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ANALYSIS OF SUBJECTIVE ACOUSTIC MEASURES AND SPEECH INTELLIGIBILITY IN PORTUGUESE CHURCHES

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ABSTRACT

This study reports on subjective acoustical field measurements made in a survey of 36 Catholic churches in Portugal built in the last 14 centuries. The same group of college students were asked to judge the quality of speech and music at all the churches. Two sets of listeners in each church evaluated live music performance (cello and oboe) at two similar locations in each of the rooms using a seven-point semantic differential rating scale. An acoustical evaluation sheet was used to measure listeners overall impression of room acoustics qualities, and each of the factors that can contribute to that perception as *loudness, reverberance, intimacy, envelopment, directionality, balance, clarity, echoes* and *background noise.* Speech intelligibility tests were also given to the same group in each church. One-hundred-word lists were used in live speech tests using a theater college student as speaker. The results are graphed and analyzed by comparisons. Variations of subjective and speech intelligibility qualities were identified among the different churches and within each of the churches as well. The subjective qualities that contributed to overall acoustical impression were also identified.

1 - INTRODUCTION

This study is part of a research program initiated in 1991 by the author at the University of Porto and University of Florida. 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, 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.

This paper presents a preparatory report regarding the second item. More complete analysis of the data gathered is been prepared. A paper in the continuation of this work is expected to be presented at the 132nd Meeting of the Acoustical Society of America in Honolulu, concerning relationships between objective and subjective acoustical parameters found in this large sample of churches.

2 - METHODOLOGY

2.1 - Method Summary

The main research hypothesis is that the perceptions of people who attend services or concerts in churches could be measured. The among-room variations of subjective scores can be viewed as differences that result from the architectural and 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 subjective analyses in almost non occupied churches. The first part was to gather subjective evaluations of the acoustical qualities of the churches from listeners, using live music performances by cello and oboe. The second part was to gather subjective speech intelligibility evaluations of the same sample of churches from the same group of listeners using a theater student as a speaker.

The limitations using this type of methodology for evaluations were fully realized. The acoustical response of the church changes when it is fully occupied. The character of the music heard during a religious service or during an actual musical performance 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 November 1995 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. Table 1 presents an alphabetical list of the churches tested in 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. A complete objective acoustical analysis of these churches is available as a Ph.D. Dissertation (Carvalho 1994).

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.

The selected churches were the same used during the field measurements concerning the objective acoustical parameters (Carvalho 1994). Only five from these 41 churches were not chosen again due to severe physical alterations in their interiors under way or done in the last 2 or 3 years, that changed their acoustical conditions.

Subjective 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.

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. AZEITÃO	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 architectural statistics for 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 - Listeners and Music Sound Sources

A group of 15 listeners was chosen to judge the quality of music and speech throughout the churches. It was decided that a group of average and randomly selected listeners was not suitable for this study due to the need of having same acoustical knowledge concerning the parameters being tested. Therefore 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.

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 R389/1964 and ANSI S3.6/1969 were performed giving results judged normal for all the members of the listeners' group.

In each church the listeners were seated in two similar locations named *Position A (*right hand seatings of the center of the longitudinal axis of the main floor) and *Position B* (central seatings at the rear main floor). A total of near 500 questionnaires were scored in the rooms.

They listened to baroque and classic music for approximately ten minutes. The music used was a live performance from oboe and cello played first individually and then in ensemble. The pieces played were 3 or 4-minute parts of the Bach's *Suite no. 3* (for the cello) and Telemann's *Fantasy* or Vivaldi's *Sonata in G minor* (for the oboe). After this, they played together the *Duet for oboe and bassoon* from Johann Gottlieb Naumann. Then they rated the acoustical qualities of the church on a questionnaire sheet.

The scores from the questionnaires were entered into a computer spreadsheet and analyzed using the *SYSTAT*® computer software package.

2.4 - Acoustics Evaluation Sheet

The acoustics evaluation sheet used throughout the tests had ten semantic differential rating scales with seven points and was adapted from Cervone, 1990 (see Appendix A). The ten subjective acoustical parameters evaluated were:

- *Loudness* (the overall loudness or strength of the sound) from *1* (extremely weak) to *7* (extremely strong);
- *Clarity* (the degree to which notes are distinctly separated in time and clearly heard) from *1* (not clear enough) to *7* (extremely clear);
- *Reverberance* (the persistence of sound in space) from *1* (totally dry) to *7* (too reverberant);
- *Intimacy* (the auditory impression of the apparent closeness of the orchestra) from *1* (absence of intimacy) to *7* (extremely intimate);
- *Directionality* (the auditory impression that the sound comes from the axis of the sound source; importance of the direct sound field) from *1* (very bad) to *7* (excellent);
- *Envelopment* (the sense of being immersed in the sound or surrounded by it; importance of the reverberant field) from *1* (not surrounding at all) to *7* (extremely surrounding);
- *Balance* (the relative levels of bass and treble frequencies) from *1* (totally unbalanced) to *7* (very well balanced);
- *Echoes* (long delayed reflections that are clearly audible) from *1* (none detected) to *7* (clearly heard);
- *Background Noise* (the sound heard other than from the source in the performance area) from *1* (not audible) to *7* (too loud);
- *Overall Impression* (the overall impression of the acoustical quality of the room) from *1* (very bad) to *7* (very good).

Remarks about *Directionality*. After the pilot-tests, done previously to engage in the full testing program, it was found that a new criterion (*directionality*) should be included together with the *envelopment*. In fact, the parameter *envelopment* was not easy for some listeners to fully comprehend and assess in churches. In this type of room the usually very large sound envelopment is not judged similarly as in many concert halls. This is due that a *large* envelopment sensation in concert halls and in churches have a different sensory meaning. The one in concert halls is usually smaller than in churches and generally considered pleasant. However, in churches the *huge* level of envelopment can make the assessment difficult by its reverberant conditions. Therefore, due to its usually large reverberant conditions, the envelopment sensation is far above the maximum optimum for music listening in many churches. Therefore, a need was determined to include an easier measure to judge spatial aspects of the experience that was conceptually similar. This was named *directionality* and it attempts to evaluate not the spatial impression given by the reverberant field but the importance of the direct sound in the sensory experience. With this parameter the confusion partially disappeared as shown by some of the correlation analyses.

2.5 - Speech Intelligibility Tests

For the speech intelligibility tests 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.

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 *words*.

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

3 - RESULTS

3.1 - Overall Results

The scores were analyzed directly as they were entered on the questionnaires. Table 6 shows a general statistical basic analysis of the results found using all data (the entire data set - all questionnaires). Table 7 presents the same analysis but done with averaged data for each church (only 36 data points, one for each church).

Table 8 presents the absolute values of the correlation coefficients (|R|) for the linear relationships among the eleven acoustical subjective criteria, using all data gathered. Table 9 presents the same analysis but using only the averaged data for each church (36 points).

Table 6 - Simple statistics of acoustical parameters (using all data).

Acoustical Parameter	Minimum	Mean	Median	Maximum	Standard deviation	Skewness	Kurtosis
Loudness	3	4.8	5	7	0.8	0.2	-0.0
Clarity	1	4.8	5	7	1.5	-0.5	-0.5
Reverberance	1	4.5	5	7	1.5	-0.3	-0.5
Intimacy	1	4.5	5	7	1.3	-0.4	-0.3
Directionality	1	4.7	5	7	1.3	-0.4	0.0
Envelopment	1	4.5	5	7	1.1	-0.1	-0.3
Balance	1	5.5	6	7	1.4	-0.8	0.4
Echoes	1	2.2	2	7	1.6	1.4	1.2
Background Noise	1	2.8	3	7	1.5	0.5	-0.8
Overall Impression	1	4.6	5	7	1.4	-0.5	-0.2
Words (%)	26	81.5	86	100	14.8	-1.1	0.9

Skewness - a measure of the asymmetry about the mean. If positive (negative) indicates a long right (left) tail;
Kurtosis - a measure of the peakedness. If significantly > 0 indicates that the variable is longer tailed than a normal distribution.

Table 7 - Simple statistics of acoustical parameters (using averaged data for each church - 36 data points).

Acoustical Parameter	**Minimum**	**Mean**	**Median**	**Maximum**	**Standard deviation**	**Skewness**	**Kurtosis**
Loudness	3.7	4.8	4.8	5.8	0.5	-0.4	-0.3
Clarity	2.3	4.8	4.9	6.9	1.2	-0.5	-0.5
Reverberance	2.2	4.5	4.6	6.8	1.2	-0.0	-0.4
Intimacy	2.3	4.5	4.5	6.3	1.0	-0.3	-0.8
Directionality	2.9	4.7	4.7	6.1	0.8	-0.6	-0.2
Envelopment	3.5	4.5	4.5	5.4	0.5	-0.1	-0.6
Balance	3.8	5.5	5.7	6.5	0.7	-0.8	-0.1
Echoes	1.0	2.2	2.2	4.7	1.0	0.8	0.1
Background Noise	1.2	2.9	2.7	5.4	1.1	0.8	-0.2
Overall Impression	2.3	4.6	4.8	6.3	1.1	-0.8	-0.1
Words (%)	47.4	81.5	84.0	95.7	13.0	-1.1	0.4

Skewness - a measure of the asymmetry about the mean. If positive (negative) indicates a long right (left) tail;
Kurtosis - a measure of the peakedness. If significantly > 0 indicates that the variable is longer tailed than a normal distribution.

Table 8 - Correlation coefficients (|R| for linear smooth) among subjective acoustical criteria (using all data).

Measure	loudness	clarity	reverberance	echoes	intimacy	direction ality	envelopm ent	balance	overall impression	words
background noise	0.14	0.15	0.04	0.08	0.17	0.17	0.08	0.25	0.20	0.04
loudness	-	0.35	0.22	0.18	0.54	0.26	0.32	0.32	0.41	0.24
clarity		-	0.70	0.53	0.62	0.66	0.04	0.48	0.80	0.55
reverberance			-	0.45	0.42	0.52	0.14	0.37	0.55	0.51
echoes				-	0.37	0.46	0.05	0.46	0.51	0.44
intimacy					-	0.52	0.29	0.50	0.68	0.45
directionality						-		0.44	0.62	0.37
envelopment							-	0.12	0.20	0.03
balance								-	0.56	0.39
overall impression									-	0.50

Table 9 - Correlation coefficients (|R| for linear smooth) among subjective acoustical criteria (using averaged data for each church, 36 points). |R| > 0.90 are bold faced.

Measure	loudness	clarity	reverberance	echoes	intimacy	directiona lity	envelopm ent	balance	overall impression	words
background noise	0.15	0.13	0.06	0.11	0.19	0.20	0.05	0.31	0.15	0.21
loudness	-	0.54	0.39	0.51	0.82	0.54	0.58	0.60	0.66	0.55
clarity		-	**0.92**	**0.90**	0.82	**0.96**	0.11	0.79	**0.94**	0.84
reverberance			-	0.84	0.69	**0.90**	0.27	0.68	0.80	0.79
echoes				-	0.74	0.89	0.18	0.85	0.88	0.81
intimacy					-	0.81	0.29	0.78	0.88	0.81
directionality						-	0.08	0.82	**0.93**	0.85
envelopment							-	0.08	0.11	0.11
balance								-	0.86	0.82
overall impression									-	0.88

In Table 9 we see that among all linear relationships, the highest correlations were found between *clarity* and *directionality* (|R| = 0.96), between *clarity* and *overall impression* (|R| = 0.94) and between *clarity* and *reverberance* (|R| = 0.92). The correlations between *background noise* and the other measures are very low (|R| < 0.31) representing a significant poor relationship among them.

Bivariate regression models (using linear or quadratic smoothes) relating several single criteria are present in Figure 1 where each data point represents a church mean value (36 points = 36 churches). Table 10 presents the best fit linear or quadratic models between pairs of selected criteria.

To find a general linear model, both the scores from all of the questionnaires in all of the locations and the church averaged data, were entered in stepwise regression procedures on *SYSTAT*®. These studies produced the models shown in Tables 11 and 12. All the variables in the stepwise model are at least significant at the 10% level. The R^2 for each model are shown as well.

Table 10 - Some of the best bivariate regression models.

MODEL	R^2
Clarity = -1.751 + 1.403 Directionality	0.92
Clarity = 6.21 + 0.456 Reverberance - 0.158 (Reverberance)^2	0.90
Overall Impression = -1.18 + 1.67 Clarity + 0.093 (Reverberance)^2	0.90
Overall Impression = -1.055 + 1.199 Directionality	0.87
Overall Impression = 2.85 + 1.66 Reverberance - 0.265 (Reverberance)^2	0.82
Clarity = 7.70 + 1.46 Echoes - 0.063 (Echoes)^2	0.81
Overall Impression = -1.343 + 0.073 Words	0.77
Clarity = -1.567 + 0.078 Words	0.70
Loudness = 2.00 + 0.846 Intimacy - 0.047 (Intimacy)^2	0.68
Echoes = 7.176 - 0.061 Words	0.65

Table 11 - Summary of stepwise program regression models (at least significant at the 10% level) for the subjective criteria on *overall impression* for all the churches (all data).

VARIABLE ENTERED	MODEL R^2
Clarity	0.64
Intimacy	0.69
Balance	0.71
Envelopment	0.72
Directionality	0.73
Echoes	0.731

Table 12 - Summary of stepwise program regression models (at least significant at the 10% level)for the subjective criteria on *overall impression* for all the churches (using averaged data for each church - 36 data points).

VARIABLE ENTERED	MODEL R^2
Clarity	0.88
Envelopment	0.92
Balance	0.94
Reverberance	0.95
Directionality	0.95
Background Noise	0.96

3.2 - Within Church Differences

A very simple measure of the spatial variation of the acoustical data gathered within each church is the standard deviation of the room average value. This standard deviation includes the effect of the seating position variation.

The Figure 2 presents the analysis regarding the within church variation where for each church (numbered 1 to 36 as in the Table 1) and for each measure, the mean value is presented together with a standard deviation, two sided interval. For instance it can be seen that the spatial variation of the *loudness* is much smaller than that of *background noise* or *echoes*. Several of the criteria, notably *reverberance* and *clarity* generally had wider ranges than the other criteria.

Figure 3 displays the 36 church mean values together with the 36 spatial standard deviation of the gathered values in each room and for each subjective acoustical measure. These Figures are summarized in Table 13 that presents simple statistics of the 36 means and their standard deviations.

Using this Figure 3 and Table 13 it can be seen that the *loudness* and the *words* values vary very little throughout these churches (a mean standard deviation of 0.67 in a *loudness* mean of 4.82 or a mean standard deviation of 7.2 in a *words* mean of 81.5).

Table 13 - Simple statistics of the data regarding the 36 church sample.

MEASURE	Mean (of 36 means)	Mean (of 36 st. dev.)	MEASURE	Mean (of 36 means)	Mean (of 36 st. dev.)
loudness	4.82	0.67	*balance*	5.50	1.09
clarity	4.83	0.88	*echoes*	2.22	1.09
reverberance	4.53	0.88	*background noise*	2.88	1.17
intimacy	4.49	0.90	*overall impression*	4.57	0.89
directionality	4.69	0.96	-	-	-
envelopment	4.48	1.02	words (%)	81.5	7.2

3.3 - Comparison of Different Seating Locations

As mentioned earlier, two seating locations were used (*Position A*, middle center right, and *Position B*, rear central). Figure 4 offers the behavior of the data regarding both seating locations. These graphs show the mean values of each subjective acoustical measure with one standard error confidence interval.

A *two-sample t test* was performed comparing the data grouped by those two seating locations (*A* and *B*). The results of the statistical analysis in which: *Ho*: $\mu_A = \mu_B$ (the means are equal) and *Ha*: $\mu_A \neq \mu_B$ (the means are different) are present in Table 14.

Table 14 - Probability-values for each acoustical measure regarding the seating location *A* vs. *B*. P-values < 0.001 indicate statistically significant differences between positions.

Probability-values controlling for seating location (*A* vs. *B*)										
loudness	*clarity*	*reverberance*	*intimacy*	*direction ality*	*envelop ment*	*balance*	*echoes*	*background noise*	*overall impression*	words
0.000	0.000	**0.160**	0.000	0.000	0.000	**0.004**	**0.805**	**0.000**	0.000	0.000

For all measures, except *reverberance, echoes* and *balance*, the *two-sample t test* does not support the idea to reject the alternative hypothesis (*Ha*). Therefore there is statistical evidence to support the conclusion that the seating location (*A* vs. *B*) affects the mean values of *background noise, loudness, clarity, intimacy, directionality, envelopment, overall impression* and *words* but not the mean values of *reverberance, echoes* and *balance*.

3.4 - Among Church Differences

Figure 5 presents the analysis regarding the differences among churches. For each church (numbered from *1* to *36* as in the Table 1) and for each subjective acoustical measure, the mean value is presented together with one standard error two sided interval. The standard *error* interval was used here and not the standard *deviation* because different means of different churches are compared. For that reason the standard *error* of the measured mean has more significance than the standard *deviation* (sd) because the sd measures the variation among the values of one room, not the variation of the mean in different rooms. Table 15 presents the range of the 36 means concerning the eleven acoustical measures.

Table 15 - Range (max.-min. value) of the 36 means (36 churches) for the 11 acoustical measures.

MEASURE	RANGE (OF 36 MEANS)	MEASURE	RANGE (OF 36 MEANS)
loudness	2.15	*balance*	2.70
clarity	4.60	*echoes*	3.70
reverberance	4.60	*background noise*	4.25
intimacy	3.97	*overall impression*	3.97
directionality	3.20	-	-
envelopment	1.92	words (%)	48.3

The church averages, shown in Figure 5, indicate very large inter church variation, clearly significant in most the cases for *clarity, reverberance* and *words*. Only *envelopment* data does not follow this clear trend perhaps due to the larger within room variation of this measure.

3.5 - Architectural Styles

3.5.1 - Analyses for the acoustical measures

The hypothesis tested concerned the effect of architectural styles and their evolution through time on these subjective acoustical measures. The 36 churches tested were grouped, according to their main interior architectural features in eight architectural styles (Table 2). When several styles could be identified in the same church, only the most significant for the overall visual and acoustical impression was considered.

Figure 6 presents the analysis of some of the acoustical measures regarding the architectural styles, chronologically ordered (from 1-*Visigothic* to 8-*Contemporary*) with a standard error interval using one point for each church (36 points). In those graphs, trends are clearly visible. *Reverberance* and *echoes* increase until style *5* and then decrease to style *8*. *Clarity* and *words* decrease until style *5* and then increase to style *8*. *Envelopment* and the others criteria do not present the same clear behavior. 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. The liturgical music also changed during this time. This can be a coincidence or an important acoustical 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 of increasing *reverberance* and *echoes* (or decreasing *clarity* and *words*) reappears perhaps due to the wave of antimodernism rules in the Church following the French Revolution, having a new positive attitude towards the past. That trend was inverted only in this century, where speech is perhaps the most important part of the Catholic religious services.

The change in the acoustics of churches with the *Baroque* style can be perhaps explained by the large amount of ornamentation that began being used, especially in the wood-carving covering very large interior surfaces and the wide use of highly decorated lateral chapels. This general increase in ornamentation can be justified as a move to impress the congregations and to attract them to the Catholic Church against the appealing approaches from new denominations. Also the size and shape of churches evolved from the forms that were common in the previous styles to a more human dimension with not so large volumes and tall ceilings.

3.5.2 - Music and reverberance

The *reverberance* values seem to increase through time with the highest mean *reverberance* occurring around the 16th-17th centuries (Figure 6). This coincides with the increased use of the organ in church music where a longer reverberance 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. However they were progressively adopted after the 10th-11th century. Longer reverberance appear when church choirs grew in size. The Papal Choir in Rome increased from 10 to 24 singers in the late 15th century (Kamien 1988). Church music in the Renaissance changed from being sung by several soloists to being performed by an entire (male) choir (Kamien 1988). It is during this period when professionals, many of whom were 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. For example Gabrieli and Buxtehude used the rich and rolling sound of counterpoint in a reverberative nave when they composed music to be performed in St. Mark's in Venice or St. Mary's church in Lübeck.

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 changes in the *reverberance* values found in churches (or increase in the *clarity* values) seemed to follow those changes. For instance, the Bach cantatas which were composed for St. Thomas Church in Leipzig had its emphasis on the understanding the sung narrative and the devotional texts, using to advantage the moderate reverberance of that church.

Today, where new organs in new churches are not common and when speech intelligibility is fundamental after the Second Vatican Council, the reverberance 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.

4 - CONCLUSIONS

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 differences among subjective criteria can be found in churches. Subjective acoustical parameters that are important to defining the overall acoustical impression in churches were also identified. *Clarity* was found as the most important of these. Some changes in the subjective acoustical measures of churches are related to changes in their architectural styles. A trend is present in the variation of some acoustical measures through time, especially *reverberance*, *echoes* and *clarity*. Additional analysis and modeling continues on this large data base to more entirely explore the topics raised in this paper.

ACKNOWLEDGMENTS

Sincere thanks go to all those who participated as listeners in this study. We are also indebted to priests and church managements for allowing subjective measurements to be made in their rooms. We must also thank Professor José Prata for valuable comments and interest along this study. The authors wish to recognize the University of Porto, the Polytechnic Institute of Porto, the Institute of Construction and the FLAD *(Fundação Luso-Americana para o Desenvolvimento*) for their financial and technical support in this project.

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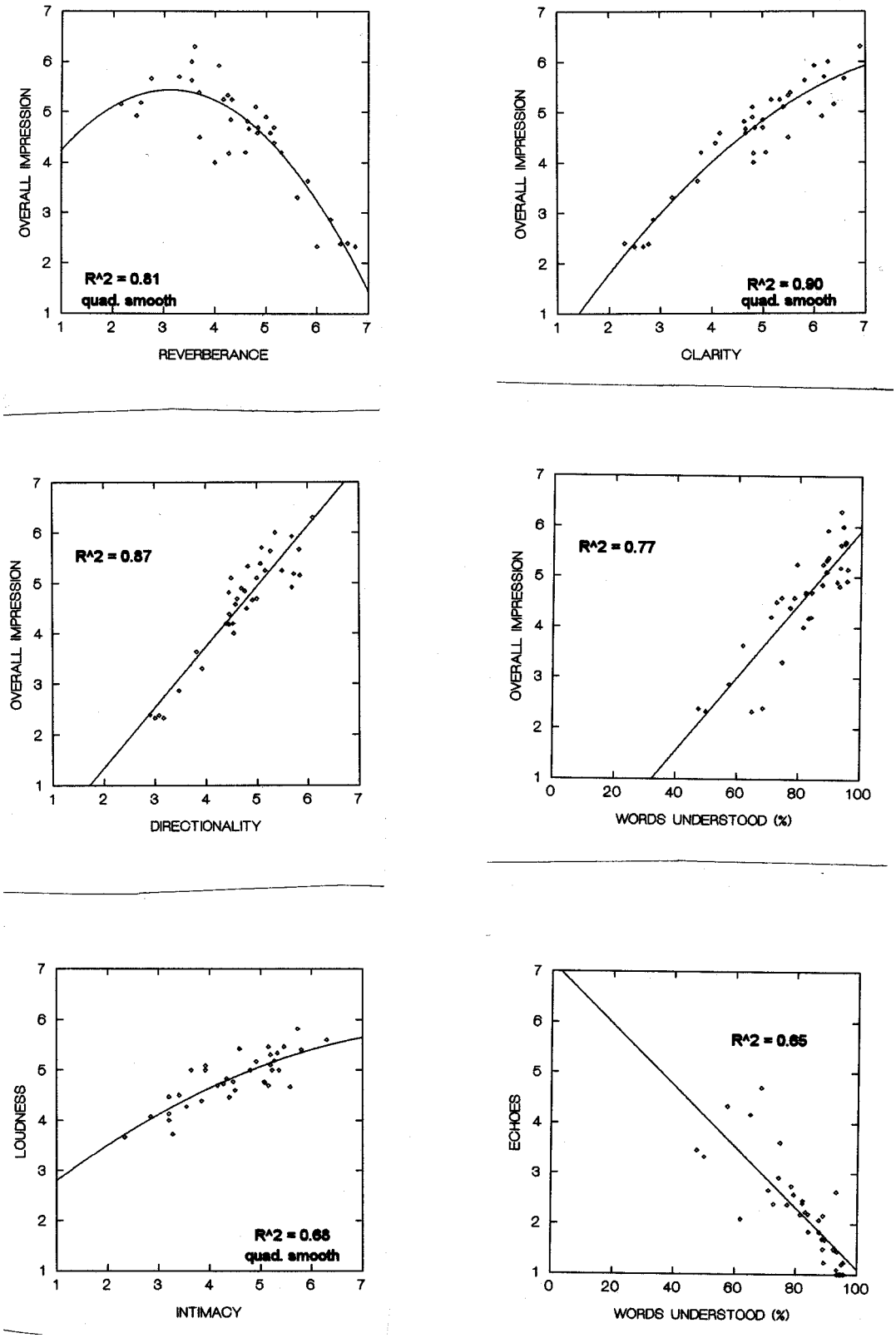

Figure 1 - Relationships between criteria with bivariate regression (linear or quadratic) models concerning church mean values (36 points = 36 churches).

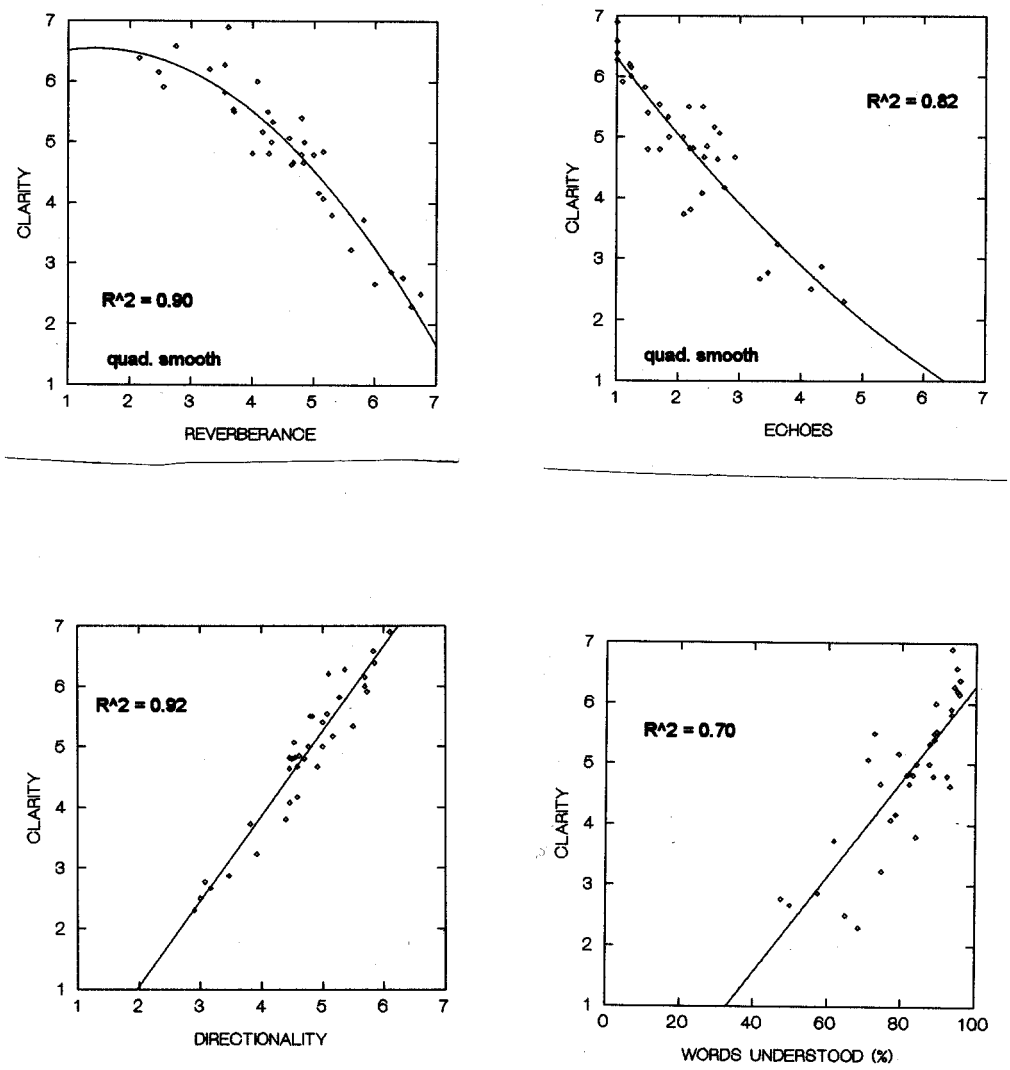

Figure 1 (cont.) - Relationships between criteria with bivariate regression (linear or quadratic) models concerning church mean values (36 points = 36 churches).

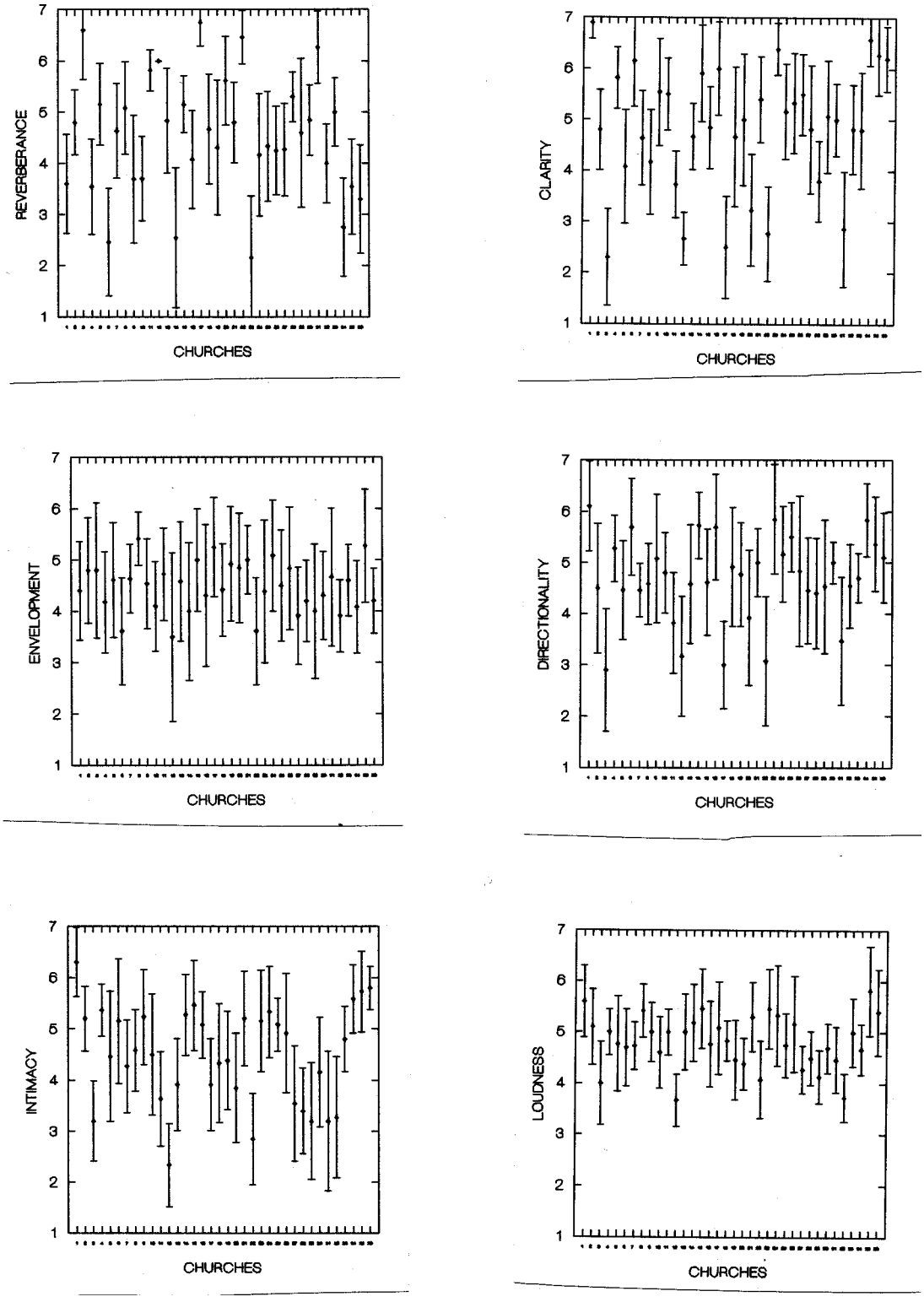

Figure 2 - Within variation of the subjective criteria in each church (the *x* axis shows the 36 churches numbered *1* to *36* from left to right). Mean values with one standard deviation confidence interval.

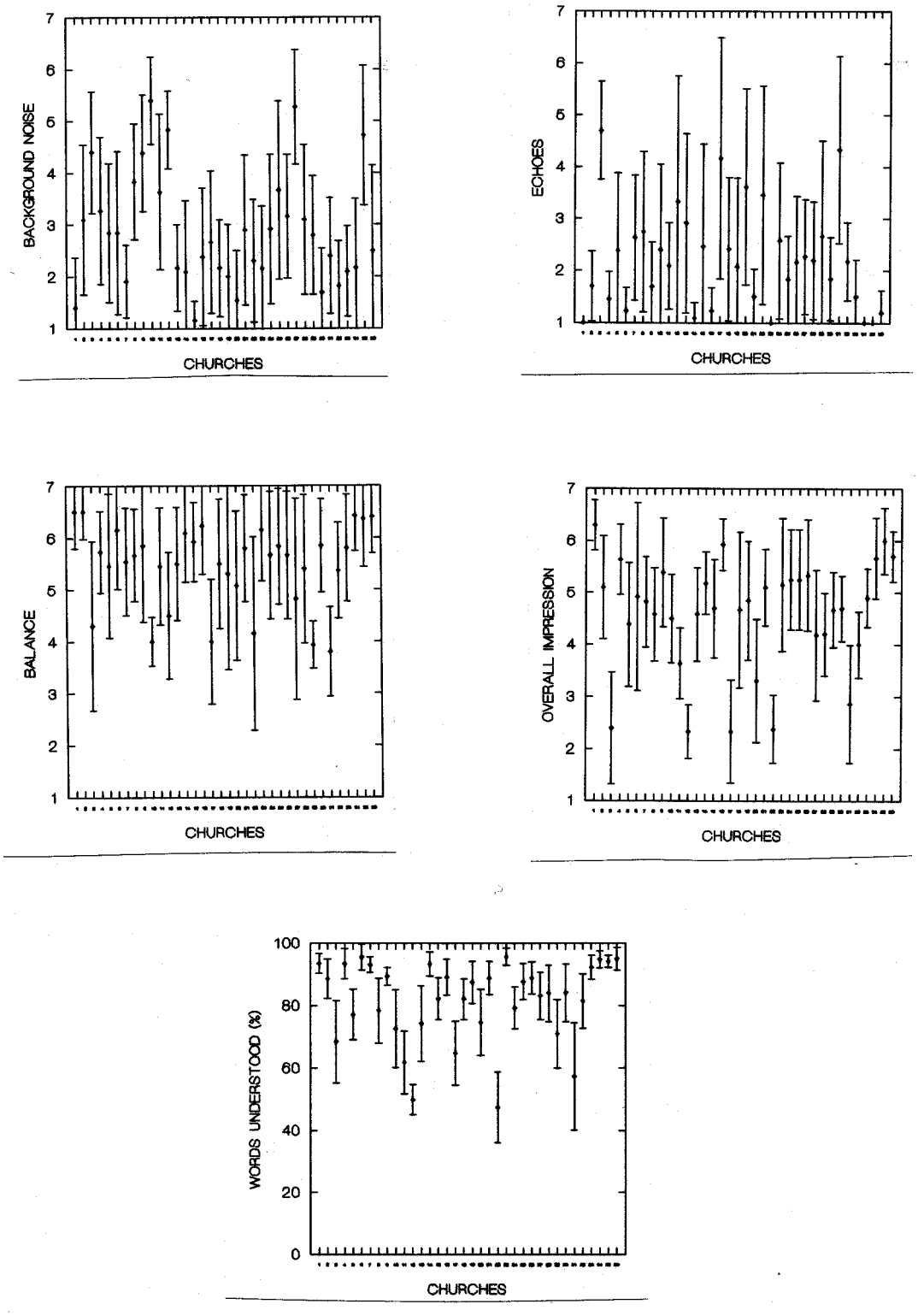

Figure 2 (cont.)- Within variation of the subjective criteria in each church (the *x* axis shows the 36 churches numbered *1* to *36* from left to right). Mean values with one standard deviation confidence interval.

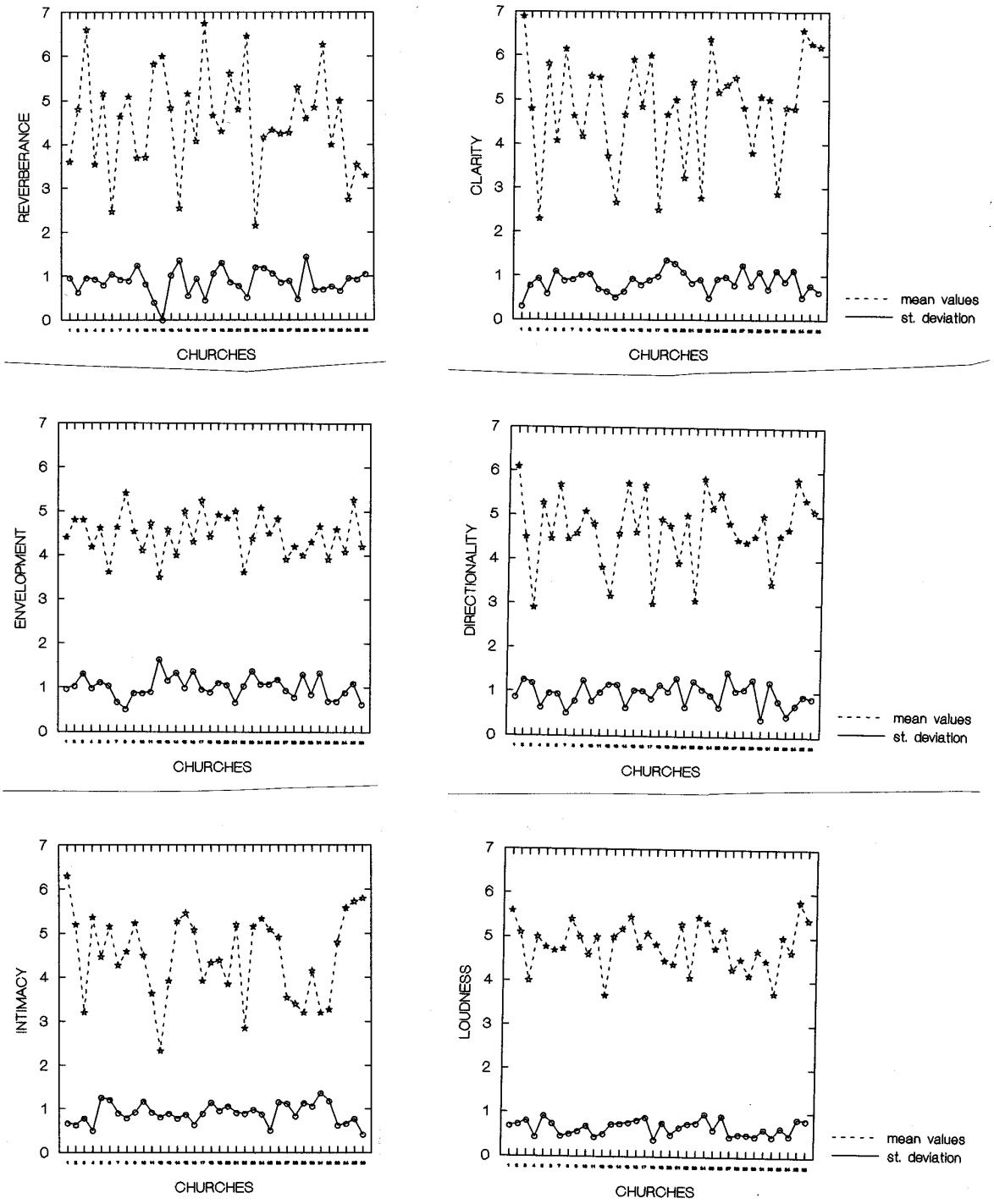

Figure 3 - Standard deviation compared with mean values for each church (the *x* axis shows the 36 churches numbered *1* to *36* from left to right) for all the subjective criteria.

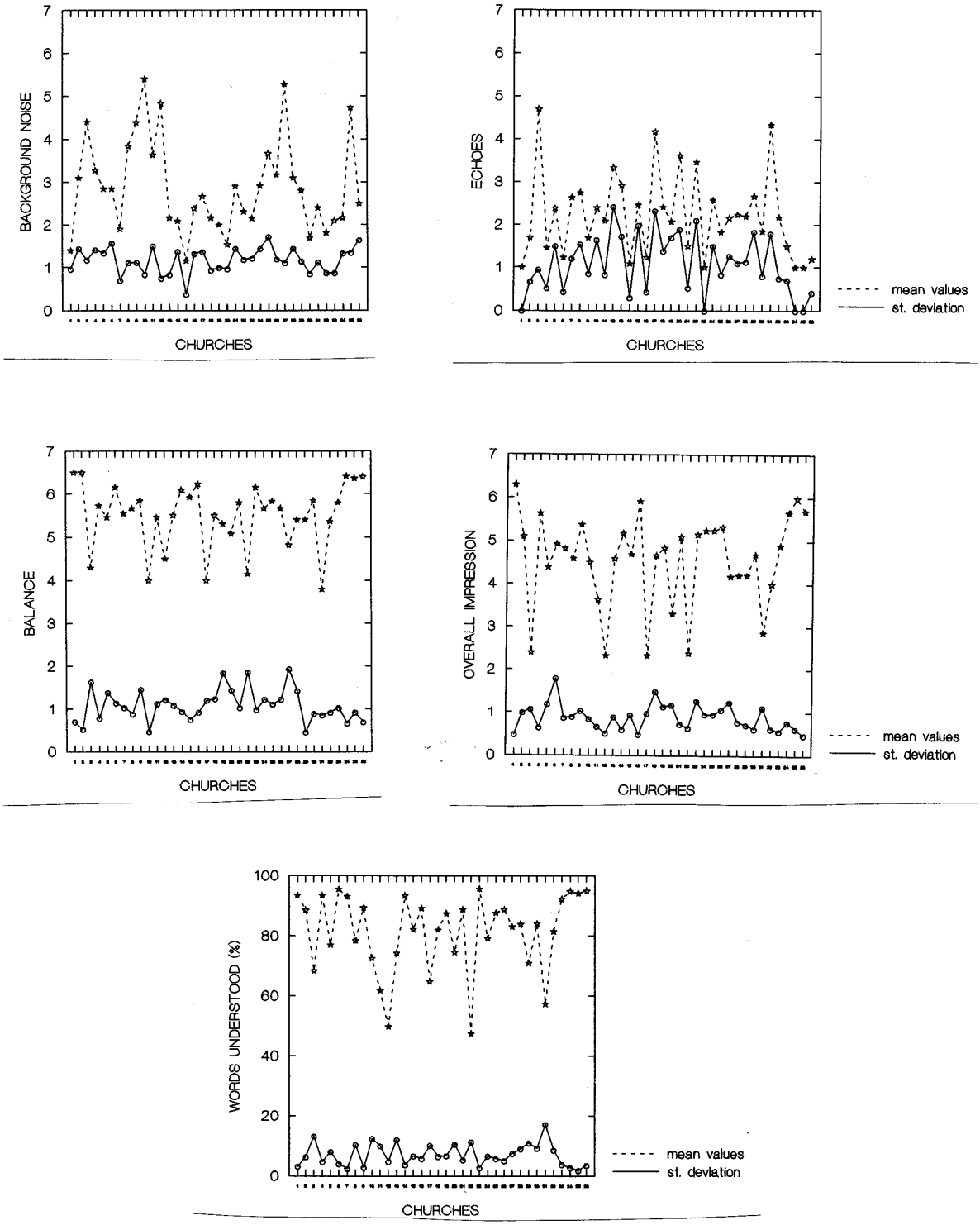

Figure 3 (cont.) - Standard deviation compared with mean values for each church (the *x* axis shows the 36 churches numbered *1* to *36* from left to right) for all the subjective criteria.

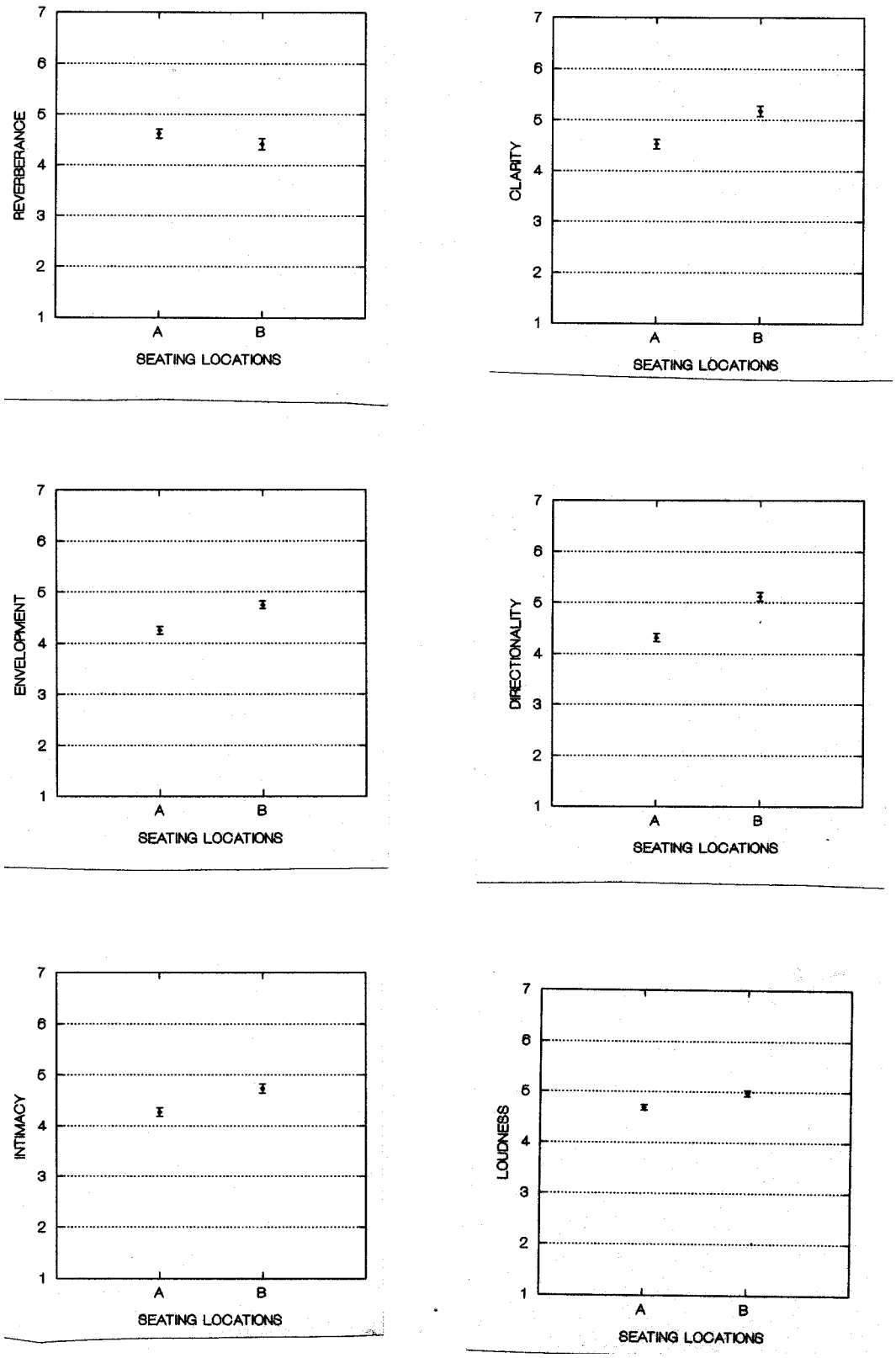

Figure 4 - Effect of seating location (*Position A* vs. *Position B*) on the values of the subjective acoustical parameters. Mean values with one standard error confidence interval are shown.

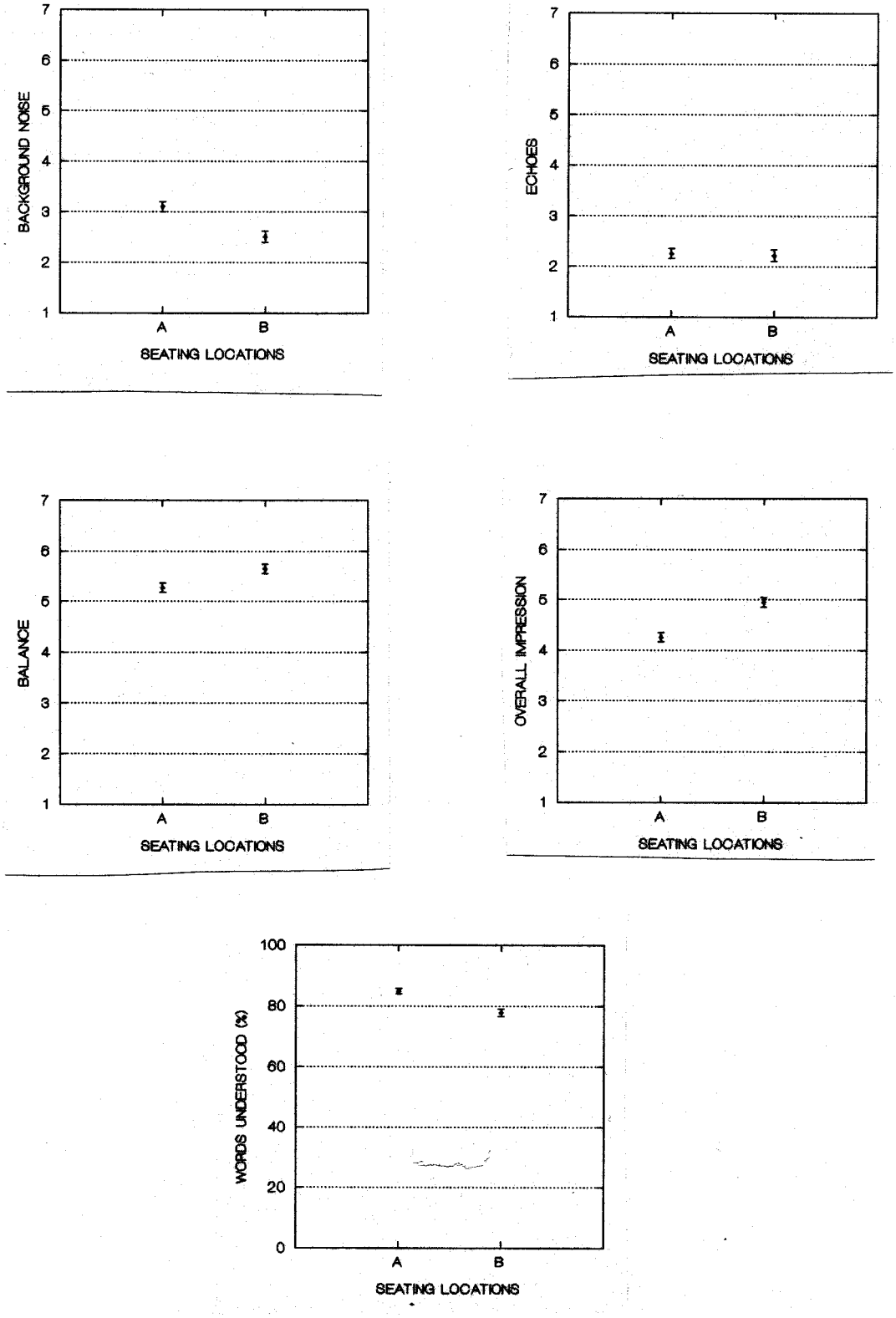

Figure 4 (cont.) - Effect of seating location (*Position A* vs. *Position B*) on the values of the subjective acoustical parameters. Mean values with one standard error confidence interval are shown.

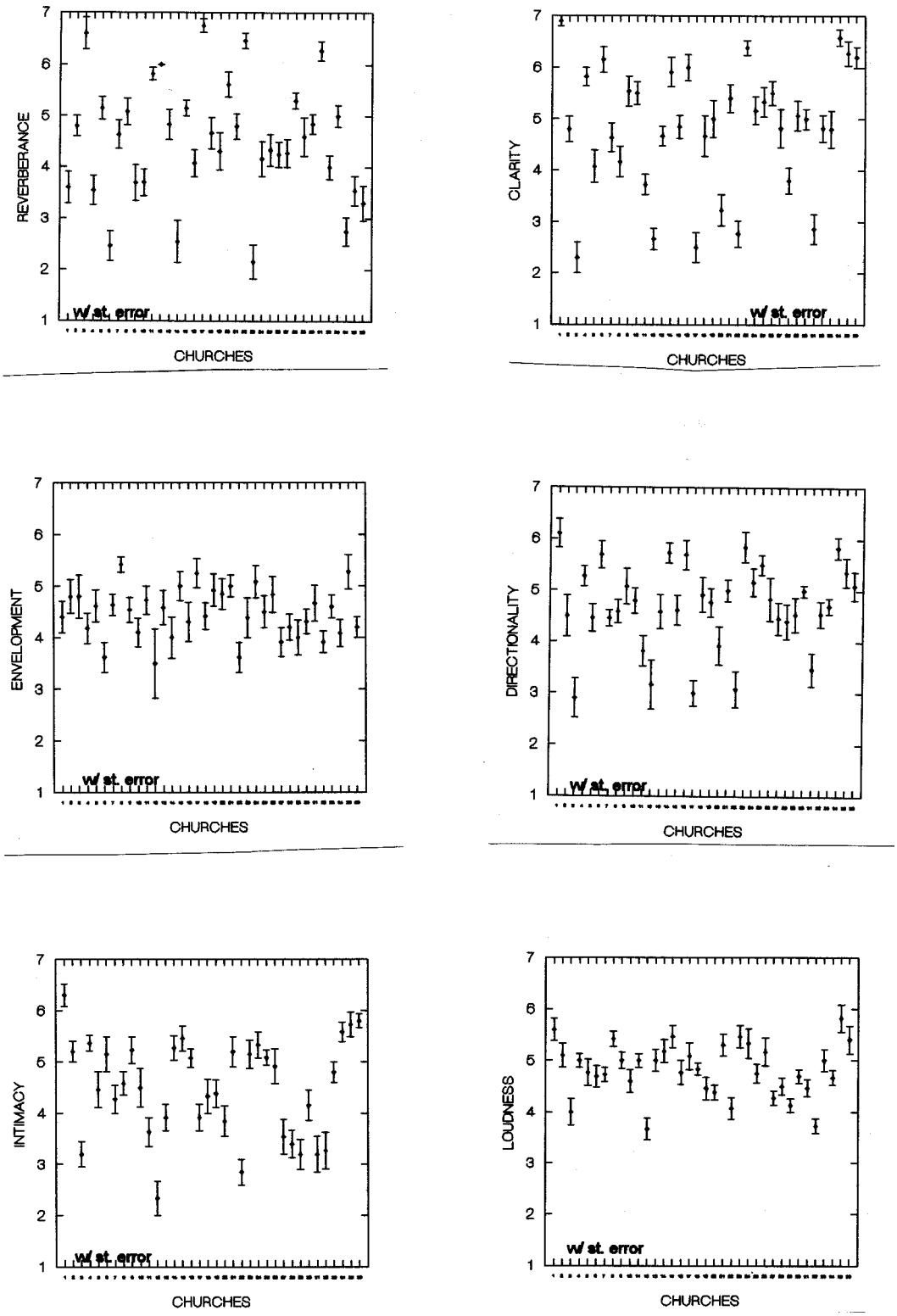

Figure 5 - Mean values of the subjective criteria with one standard error confidence interval in each church (the *x* axis shows the 36 churches numbered *1* to *36* from left to right).

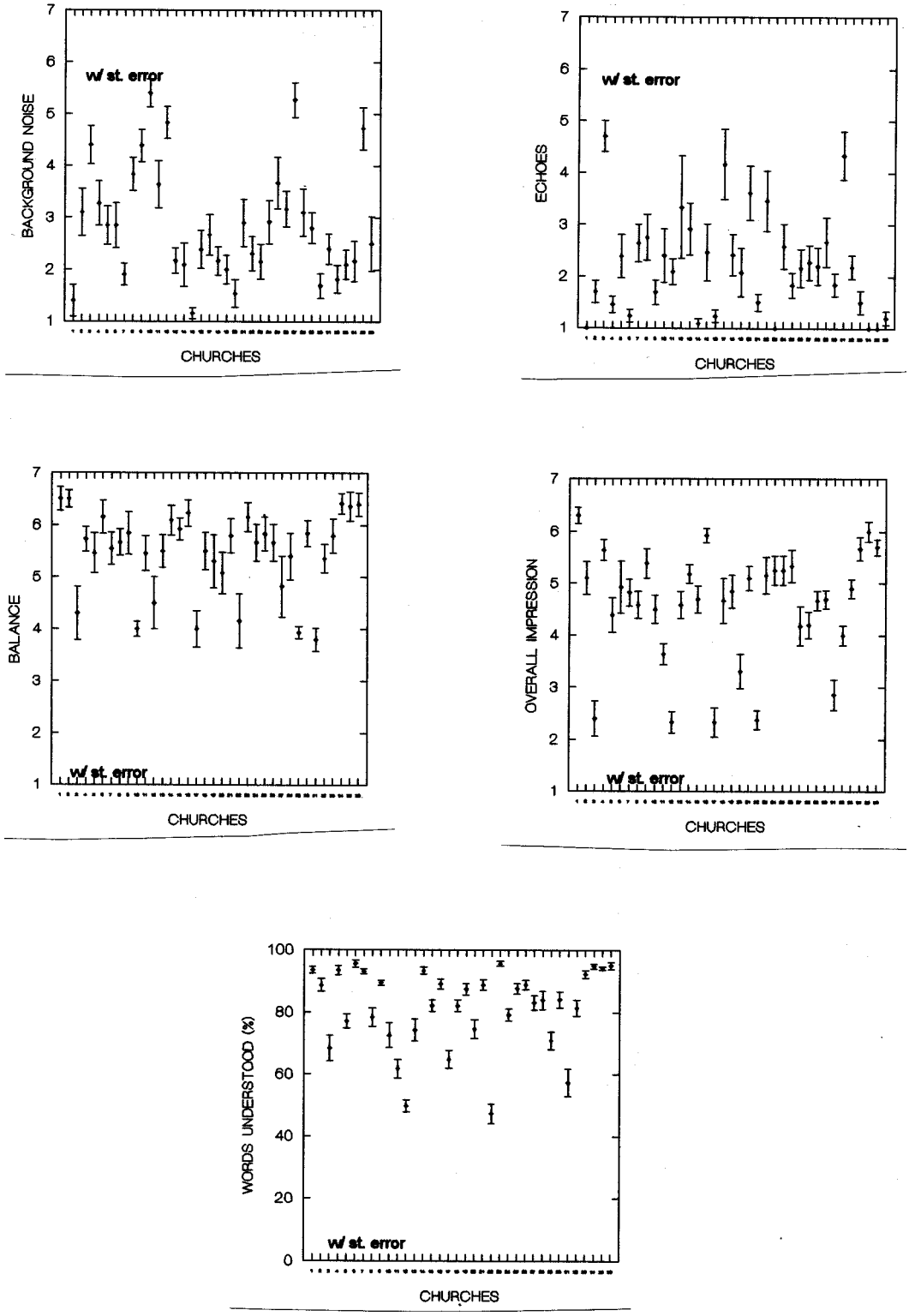

Figure 5 (cont.) - Mean values of the subjective criteria with one standard error confidence interval in each church (the *x* axis shows the 36 churches numbered *1* to *36* from left to right).

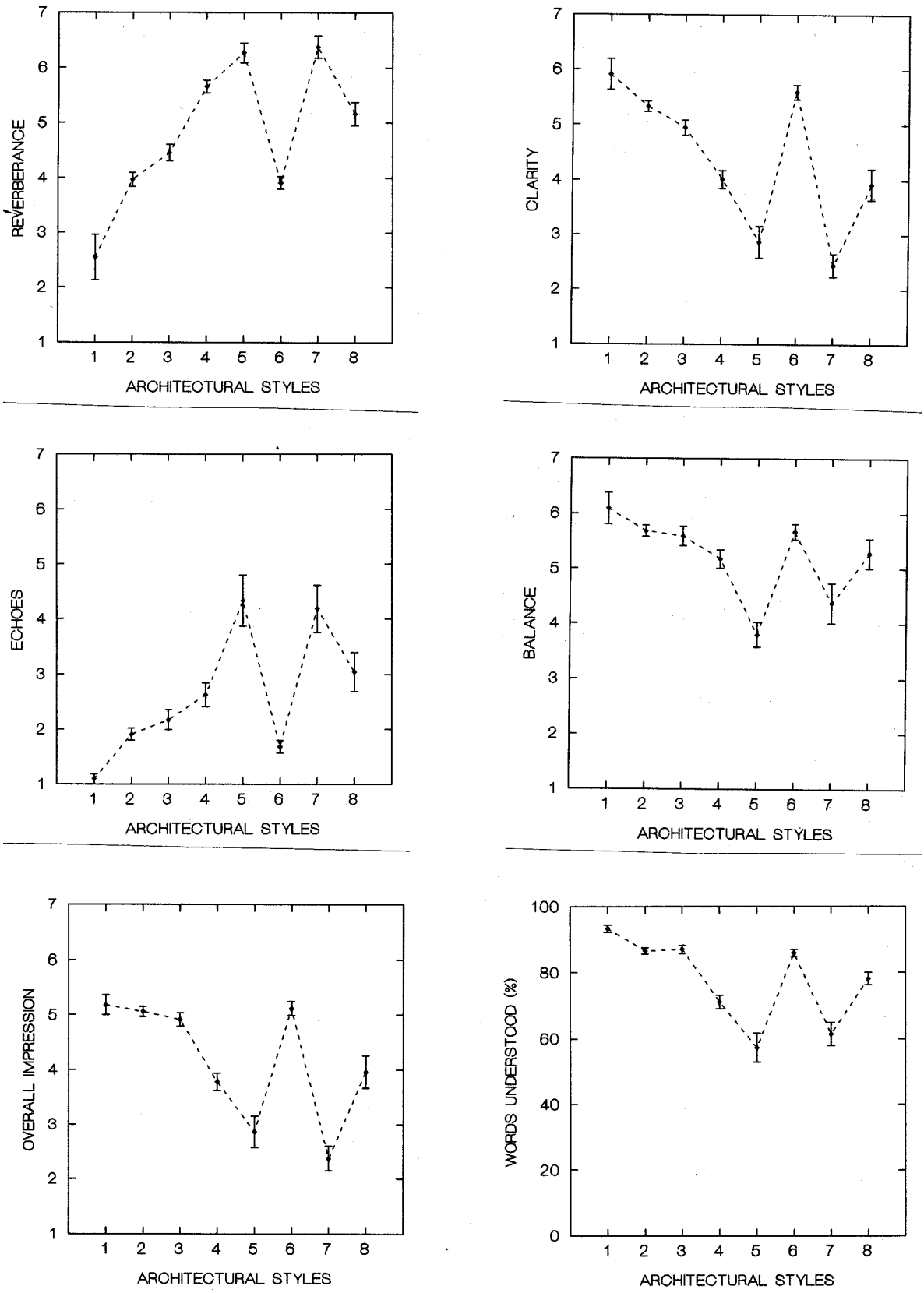

Figure 6 - Averaged data for some of the subjective acoustical criteria with one standard error confidence intervals plotted vs. the architectural styles in chronological order from left to right (1-*Visigothic*, 2-*Romanesque*, 3-*Gothic*, 4-*Manueline*, 5-*Renaissance*, 6-*Baroque*, 7-*Neoclassic*, 8-*Contemporary*).

APPENDIX A - (Questionnaire used)

AVALIAÇÃO ACÚSTICA

RUÍDO DE FUNDO: Os sons escutados no local, que não os da fonte ou dos auditores

1	2	3	4	5	6	7
não audível	muito fraco	fraco	aceitável	forte	bastante forte	extremamente forte

INTENSIDADE DO SOM: A intensidade geral ou "volume" do som, que está a ser sentido nesse local

1	2	3	4	5	6	7
extremamente fraco	muito fraco	fraco	com razoabilidade	forte	bastante forte	extremamente forte

CLAREZA DO DISCURSO MUSICAL: O grau em que as notas musicais são claramente separadas no tempo e distintamente ouvidas

1	2	3	4	5	6	7
nada claro	muito pouco claro	pouco claro	clareza aceitável	clareza boa	clareza bastante boa	extremamente claro

REVERBERÂNCIA: A persistência do som no espaço

1	2	3	4	5	6	7
totalmente seco	muito pouco reverberante	pouco reverberante	reverberância aceitável	boa reverberância	reverberância bastante alta	extremamente reverberante

ECO: Reflexões atrasadas do som e claramente audíveis

1	2	3	4	5	6	7
não detectado(s)	quase imperceptível	pouco audível	audível	moderadamente audível	muito audível	manifestamente audível

INTIMIDADE: A sensação auditiva de proximidade da fonte sonora

1	2	3	4	5	6	7
ausência de intimidade	muito pouco íntimo	pouco íntimo	intimidade aceitável	boa intimidade	intimidade bastante boa	extremamente íntimo

DIRECCIONALIDADE: A sensação de que o som vem no eixo da fonte sonora

1	2	3	4	5	6	7
muito má	má	medíocre	suficiente	boa	muito boa	excelente

ENVOLVIMENTO: O sentimento de estar imerso no som ou rodeado por ele

1	2	3	4	5	6	7
nada envolvente	muito pouco envolvente	pouco envolvente	envolvência aceitável	envolvência boa	muito envolvente	extremamente envolvente

EQUILÍBRIO TÍMBRICO: Níveis relativos das frequências graves e agudas

1	2	3	4	5	6	7
desiquilibrado						equilibrado

IMPRESSÃO GERAL: A impressão geral da qualidade acústica sentida

1	2	3	4	5	6	7
muito má	má	medíocre	suficiente	boa	muito boa	excelente

APPENDIX B - (One of the 100-word lists used)

TESTE DE ARTICULAÇÃO DE PALAVRAS
LISTA DE PALAVRAS

IGREJA .....DATA .....

1 - vazio	39 - teima	77 - maço
2 - pato	40 - dádiva	78 - moer
3 - missa	41 - escapa	79 - perfume
4 - melão	42 - casa	80 - disco
5 - engate	43 - medo	81 - fato
6 - duque	44 - reinar	82 - madeira
7 - descanso	45 - taberna	83 - cabra
8 - aval	46 - vento	84 - alto
9 - banha	47 - óleo	85 - bico
10 - baga	48 - nada	86 - picar
11 - bardo	49 - rádio	87 - maçã
12 - igreja	50 - altivo	88 - hospital
13 - sacar	51 - agonia	89 - garra
14 - ajuda	52 - empurrão	90 - malha
15 - abrir	53 - sigilo	91 - pelar
16 - embrulhar	54 - soalho	92 - farto
17 - mentor	55 - bata	93 - culpa
18 - parte	56 - gato	94 - acuda
19 - tanque	57 - oito	95 - estudo
20 - quartzo	58 - rebolar	96 - objecto
21 - alta	59 - incidir	97 - recta
22 - asa	60 -acalmar	98 - içar
23 - bota	61 - deslizar	99 - bulir
24 - chacal	62 - prego	100 - alface
25 - quite	63 - ver	
26 - micra	64 - touro	
27 - trapo	65 - rabo	
28 - tia	66 - afixar	
29 - contar	67 - cerco	
30 - ladrar	68 - entulhar	
31 - moita	69 - filtro	
32 - urânio	70 - ritmo	
33 - repto	71 - tojo	
34 - debate	72 - mina	
35 - fava	73 - olho	
36 - maca	74 - arrolhar	
37 - lado	75 - agudo	
38 - pega	76 -vime	

APPENDIX C - (Evaluation sheet for speech intelligibility tests)

TESTE DE ARTICULAÇÃO DE PALAVRAS

NOME .....IDADE .....

IGREJA .....POSIÇÃO .....

1 -	36 -	71 -
2 -	37 -	72 -
3 -	38 -	73 -
4 -	39 -	74 -
5 -	40 -	75 -
6 -	41 -	76 -
7 -	42 -	77 -
8 -	43 -	78 -
9 -	44 -	79 -
10 -	45 -	80 -
11 -	46 -	81 -
12 -	47 -	82 -
13 -	48 -	83 -
14 -	49 -	84 -
15 -	50 -	85 -
16 -	51 -	86 -
17 -	52 -	87 -
18 -	53 -	88 -
19 -	54 -	89 -
20 -	55 -	90 -
21 -	56 -	91 -
22 -	57 -	92 -
23 -	58 -	93 -
24 -	59 -	94 -
25 -	60 -	95 -
26 -	61 -	96 -
27 -	62 -	97 -
28 -	63 -	98 -
29 -	64 -	99 -
30 -	65 -	100 -
31 -	66 -	Número de palavras certas:
32 -	67 -	
33 -	68 -	
34 -	69 -	
35 -	70 -	