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HOW DOES *RASTI* CHANGE WITH SOUND REINFORCEMENT SYSTEMS IN CHURCHES?

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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 involves field measurements in a very large number of Portuguese Catholic churches and has included two major components to date:

- *Objective studies* - Measurements of objective acoustical parameters were taken at multiple locations in each church (RT, EDT, C_{80}, D_{50}, TS, L, BR_RT, BR_L and RASTI). [1, 2, 3]
- *Subjective studies* - This has included both evaluating live musical performances and speech intelligibility testing. This work is characterized by the use of a sample of listeners and evaluation of several locations in each church. [2, 4, 5]

This paper presents a report regarding the first item and concerning the RASTI (Rapid Speech Transmission Index) measurements that were taken in 31 churches.

2 - METHODOLOGY

2.1 - Method Summary

The main research hypothesis is that the RASTI differences among churches, with and without the use of their Sound Reinforcement Systems (SRS), could be measured.

The study consisted of two parts both regarding RASTI analyses in non occupied churches (apart from the experimenters). The first part was to gather objective evaluations of the acoustical qualities of the churches from the use of the RASTI, using only its own sound source at the altar area (parameter named RASTI_SRS.off). The second part was to gather the same type of evaluations of the same sample of churches but with the use of the churches' SRS (parameter named RASTI_SRS.on). The loudspeaker arrangement commonly present in the churches tested was the distributed line source system (but with no signal-delayed), which is the standard in Portugal (see Figure 1).

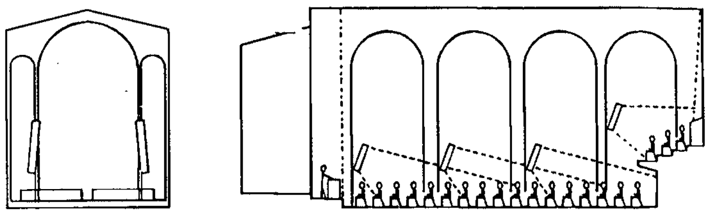


Figure 1 - The loudspeaker arrangement commonly present in the churches tested was the distributed line source system (but with no signal-delayed), which is the standard in Portugal Adapted from [6].

The limitations using this type of methodology for evaluations were fully realized. The acoustical response of the church changes when it is fully occupied. Nevertheless this methodology gives a normalized sound environment that could be easily compared among churches. The empty churches without any speech reinforcement is referred to as the normal state (parameter RASTI_SRS.off).

For the RASTI measurement in each church, the transmitter location was in front of the main altar at about 1.65 m above the floor to represent a standardized speech situation during services. The level of the source was +10 dB compared with the RASTI standard level [6] due to the large volume of some of the churches. Four positions in each church were used for the receiver location (*A*, *B*, *C* and *D* as seen in Figure 2). In each receiver position three or four RASTI measurements were taken and then averaged to give the RASTI value at that location. All the statistical analyses were done using the *SYSTAT®* software.

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 January and March 1998 in a survey of 31 Roman Catholic churches in Portugal that were built between the 10th century and 1997 (Table 1). The churches are a sample of 11 centuries of church building in Portugal. The oldest churches tested were no. 13 and 23, which were built around the 10-11th centuries. The most recent was church no. 20 (the new church of Architect Siza Vieira in Marco de Canaveses) that was completed in 1997. A more complete acoustical analysis of the churches is available [1 to 5].

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 17500 m^3 were selected for the study.

The evaluations were held in churches grouped by large periods of history and architecture: 6 *Romanesque* churches (10th-13th centuries), 5 *Gothic* churches (13th-15th centuries), 8 *Baroque* churches (16th-18th centuries), 6 *Neoclassic* (18th-19th centuries) and 6 *Contemporary* churches (20th century). The main architectural features of these churches are displayed in Table 2.

Table 1 - List of the churches tested.

No.	Church Name (Town)	Vol. (m^3)	No.	Church Name (Town)	Vol. (m^3)
1	Lapa (Porto)	11423	17	Tibães	8608
2	Clérigos (Porto)	5130	18	Sé (Braga)	13662
3	Santo Ildefonso (Porto)	3813	19	Pombeiro (Felgueiras)	11380
4	Santíss. Sacramento (Porto)	6816	20	S.ta Maria (Marco Canaves.)	8994
5	Gondarém (Porto)	3904	21	Bustelo (Penafiel)	6476
6	S. Francisco (Porto)	12045	22	Cete (Paredes)	1515
7	Grilos (Porto)	14497	23	Paço de Sousa (Penafiel)	6028
8	S. Bento da Vitória (Porto)	17460	24	Cabeça Santa (Penafiel)	751
9	Nevogilde (Porto)	1137	25	S. Pedro (Paços de Ferreira)	2912
10	Sé (Porto)	15260	26	S. João Baptista (Porto)	6048
11	Santa Clara (Porto)	2491	27	Nª Sª Conceição (Porto)	12532
12	Cedofeita - New (Porto)	8470	28	Santa Maria (Azurara)	7212
13	Cedofeita - Old (Porto)	1117	29	Matriz (Vila do Conde)	8408
14	Nª Sª da Boavista (Porto)	3740	30	S. Pedro (Rates)	3918
15	Serra do Pilar (Gaia)	11566	31	Santa Clara (Vila do Conde)	5394
16	Mosteiro de Grijó (Gaia)	13818			

Table 2 - Simple architectural statistics for all churches tested.

ARCHITECTURAL FEATURE	MINIMUM	MEDIAN	MEAN	MAXIMUM
VOLUME (m^3)	751	6816	7630	17460
AREA (m^2)	108	549	586	1300
MAXIMUM HEIGHT (m)	5.9	16.1	15.7	35.1
MAXIMUM LENGTH (m)	17.9	37.2	39.3	63.0
WIDTH NAVE (m)	5.4	13.0	13.7	26.1

2.3 - The Parameter RASTI

The RASTI method involved measurement (with a Brüel & Kjaer type 3361 set) of the reduction of a transmitted test signal that has certain characteristics representative of the human voice. This method, a simplified version of the Speech Transmission Index (STI), was developed in 1984 [7] and has been related to subjective intelligibility [7, 8, 9] (see Table 3).

The advantage of RASTI regarding other 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 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 (situation used in this survey), for the 500 Hz and 2 kHz 1/1 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 9 discrete modulation frequencies. A microphone receives the signal that is analyzed by the receiver unit to calculate the RASTI from the modulation reduction factors.

The RASTI is a value between 0 and 1 derived from the measured reduction in signal modulation between the transmitter and receiver positions. It automatically includes the effect of reverberation and background noise because it is derived from the measured signal degradation.

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.

Table 3 - Definition of the RASTI transfer function. [9]

RASTI	Subjective Intelligibility Scale	RASTI	Subjective Intelligibility Scale
0 - 0.30	Bad	0.60 - 0.75	Good
0.30 - 0.45	Poor	0.75 - 1	Excellent
0.45 - 0.60	Fair		

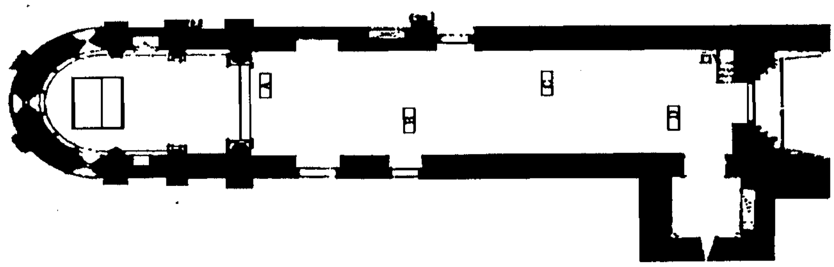


Figure 2 - The 4 standard receiver positions from left - altar - to right: *A*, *B*, *C* and *D*.

3 - RESULTS

3.1 - Overall Results

Table 4 presents a simple general statistical analysis concerning all data collected. Figures 3 and 4 present general analyses of the RASTI data collected. They show, for each church, a boxplot. Each bar represents the within church variation. In a box plot, the center vertical line marks the median of the sample. The length of each box shows the range within which the central 50% of the values fall, with the box edges (called *hinges*) at the 1st and 3rd quartiles. The *whiskers* show the range of observed values that fall within 1.5*Interquartile Range (the difference between the values of the 2 hinges). Values outside the *whiskers* (the outliers) are plotted with asterisks.

The mean church values range from 0.18 to 0.66. Only one church has its mean RASTI value 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 [10].

Figures 5 and 6 display the RASTI behavior controlling for the receiver location (*A*, *B*, *C* and *D*).

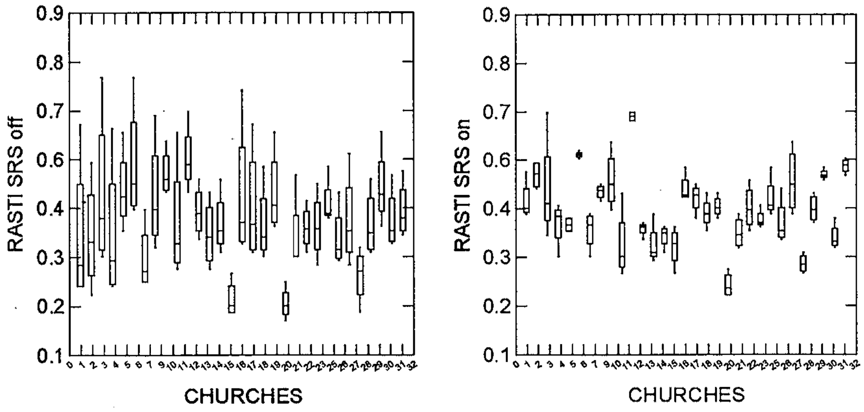
These Figures 3 to 6 show that the SRS.On contributes for a sound field homogenization within the churches.

Figures 7 and 8 plot the variation of the RASTI values with the distance to the sound source with a logarithmic smoothing. 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 receiver positions are located in the reverberant field. The best-fit equation is:

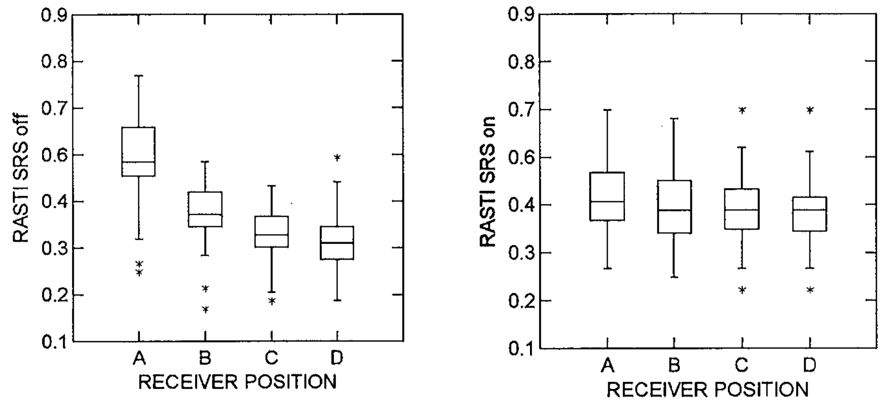
$$RASTI\_SRoff = 0.797 - 0.148 \log (Distance) \quad \text{, with a } R^2 = 0.52.$$

Table 4 - Simple general statistics regarding all RASTI data collected.

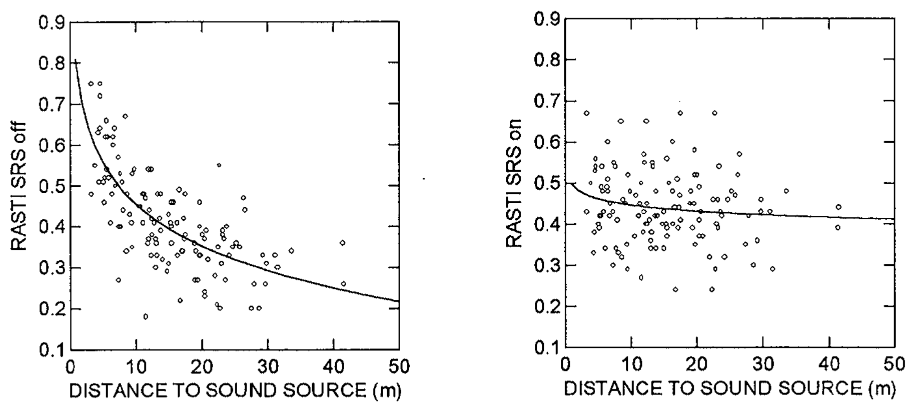
PARAMETER	RASTI SRS Off	RASTI SRS On	PARAMETER	RASTI SRS Off	RASTI SRS On
Minimum	0.18	0.24	Maximum	0.75	0.67
Mean	0.42	0.44	Median	0.40	0.43
Range	0.57	0.43	Standard deviation	0.12	0.09



Figures 3 and 4 - Within church variation of the RASTI values (SRS Off and On) (the *x*-axis shows the 31 churches numbered *1* to *31* from left to right).



Figures 5 and 6 - RASTI values (SRS Off and On) controlling for the receiver position within the churches (*A* is the closest to the altar).



Figures 7 and 8 - RASTI values (SRS Off and On) with the distance to the sound source.

3.2 - Comparison between RASTI with the SRS On and Off

The Figure 9 presents the RASTI values (all 4 receiver positions) measured for both situations: SRS On and Off with a logarithmic best-fit smoothing curve:

$$RASTI\_SRS.on = 0.602 + 0.402*\log(RASTI\_SRS.off) \quad \text{, with a } R^2 = 0.34.$$

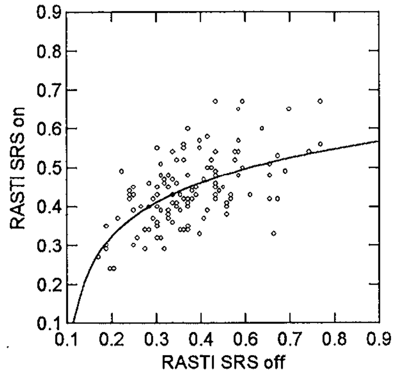


Figure 9 - Comparison among RASTI values (SRS Off and On) with a logarithmic smooth.

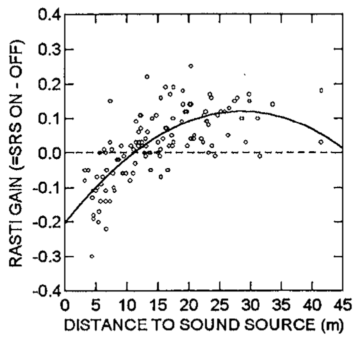


Figure 10 - Gain in the RASTI values with the SRS On with the Distance to Sound Source.

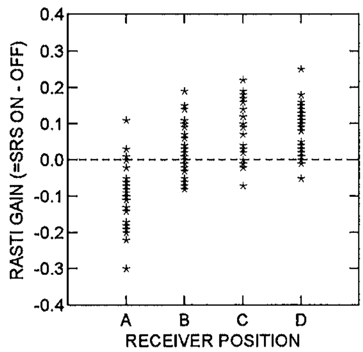


Figure 11 - Relationship between the RASTI Gain (SRS On and Off) and the Receiver positions (A: the closest to the altar).

To check the effect of the SRS a new parameter was defined, the RASTI_Gain, which represents the difference between the RASTI measured with the SRS On and Off:

$$RASTI\_Gain = (RASTI\_SRS.on) - (RASTI\_SRS.off)$$

If RASTI_Gain is positive it represents that the SRS On improves the RASTI values; if negative it shows a decrease in the RASTI values on that receiver position by the of the SRS. The Figure 10 displays the RASTI_Gain with the Distance to the Sound Source. For distances up to about 11 m it is shown that the RASTI_SRS.on is usually smaller than the RASTI_SRS.off. Its best-fit equation is:

$$RASTI\_Gain = -0.00040*(Distance)^2 + 0.0226*(Distance) - 0.202 \quad \text{, with a } R^2 = 0.55.$$

Figure 11 presents the RASTI_Gain data controlling for each receiver position (*A*, *B*, C and *D*). It is shown that for Position A (the closest to the altar) the use of the SRS generally decreases the RASTI values. Almost the opposite happens with receiver positions *B*, C and *D* where the SRS On, usually increases the RASTI values (up to 0.25).

To better understand the effect of the SRS on the RASTI values within the churches an Improvement Factor (*IF*) was defined as follows:

$$IF = \frac{(RASTI\_SRS.on)_{church.average}}{(RASTI\_SRS.off)_{church.average}}$$

Table 5 - Improvement Factors (*IF*) calculated for all 31 churches, listed by increasing *IF* values.

Church No.	RASTI SRS Off (church avg.)	RASTI SRS On (church avg.)	*IF* (=On/Off)	RASTI SRS On - RASTI SRS Off	*IF* (without position *A*)
5	0.49	0.41	**0.83**	-0.08	0.90
10	0.41	0.36	**0.87**	-0.05	0.93
30	0.42	0.38	**0.90**	-0.04	0.95
12	0.44	0.40	**0.91**	-0.04	0.96
14	0.41	0.38	**0.93**	-0.03	1.01
19	0.48	0.45	**0.93**	-0.03	1.01
13	0.38	0.36	**0.93**	-0.03	0.95
9	0.53	0.51	**0.97**	-0.02	0.96
21	0.38	0.39	**1.02**	0.01	1.12
3	0.48	0.49	**1.02**	0.01	1.10
8	0.47	0.48	**1.02**	0.01	1.17
24	0.46	0.47	**1.03**	0.01	1.04
16	0.48	0.49	**1.03**	0.02	1.20
6	0.55	0.57	**1.04**	0.02	1.19
23	0.40	0.42	**1.04**	0.02	1.11
17	0.45	0.47	**1.04**	0.02	1.26
29	0.49	0.52	**1.06**	0.03	1.17
4	0.38	0.41	**1.07**	0.03	1.44
18	0.41	0.43	**1.07**	0.03	1.16
28	0.41	0.44	**1.09**	0.04	1.23
27	0.29	0.31	**1.10**	0.03	1.22
25	0.37	0.41	**1.10**	0.04	1.14
22	0.40	0.45	**1.12**	0.05	1.23
11	0.56	0.66	**1.18**	0.10	1.27
20	0.22	0.26	**1.19**	0.04	1.23
7	0.33	0.39	**1.21**	0.07	1.44
1	0.38	0.46	**1.22**	0.08	1.50
26	0.42	0.51	**1.22**	0.09	1.47
31	0.44	0.54	**1.24**	0.11	1.34
2	0.38	0.52	**1.38**	0.14	1.64
15	0.23	0.35	**1.53**	0.12	1.60
		Average	**1.07**	**0.03**	**1.19**

Table 5 shows the IF's calculated for all churches, listed by its increasing values. The use of the SRS considering all receiver positions within the churches increases, on average, 7 per cent the RASTI or 0.03 its absolute values. However, only 30 per cent of the churches tested show a noticeable average improvement of more than 10 per cent on their RASTI values by the use of the SRS and 26 per cent even decrease its RASTI values. In fact, only in 7 churches (23 per cent) the RASTI values achieved the minimum performance of 0.50 required in many spaces when using voice systems [10]. The highest IF values found are for churches no. 15 and 2 that have a circular (or almost circular) plan shape. Due to their plan shape there is no largely delayed signal arriving, to the majority of the receiver positions, from the surrounding loudspeakers as normally happens. Table 5 also shows the RASTI IF's but calculated without the values measured on receiver position *A* (direct field). In this situation the RASTI values, with the SRS on, increase an average of 19 per cent.

4 - SUMMARY

The RASTI was measured in 31 Catholic churches built in the last 11 centuries in Portugal. Four receiver locations were used in each church, with and without the use of sound reinforcement systems (SRS) from the altar area. The loudspeaker arrangement commonly present in the churches tested was the distributed line source system (but with no signal-delayed), which is the standard in Portugal.

This paper concentrates on the RASTI values within churches and on their differences with the SRS Off and On. The vast majority of churches tested (70per cent) have RASTI values, with the SRS Off, not greater than 0.45 (0.40 was the calculated median) giving a poor rating in the quality of speech intelligibility. The mean RASTI values without SRS varied from 0.22 to 0.56 while the ones measured with the SRS On changed from 0.26 to 0.66.

Regarding the RASTI_Gain by the use of SRS, a best-fit equation with a R^2 of 0.55 was found for its relationship with the Distance to the Altar. It was detected that only for distances greater than about 11 m from the altar area is the SRS useful in increasing the RASTI values.

In general, the standard SRS systems used in Portuguese churches induce an average increase of 7 per cent in the RASTI values or about 0.03 in their absolute values if considering all receiver positions. Excluding the closest position to the sound source, the average increase of the RASTI is about 19 per cent from the RASTI values measured with the SRS Off.

ACKNOWLEDGMENTS

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