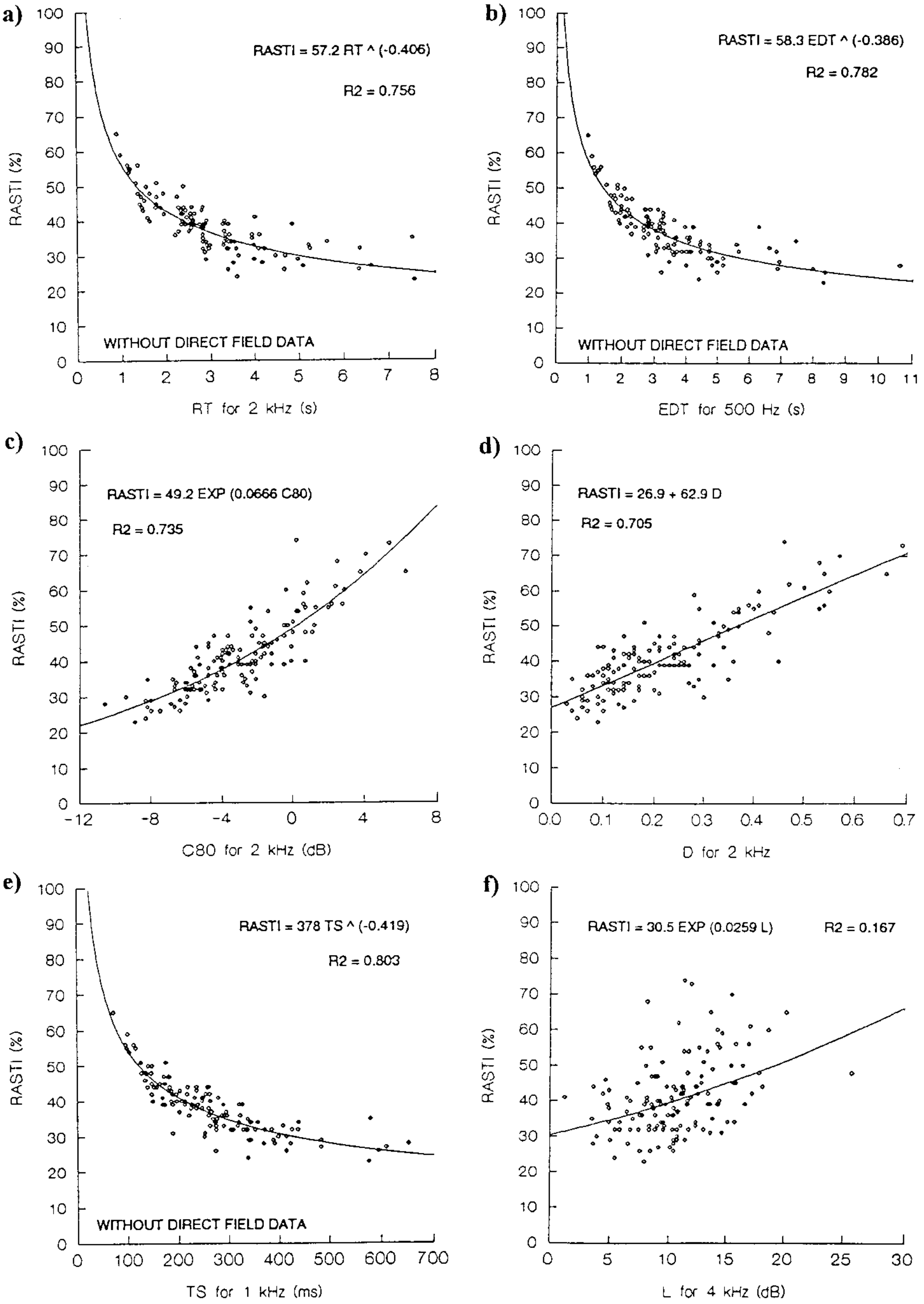

Fig. 4. Plots of RASTI vs. six acoustical measures for all churches with regression models.

the intelligibility of speech under reverberant conditions depends usually on the direct sound being at greater intensity than the reverberant sound.

To find a better fit, a *general linear model* was calculated using the forward stepwise modeling method (with an α-to-enter/remove $= 0.05$), to predict RASTI (with $R^2 = 0.84$) in any position within a church (not in the sound source's direct field) using the other objective acoustical measures. Some of the 38 acoustical measures (considering each of the frequency bands) tested can be used together in a general linear model to explain 84% of the variance of the RASTI:

$$\mathrm{RASTI} = -6.139\ \mathrm{EDT}(4k) + 1.479\ \mathrm{C80}(2k) + 12.417\ D(125) + 0.046\ \mathrm{TS}(4k) + 0.692\ \mathrm{BR\_L}$$

4. RASTI and architectural parameters

4.1. Architectural parameters

The 15 architectural parameters used to characterize each church are described in Table 6.

4.2. RASTI single number average

With the 15 architectural parameters used, there is a need for a corresponding single RASTI value representative of each church. Three options were tested as described in Table 7.

4.3. Linear models

Linear models were tested between each of the 15 architectural parameters and the three options of determining a single RASTI value for each church. The results of the Pearson correlation coefficient found are displayed in Table 8. The highest correlation

Table 6
Architectural parameters used

Architectural parameters
SEATS (number of seats)
VOLUME TOTAL (m^3)
VOLUME NAVE (m^2)
AREA TOTAL (m^2)
AREA NAVE (m^2)
LENGTH MAXIMUM (m)
LENGTH NAVE (m)
HEIGHT MAXIMUM (m)
HEIGHT NAVE (m)
HEIGHT AVGERAGE (vol.total/area total) (m)
WIDTH NAVE (m)
WIDTH AVERAGE (m)
ALPHA AVERAGE (average value for all surfaces)
R LOCAL [$=A/(1-\alpha_{\mathrm{avg}})$]
ABSORPTION TOTAL (m^2)

Total stands for the entire church including lateral chapels and main altar; Nave stands for the entire church excluding lateral chapels and main altar.

Table 7
Three options to calculate averaged RASTI in each church

Code	Definition
RASTI.001	Using only one point in each church (the one in the middle of the longitudinal axis)
RASTI.AVG	Average of all positions tested in each church
RASTI.NDF	Average of all positions Not in the direct field of the sound source (excluding positions less than 5 m from sound source or not in the main volume of the church, like lateral chapels)

Table 8
Pearson correlation coefficients (R) for architectural parameters vs. averaged RASTI

Architectural parameter	RASTI.001	RASTI.AVG	RASTI.NDF
SEATS	−0.362	−0.457	−0.459
VOLUME TOTAL	−0.481	−0.492	−0.522
VOLUME NAVE	−0.486	−0.496	−0.528
AREA TOTAL	−0.493	−0.552	**−0.558**
AREA NAVE	−0.474	−0.546	−0.550
LENGTH MAXIMUM	−0.487	−0.497	−0.515
LENGTH NAVE	−0.479	−0.506	−0.522
HEIGHT MAXIMUM	−0.474	−0.462	−0.509
HEIGHT NAVE	−0.511	−0.438	−0.490
HEIGHT AVERAGE (volume total/area total)	−0.492	−0.432	−0.486
WIDTH NAVE	−0.440	−0.530	−0.512
WIDTH AVERAGE	−0.439	−0.541	−0.526
ALPHA AVERAGE	0.422	0.458	0.469
R LOCAL $[A/(1-\alpha_{\text{avg}})]$	−0.017	−0.039	−0.030
ABSORPTION TOTAL	−0.076	−0.098	−0.093

values were found using RASTI.NDF, that is, average without the positions in the direct field of the sound source. The reason for this is finding that, near the sound source (in a small area of the church), the RASTI values increase significantly, therefore greatly changing the total average. Also those positions are not representative of the real speech intelligibility because few or none of the people attending services sit so close to the sound source (the priest).

The highest $|R|$ found was 0.56 between RASTI.NDF and the area total. However this only explains 31% of the existent variance ($R^2=0.31$). Other models were then sought.

4.4. Nonlinear models

Nonlinear models were tested between each of the 15 architectural parameters and the three options to determine a single RASTI value in each church. The models used were the logarithmic ($y=a+b\cdot\log_n x$), power ($y=a\cdot x^b$) and exponential ($y=a+b\cdot e^{c.x}$). The results of the squared R coefficients found are presented in Table 9. The highest squared R ($R^2=0.46$) was determined to be between RASTI.NDF and the volume of the nave. Fig. 5 shows the plot of that relationship where it can be seen that only in small churches (volume < 3000 m^3) the average RASTI is significantly different from 0.35.

Table 9
Squared correlation coefficients for architectural parameters vs. averaged RASTI

Architectural parameter	RASTI 001		RASTI AVG		RASTI NDF	
	R^2	Model	R^2	Model	R^2	Model
SEATS	0.131	LI	0.209	PW	0.215	EX
VOLUME TOTAL	0.376	LG	0.408	LG	0.443	PW
VOLUME NAVE	**0.389**	LG	0.419	PW	**0.456**	PW
AREA TOTAL	0.347	LG	**0.422**	LG	0.430	PW
AREA NAVE	0.341	LG	0.418	LG	0.425	PW
LENGTH MAXIMUM	0.267	LG	0.285	LG	0.303	LG
LENGTH NAVE	0.291	LG	0.328	LG	0.342	LG
HEIGHT MAXIMUM	0.262	PW	0.256	PW	0.315	PW
HEIGHT NAVE	0.276	EX	0.204	PW	0.267	EX
HEIGHT AVGERAGE (vol.total/area total)	0.266	PW	0.209	PW	0.271	PW
WIDTH NAVE	0.305	LG	0.392	PW	0.379	PW
WIDTH AVERAGE	0.283	LG	0.384	PW	0.377	PW
ALPHA AVERAGE	0.178	LI	0.209	PW	0.220	LI
R LOCAL $[=A/(1-\alpha_{avg})]$	0.107	PW	0.122	LI	0.135	PW
ABSORPTION TOTAL	0.126	LG	0.143	PW	0.158	PW

EX—exponential, LG—logarithmic, LI—linear, PW—power.

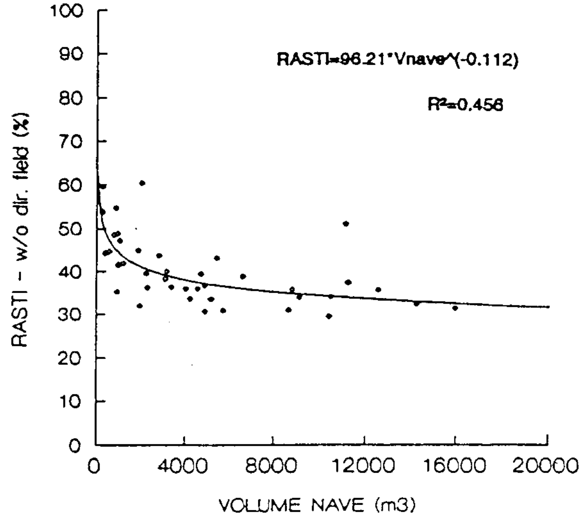

Fig. 5. Plot of the RASTI values without the direct field positions vs. the volume of the nave (the best predictor within the 15 architectural parameters). Prediction equation with power smoothing and R^2 are shown.

4.5. General linear models

To increase the fitness of the models under study, general linear models were tested, between RASTI.NDF and the 15 architectural parameters. The best model using only two architectural parameters was determined to be with the width of the nave (WIDTH NAVE) and the average absorption coefficient (ALPHA AVERAGE) ($R^2 = 0.54$). Fig. 6 presents the plot of this general linear model. There, it can be seen that RASTI increases with the decreasing width of the nave or with increasing the α average of the church.

The best model using three architectural parameters was found to be with WIDTH NAVE the ALPHA AVERAGE and the HEIGHT NAVE ($R^2 = 0.73$). This general linear model was determined with the forward stepwise procedure (α-to-enter/remove = 0.05). Therefore 73% of the inter-church variance of the averaged RASTI is explained by the average absorption of the church and the width and height of the nave area, using the following model (standard error of the estimate = 0.04):

$$\text{RASTI.NDF} = 0.485 + 1.07\ \text{ALPHA AVG} - 10^{-2}\ (0.703\ \text{HEIGHT NAVE} \\ -0.594\ \text{WIDTH NAVE})$$

In summary, the best models to predict an average value of RASTI in churches are presented in Table 10.

5. RASTI and architectural styles

In the act of worship sound has greater impact than any other factor. Activities related to speech and music are an essential part of almost all services in Catholic churches. Today the Roman Catholic Church follows the directives of the Vatican II Council (1965) but in the previous twenty centuries, different behaviors and other

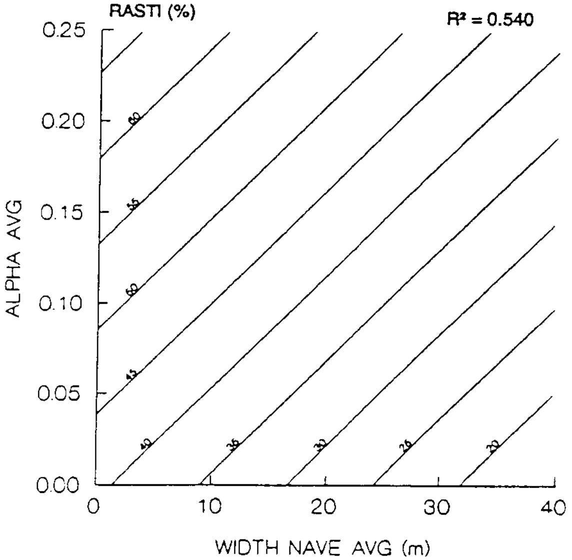

Fig. 6. Plot of the best general linear model to predict RASTI with 2 architectural parameters (average width of the nave and the average absorption coefficient) with R^2.

Table 10
Summary of best models to predict an average RASTI in churches

Model	R^2	Architectural parameters used in model
Best linear	0.31	Area total
Best nonlinear (power smoothing)	0.46	Volume nave
Best linear w/2 architectural parameters	0.54	Alpha average + Width nave
Best linear w/3 architectural parameters	**0.73**	Alpha average + Width nave + height nave

habits existed. Churches developed and adapted through time the need for a specific acoustical environment.

That Council introduced very important alterations in the liturgy and worship services that can have strong implications in the acoustical environment in which they are performed. The Council decided to preach sermons in the vernacular to its congregations and for service music that people can sing. These relevant changes in the *speech* and *music* of the worship services require suitable acoustical conditions of the churches. But this was not the first time in the history of the Catholic Church that *speech* and *music* underwent noteworthy transformations. Until the fourth century the language of the church was Greek. Then Latin became the official language and remained for 16 centuries. Only 30 years ago it changed again, this time to the vernacular, a radical innovation. In the history of the Church, in 99% of its past, there was not an emphasis on the understanding of what was said. Therefore, no suitable acoustical conditions were needed for that task.

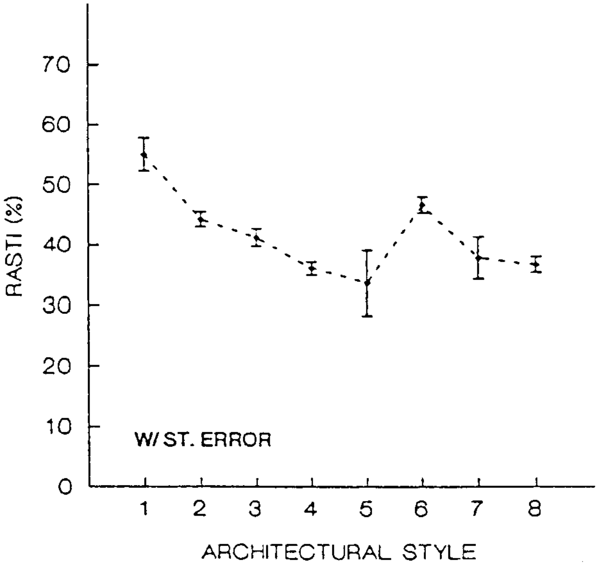

Fig. 7. Average RASTI data with one standard error confidence intervals plotted vs. the architectural styles in chronological order from left to right (1—Visigothic, 2—Romanesque, 3—Gothic, 4—Manueline, 5—Renaissance, 6—Baroque, 7—Neoclassic, 8—Contemporary).

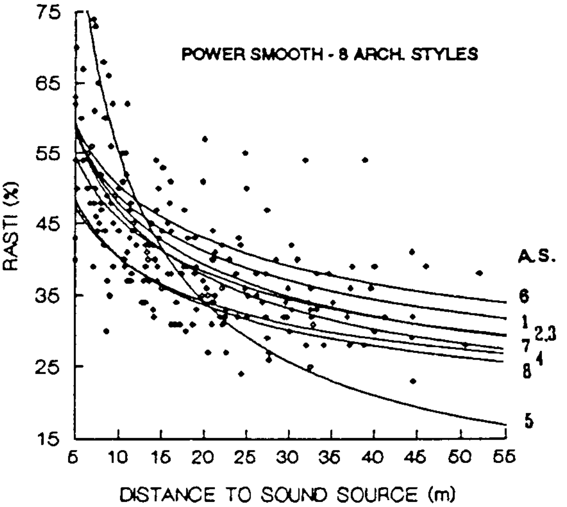

Fig. 8. RASTI plotted vs. receiver distance to sound source (altar) excluding the direct field positions with power smooth regression models for each architectural style (1—Visigothic, 2—Romanesque, 3—Gothic, 4—Manueline, 5—Renaissance, 6—Baroque, 7—Neoclassic, 8—Contemporary).

Figs. 7 and 8 present the analyses of the RASTI behavior controlling for the eight architectural styles as listed in Table 2. In Fig. 7, mean RASTI values decrease until style 5 (Renaissance) and then sharply increase in style 6 (Baroque) to again decrease until style 8 (Contemporary). The break point in time where the general trend of the data changes is the period of the Protestant and Catholic Reformations where speech in Catholic churches became more important than it had been previously. Style 6 (Baroque) radically changed the acoustical behavior of the churches tested. Those changes seem to be soon forgotten. With the Neoclassic the previous trend of decreasing RASTI reappears perhaps due to the wave of antimodernism rules in the Church. That trend was leveled only in this century, where speech is perhaps the most important part of the religious services.

Fig. 8 displays the RASTI variation with the distance to the sound source, near the altar (excluding the direct field, distance less than 5 m), with the regression lines for each architectural style. The Renaissance appears as the style with the lowest RASTI values and the Visigothic and Baroque as the ones with the highest RASTI values.

6. Pulpit effect

Pulpits are now common in churches and other temples. The earliest documentary reference to a pulpit occurs in the 12th century [9] however they were uncommon in churches until the 15th century. After the 15th century they become increasingly common. Rules appeared in the related literature about their position and height within the church [9–13]. Others even have drawings showing preferred acoustical design techniques for pulpits [14].

The improvement in speech intelligibility provided by pulpits was tested in two churches: Church 12 (*Golegã*, 15th century) and Church 21 (*Santíssimo Sacramento*-Porto, 20th century). Fig. 9 displays the variation in the RASTI values with distance from the main altar using the sound source in the pulpit and in the altar. In both churches tested a higher RASTI was found for specific positions between 10 and 30 m from the altar when the sound source was in the pulpit. For longer distances, no improvement was determined and for shorter distances, a decrease in RASTI was found because those locations were behind the sound source usually in the apse or main altar area. Looking to these two figures it seems that the use of a pulpit increases speech intelligibility. However, the improvement in the RASTI values was caused by the shorter distance between the sound source and each receiver due to the method used to measure distance. With the sound source in the pulpit, the distance to each receiver was smaller and therefore the RASTI was higher. This is supported by Fig. 10. In this figure the x axis represents the distance from the sound source not the distance to the main altar as in the previous figure. That is, the distance to the altar or to the pulpit depending upon which position the sound source was emitting. In this analysis, there was no improvement in measured RASTI at a given distance when a pulpit was used. In fact, a small decrease in the RASTI values for the pulpit positions was found.

Therefore it can be stated that the use of pulpits that do not have large canopies above them, as in these two cases, only improves the speech intelligibility due to the diminution of the distance between the receiver and the source. Pulpits were found not to be a direct acoustical resource but only an indirect way to increase the intelligibility of speech by decreasing the distance from the speaker to the listener.

These results were found using unoccupied churches. If occupied churches were used perhaps the effect of the absorption of the persons in the path of the direct sound from the altar would change the results. In this case, the use of an elevated pulpit and the emission of sound power over the congregation area could improve

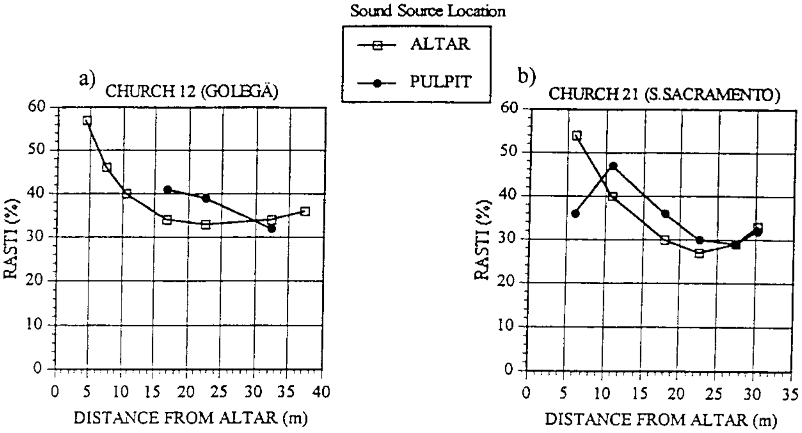

Fig. 9. RASTI values vs. receiver distance from altar with the sound source in the altar or on the pulpit: (a) Church 12—*Golegã*—15th century; (b) Church 21—*S. Sacramento*, Porto—20th century.

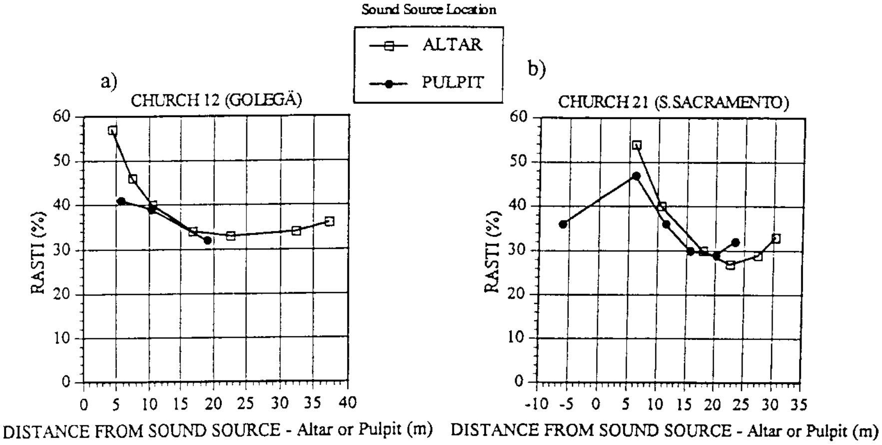

Fig. 10. RASTI values vs. receiver distance from sound source (altar or pulpit) with the sound source in the altar area or on the pulpit. (a) Church 12—*Golegã*—15th century; (b) Church 21—*S. Sacramento*, Porto—20th century.

the speech intelligibility. In that situation, when the sound source was in the altar position, the RASTI values would be perhaps smaller than in the unoccupied church, due to the effect of the absorption of the persons seated in the previous rows, in the path of sound. Therefore, the effect of the pulpit could be different than the one tested.

7. Conclusions

The use of RASTI in churches was studied and the relationships with acoustical and architectural parameters identified. The vast majority of churches tested have RASTI values below 0.45 (0.40 was the calculated median) giving a poor rating in the quality of speech intelligibility.

RASTI values within churches, in positions not in the direct field of the sound source, can be predicted by the use of TS (1 kHz) in the same position, with a $R^2 = 0.80$. The EDT (500 Hz) and RT (2 kHz) are almost as effective in that task with $R^2 = 0.78$ or 0.76, due to the correlation among measures. If the assumption that RASTI is a good predictor of speech intelligibility is correct [5–7], then TS (1 kHz) will also be an accurate predictor of speech intelligibility. Even regardless of the receiver position within a church, RASTI was found to be easily predicted, with $R^2 = 0.74$, by the use of C80 (2 kHz). Loudness (L) does not appear as an important characteristic regarding RASTI values with $R^2 < 0.17$ supporting the idea that the intelligibility of speech, under reverberant conditions does not depend on loudness. This agrees with the idea that speech intelligibility is related to the direct sound being at greater intensity than the reverberant sound. A prediction equation using three architectural parameters (nave width, nave height and the average absorption coefficient) was calculated to estimate, with $R^2 = 0.73$, the average RASTI in churches.

The effect of the architectural styles on RASTI values was found to show a negative trend regarding the first five styles i.e. speech intelligibility generally decreased until the Renaissance style with a strong improvement in the Baroque style (Reformation period). There were no statistically significant variations in the last two styles (19th–20th centuries). The Renaissance appears as the style with the lowest RASTI values and the Visigothic and Baroque are the ones with the highest RASTI values.

The use of pulpits without large canopies was found to increase the RASTI values. This was justified only by the decrease of the distance between the receiver and the source. Pulpits were found not to be a direct acoustical resource but only an indirect way to increase the intelligibility of speech by decreasing the distance from the speaker to the listener.

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