EFFECT OF ARCHITECTURAL STYLES ON OBJECTIVE ACOUSTICAL MEASURES IN PORTUGUESE CATHOLIC CHURCHES

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ABSTRACT

This study reports on acoustical field measurements made in a major survey of 41 Roman Catholic churches in Portugal that were built from the sixth century AD until 1993. The survey involved eight monaural acoustical measures that were taken at multiple source/receiver locations using the impulse response with noise bursts method - Reverberation Time (RT), Early Decay Time (EDT), Early to Late Sound Index or Clarity (C80), Early to Total Energy Ratio or Definition (D), Center Time (TS), Loudness (L), two Bass Ratios - and RASTI. This paper concentrates on one specific analysis regarding that survey: the effect of architectural styles on those nine acoustic measures. The hypothesis tested concerns the effect of architectural styles and their evolution through the last 14 centuries on some acoustic measures. The churches tested were grouped in 8 architectural styles: Visigothic, Romanesque, Gothic, Manueline, Renaissance, Baroque, Neoclassic, and Contemporary mainly regarding the style of their interior decoration, finishing and shape. Summary graphs showing statistical analyses of each parameter measured regarding the architectural styles are presented. A trend seems to be present in the variation of some acoustical measures through time and statistically significant differences can be found regarding some architectural styles.

1. INTRODUCTION

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. However music and speech have divergent acoustical needs. Today the Roman Catholic Church follows the directives of the Vatican II Council (1965) but in the previous twenty centuries, different behaviors and other 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 the Greek. Then Latin became the official language and remained for 16 centuries. Only thirty 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.

Music in the Church experienced even more changes over time from an important role in the worship until its total disappearance. Music was very important at the birth of Christianity. St.

Paul wrote: "Speaking to yourselves in psalms and hymns and spiritual songs, singing and making melody in your heart to the Lord" (Ephesians 5:19). It followed the tradition of life and worship in Israel where music was central. Musical instruments were allowed. The Bible mentions the use of trumpets, cymbals and other instruments. Then, in the fourth century, music in church changed. A ban against the liturgical use of instruments in the services of the church was in use. St. Jerome (340-420) - Doctor of the Church - condemned all musical instruments[10]. Nevertheless, vocal music was allowed. In the absence of written notation, it remained simply monophonic. With the years, the assembly's voice was muted and Catholics began to ritualize without music. Experts took over the song of the faithful. The church changed from groups of performers to a multitude of listeners. Another change in the church's repertoire appeared with the Gregorian chant (7th-13th centuries) due to the rise of large monastic communities. The first organ was installed in a church. A few centuries later, the song of the church was transformed by polyphony. The Reformation caused the return of vernacular songs.

All those changes that happened in the past in what people heard in the churches could have had implications on the design of the churches of those times. Or, perhaps, acoustical conditions were totally forgotten overpowered by liturgical considerations. Therefore, several monaural acoustical measures pertinent to churches were evaluated and their relationships with the Architectural Styles evaluated in a major survey of Portuguese churches built in the last 14 centuries.

2. PROCEDURE

2.1 Description of Churches

This paper reports on acoustical field measurements in a major survey[1,2,3] 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 main architectural styles in church construction in Portugal. Therefore, acoustical measurements were taken in 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 Table 1:

TABLE 1. Simple Statistics for all churches tested.

ARCH. FEATURE	Min.	Max.	Mean	Median
VOLUME (m^3)	299	18674	5772	3918
AREA (m^2)	56	1031	450	427
MAX. HEIGHT (m)	7	39	15	13
MAX. LENGTH (m)	12	62	33	31

2.2 Measurement Method

Eight room acoustics parameters were calculated for each church from impulse responses:
RT - Reverberation Time (calculated from -5 to -35 dB);
EDT - Early Decay Time (calculated from 0 to -10 dB);
C80 - Early/Late Sound Index or Clarity (time window of 80 ms). $C80 = 10 \log E(0,80)/E(80,\infty)$;
D - Early/Total Energy Ratio, Early Ener. Fract. or Definition (time window of 50 ms). $D=E(0,50)/E(0,\infty)$;
TS - Center Time (point in time where: energy received before it = energy received after it);
L - Loudness or Total Sound Level;
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.

Speech intelligibility was estimated by the calculation of the RASTI, which has been related to subjective intelligibility[4] (see Table 2). The RASTI method[5] involved measurement (with B&K-3361) of the reduction of a transmitted test signal that has certain characteristics representative of the human voice. Table 2 presents a general statistical summary of all data. 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) 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 a software (*Room Acoustics* B&K-BZ7109 and VP7155) from a notebook computer (*Compaq* LTE). 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 (just at the altar for the RASTI). The sound source was positioned at 0.8 m above the floor and at a 45^{o} angle with the horizontal plane (at 1.65 m for the RASTI and without using the churches' PA system). Each measurement was calculated by average from an ensemble of three or four consecutive responses in each position. Five (or eight for the RASTI) 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) - other 1200 data-points for the RASTI.

TABLE 2. Relation between RASTI and acoustical quality.

RASTI (%)	SUBJECT. ACOUST. QUALITY	RASTI (%)	SUBJECT. ACOUS. QUALITY
0 - 30	BAD	60 - 75	GOOD
30 - 45	POOR	75 - 100	EXCELLENT
45 - 60	FAIR		

2.3 - Architectural Styles

The hypothesis tested concerns the effect of architectural styles and their evolution through time on some acoustic measures in use today. The 41 churches tested were grouped, according to their main interior architectural features[7,8] in 8 architectural styles (when several styles could be identified in the same church, only the most significant for the overall acoustic impression was considered):

1 - VISIGOTHIC (6th-11th centuries);
2 - ROMANESQUE (12th-13th centuries);
3 - GOTHIC (13th-15th centuries);
4 - MANUELINE (15th-16th centuries);
5 - RENAISSANCE (16th-17th centuries);
6 - BAROQUE (17th-18th centuries);
7 - NEOCLASSIC (18th-19th centuries);
8 - CONTEMPORARY (20th century).

3. RESULTS AND ANALYSIS

3.1 Acoustic Measures Through Time

3.1.1 Room Acoustic Parameters. Figures 1 to 6 present the analysis of the room acoustic parameters regarding the architectural styles, chronologically ordered (from 1-Visigothic to 8-Contemporary) with a standard error interval one averaged point (all six frequency bands) for each church (41 points). In those graphs, trends are clearly visible: RT, EDT and TS increase until Style 5 and then decrease to Style 8; C80 and D decrease until Style 5 and then increase to Style 8; L, BR_RT and BR_L do not present the same clear behavior. That break point, in time, where the general trend of the data changes, is the period of the Reformation and Counter Reformation where speech in Catholic churches began being important and the liturgical music changed. Is this coincidence or is it an acoustical important change? 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 reappears to be inverted only in this century, where speech is perhaps the most important part of the religious services.

3.1.2 Music and reverberation time. The Reverberation Time values seem to increase through time with the highest RT occurring around the 16th-17th centuries (Figure 1). This coincides with the increased use of the organ in church music where a longer RT is desired. In early days, organs - which are known to have been used for other purposes before the second century BC - were banned from all churches because of their association with pagan rites and gladiator combats[8]. However they were progressively adopted after the 10th-11th century. Higher RT and EDT appear when church choirs grew in size (the Papal Choir in Rome increased from 10 to 24 singers in the late 15th century[9]). Church music in the Renaissance changed from being sung by several soloists to being performed by an entire (male) choir[9]. It is during this period when professionals (many even organ composers) had the control of church music (16th-17th centuries) like Desprez, Palestrina, Gabrieli and later Bach. They took advantage of the reverberant conditions found in churches in the music they composed, like Gabrieli and Bach for St. Mark's or Leipzig. The Council of Trent (1563) decreed that church music should be composed not to give empty pleasure to the ear but to inspire religious contemplation. This was during the time of the Counter Reformation and the corresponding in the RT and EDT found in churches (or increase in the C80 and D) seemed to follow those changes. Today, where new organs in new churches are not common and when speech intelligibility is fundamental (after Vatican II Council), the RT and EDT values seem to decrease to adjust to these new requirements. Contemporary churches are moving towards the acoustical conditions of early churches perhaps in part for the same reason: different musical instruments (less *organ*) are used.

3.1.3 RASTI. Figures 6 and 7 present the analyses of the RASTI behavior controlling for the architectural styles. In Figure 6, a similar trend to those present in the RT or EDT plots, appear. This seems to agree with the idea that also speech seems to have played a role in the changes that occurred in the period of the Counter Reformation. Figure 7 displays the RASTI variation with the distance to the Sound Source, near the Altar (excluding the direct field, distance < 5 m), with the regression lines for each architectural style. Also here the Renaissance appears as the style with the lowest speech intelligibility rating while the Visigothic and the Baroque, were the styles with the highest RASTI values.

3.2 Standard Error versus Standard Deviation

The use of the standard error was chosen because in this situation, a mean (or an interval) representative of one acoustic measure was desired for one architectural style (Figures 1 to 6). Therefore, a standard error of that mean will be better. But, if one wanted to look to one receiver position in a particular church of a specific architectural style and to predict its own acoustic measure (or confidence interval for that parameter) a standard *deviation* data would be more useful and significant.

3.3 ANOVA Tests

TABLE 3. Number of architectural style differences found statistically significant (p-value < 0.1) out of a maximum total of 7 (Style 1 vs 2, Style 2 vs 3, ... , Style 6 vs 7).

RT	4	C80	1	TS	3	BR_L	0	RASTI	3
EDT	4	D	0	L	0	BR_RT	0		

The results of ANOVA tests done with averaged data (41 points for each acoustical measure - one for each church) are presented in Table 3. The goal was to verify if there were statistically significant differences among consecutive architectural styles' values for each of the nine acoustical measures. These results confirm that there is statistical evidence to support the hypothesis of differences in some of the acoustic measures regarding architectural styles especially RT, EDT and TS. These differences appear in the last five Styles, that is, after the 13th century. RT and EDT appears most suitable to identify differences among architectural styles. Also these are the two acoustic measures (of the nine studied) that are perhaps the most used to rate the acoustical quality of church music (especially church organ music).

4. CONCLUSIONS

As presented above, statistical analyses were done to analyze the relationships between Architectural Styles and nine objective acoustical measures. The following conclusions apply: Statistically significant differences can be found in churches regarding their Architectural Styles for RT, EDT and TS specifically later than the Gothic Style (15th century). A visible trend seems to be present in the variation of some acoustic measures through time, especially RT, EDT, TS and RASTI. Statistically significant differences cannot be found in churches regarding their Architectural Styles for D, L, BR_RT and BR_L. The changes in the RASTI do not appear as suggestive as those in other acoustic measures. Changes in church music and other church practices and transformations in the mean values of some acoustical measures seem to have happened in the same historical periods. In general this study suggests that some changes in the acoustical behavior of churches are possibly related to changes in the architectural styles.

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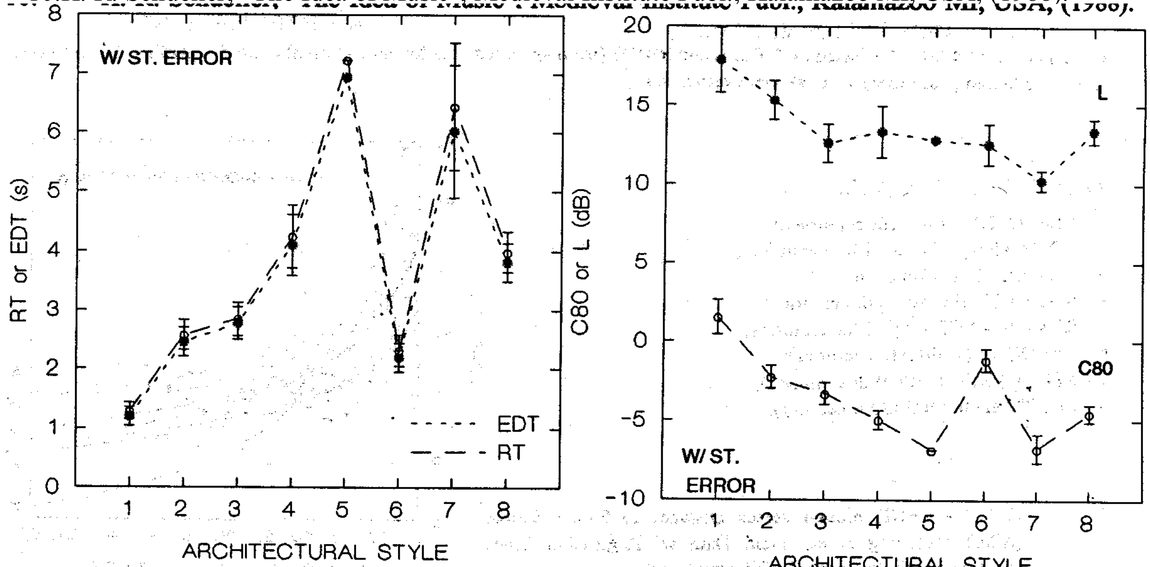
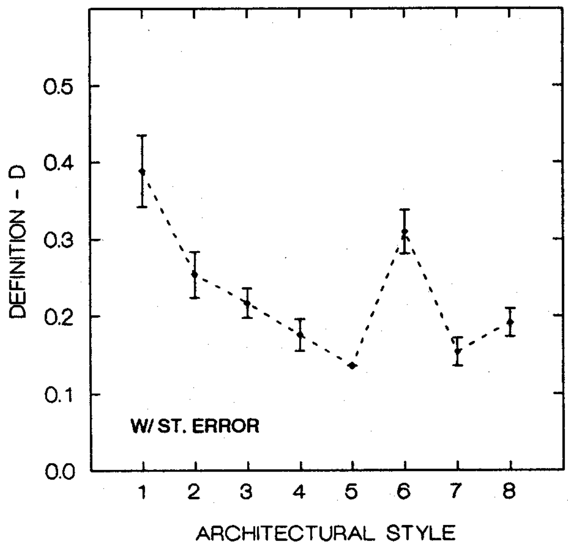


FIG. 1 and 2 - RT-EDT and C80-L (from averaged data for each church) plotted regarding the architectural styles (in chronological order) with standard error bars.



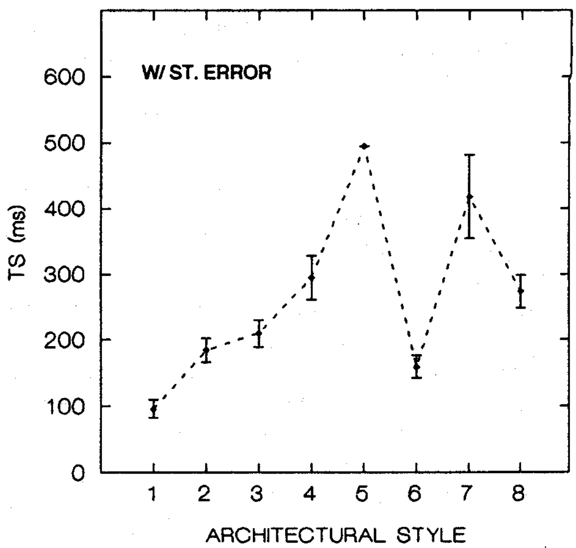
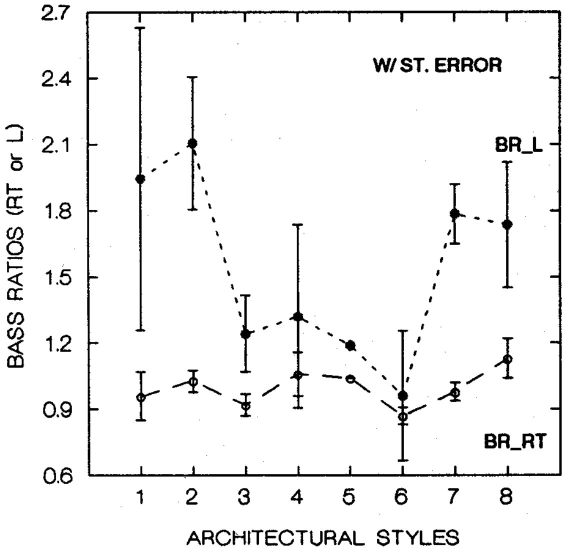


FIG. 3 and 4 - D and TS (from averaged data for each church) plotted regarding the architectural styles (in chronological order) with standard error bars.



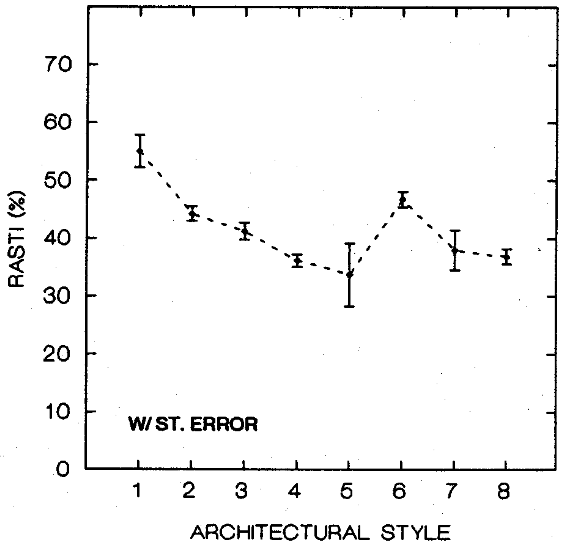


FIG. 5 and 6 - BASS RATIOS based on RT or L and RASTI (from averaged data for each church) plotted regarding the architectural styles (in chronological order) with standard error bars.

ARCHITECTURAL STYLES

1 - VISIGOTHIC (6th-11th centuries);
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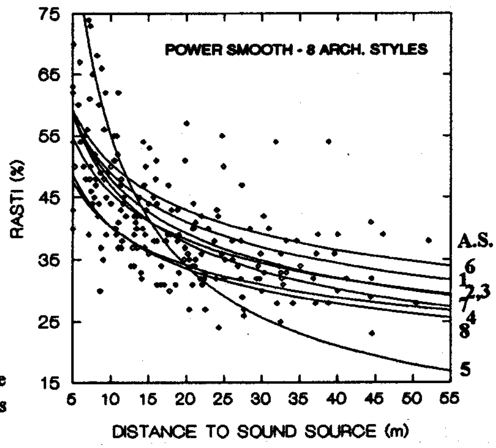

FIG. 7 - RASTI plotted versus Distance to Sound Source (Altar) excluding Direct Field Data w/ Regression Lines (power smooth) for each Architectural Style.