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SUBJECTIVE ACOUSTIC MEASURES AND SPEECH INTELLIGIBILITY IN CHURCHES

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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 (this paper presents a report regarding the second topic):

- *Objective studies of existing churches* - Measurements were taken in 41 Portuguese Catholic churches, at multiple locations in each room (RT, EDT, C80, D50, TS, L and RASTI) (Carvalho 1994).
- *Subjective studies of existing churches* - This has included both evaluating live musical performances in 36 churches and speech intelligibility testing. This work is characterized by the use of a sample of listeners, evaluation of several locations in each room, assessment of many rooms and comprehensive statistical analysis of the data.

METHODOLOGY

Method Summary. The main research hypothesis is that the perceptions of people who attends services or concerts in churches could be measurable. 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 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 performance for evaluations were fully realized. The acoustical response of the church mutates when it is fully occupied. The character of the music heard during a religious service or during an actual musical performance is also different. Nevertheless this methodology gives a normalized sound environment that could be easily compared among churches.

Sample of Churches Used. 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. The churches are a sample of 14 centuries of church building in Portugal. Portugal is one of the oldest European countries and played a prominent role in some of the most significant events in worldwide 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.

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 1. For more uniformity of the sample, only churches with a 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 (António P. O. Carvalho, *Influence of architectural features and*

styles on various acoustical measures in churches, PhD. Dissert. U. Florida 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 few years, that changed their acoustical conditions.

Subjective acoustical evaluations were held in churches grouped by large periods of history: 12 *Visigothic* or *Romanesque* churches, 11 *Gothic* or *Manueline* churches, 9 *Renaissance* or *Baroque* churches and 4 *Neoclassic* or *Contemporary* churches. The main architectural features of these churches are displayed in Table 2.

Table 1 - Architectural styles of the 36 churches tested.

1 - Visigothic	(6th-11th centuries)	4 - Manueline	(15th-16th centuries)	7 - Neoclassic	(18th-19th centuries)
2 - Romanesque	(12th-13th centuries)	5 - Renaissance	(16th-17th centuries)	8 - Contemporary	(20th century)
3 - Gothic	(13th-15th centuries)	6 - Baroque	(17th-18th centuries)		

Table 2 - 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

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 considered that a group of randomly selected average listeners was not suitable for this study due to the need of having same previous 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 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. The results were 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 by 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 J. G. Naumann. Then the listeners 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.

Acoustics Evaluation Sheet. The acoustics evaluation sheet used throughout the tests had ten semantic differential rating scales with seven points and was adapted from Richard Cervone (*Subjective and objective methods for evaluating the acoustical quality of buildings for music*, M. Arch. Thesis U. Florida 1990). 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 or players) 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*. During the pilot-tests, before engaging 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 rooms 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 has a different sensory meaning. The one in concert halls is usually smaller than in churches and generally pleasant when exists. In contrary, in churches the *huge* amount 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 but conceptually similar. This was named *directionality*, that tries 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 proven by some of the correlation analyses.

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. Only words with 1 to 4 syllables (according to Portuguese grammar) were used, but the 2-syllable words were predominant (64%). 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*.

RESULTS

Overall Results. The scores were analyzed directly as they were entered on the questionnaires. Table 3 shows a basic general statistical analysis of the results found using averaged data for each church (36 data points, one for each church). Table 4 presents the absolute values of the correlation coefficients (|R|) for the linear relationships among the eleven acoustical subjective criteria using averaged data for each church (36 points).

In Table 4 is seen that among all linear relationships, the highest correlations (|R| = 0.92 to 0.96) were found between *clarity* and *directionality*, *clarity* and *overall impression* and between *clarity* and *reverberance*. 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 5 presents the linear or quadratic best fit 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. These studies produced the models shown in Table 6. 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 3 - Simple statistics of acoustical parameters (using averaged data for each church - 36 data points).

ACOUST. PARAMETER	MINIMUM	MEAN	MEDIAN	MAXIMUM	ST. 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 4 - Linear correlation coefficients (|R|) among subjective criteria using averaged data for each church.

MEASURE	loudness	clarity	reverberance	echoes	intimacy	direction.	envelopm.	balance	overall impr.	words
backgr. 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 impr.									-	0.88

Table 5 - 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 6 - Summary of stepwise regression models for the subjective criteria on *overall impression* for all churches. A) Using all data; B) Using averaged data for each church (36 data points).

A)	VARIABLE ENTERED	*Clarity*	*Intimacy*	*Balance*	*Envelopment*	*Directionality*	*Echoes*
	MODEL R^2	0.64	0.69	0.71	0.72	0.73	0.731
B)	VARIABLE ENTERED	*Clarity*	*Envelopment*	*Balance*	*Reverberance*	*Directionality*	*Background Noise*
	MODEL R^2	0.88	0.92	0.94	0.95	0.95	0.96

Within Church Differences. A measure of the spatial variation of the data gathered within each church is the standard deviation of the room average value (includes the the seating position variation) and is summarized in Table 7. Figure 2 displays the 36 church means and the 36 spatial standard deviation of the gathered values in each room and for selected subjective acoustical measures. It can then be seen that the *loudness* and the *words* values vary very little throughout these churches in contrast to the spatial variation of *background noise* or *echoes*. Several of the criteria, notably *reverberance* and *clarity*, generally had wider ranges than the other criteria.

Among Church Differences. Figure 3 presents the analysis regarding the differences among churches. For each church and for selected subjective acoustical measures, the mean value is presented together with one standard error two sided interval. Table 8 presents the range of the 36 means concerning all measures. The church averages (Figure 3) 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 its larger within room variation.

Two-sample t tests were performed comparing the data grouped by the two seating locations used (middle center right vs rear central). Statistical evidence was found to support the idea that the seating location affects the mean values of all the parameters except *reverberance, echoes* and *balance*.

Table 7 - Simple statistics of the data regarding within church variation of the 36 church sample. Avg.M - Average Mean (mean of 36 church means); Avg.StDev - Average Standard Deviation (mean of 36 church standard deviations).

MEASURE	Avg.M	Avg.StDev	Avg.M / Avg.StDev	MEASURE	Avg.M	Avg.StDev	Avg.M / Avg.StDev
loudness	4.82	0.67	0.14	*balance*	5.50	1.09	0.20
clarity	4.83	0.88	0.18	*echoes*	2.22	1.09	0.49
reverberance	4.53	0.88	0.19	*background noise*	2.88	1.17	0.41
intimacy	4.49	0.90	0.20	*overall impression*	4.57	0.89	0.19
directionality	4.69	0.96	0.20	-	-	-	-
envelopment	4.48	1.02	0.23	words (%)	81.5	7.2	0.09

Table 8 - Range (max.-min. value) of the 36 means (36 churches) for the 11 acoustical measures.

Measure	*loudness*	*clarity*	*reverbe.*	*intimacy*	*directio.*	*envelop.*	*balance*	*echoes*	*b. noise*	*ov. impress.*	words
Range	2.15	4.60	4.60	3.97	3.20	1.92	2.70	3.70	4.25	3.97	48.3

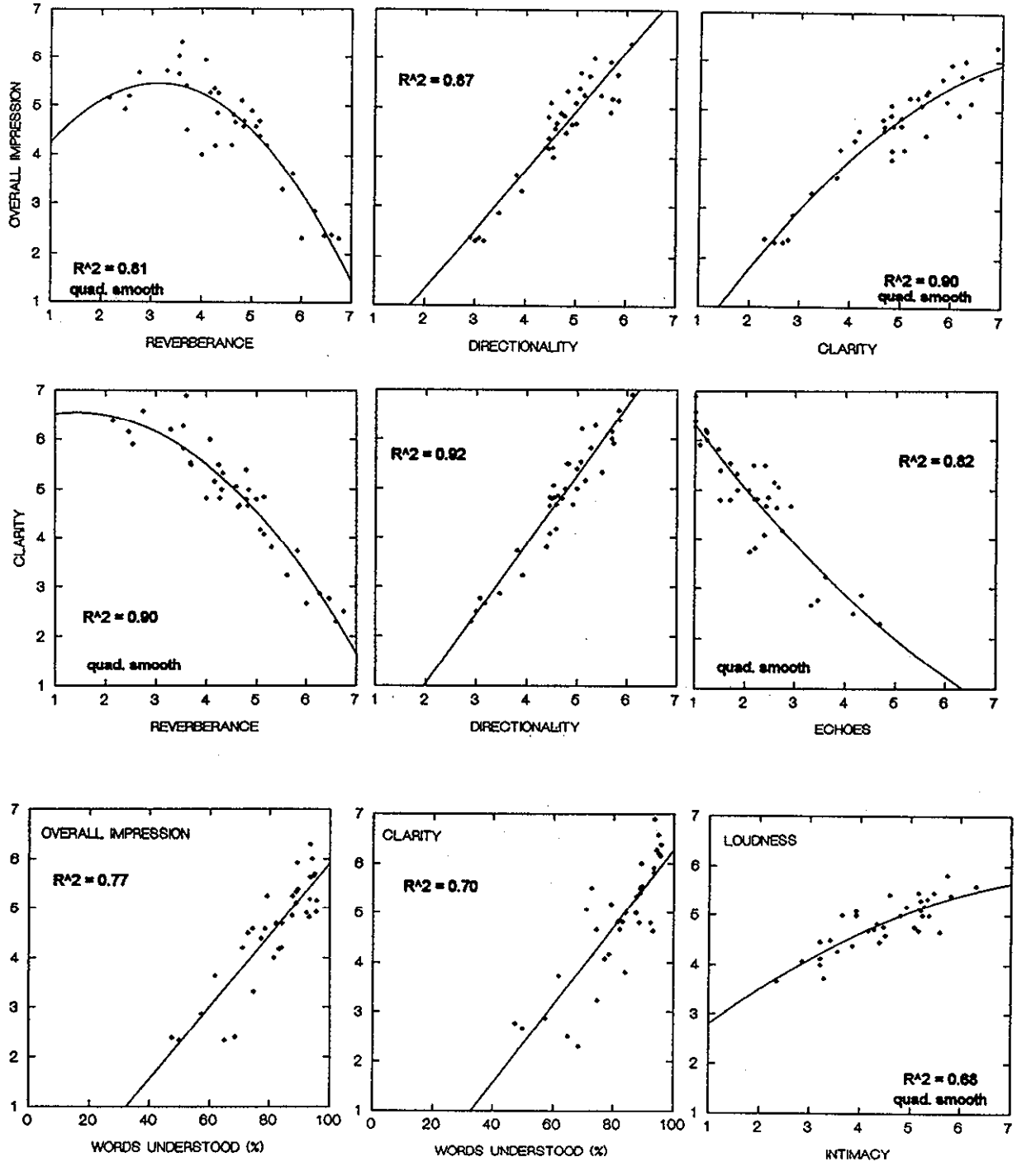

Figure 1 - Relationships between selected criteria with bivariate regression (linear or quadratic) models concerning church mean values (36 points = 36 churches).

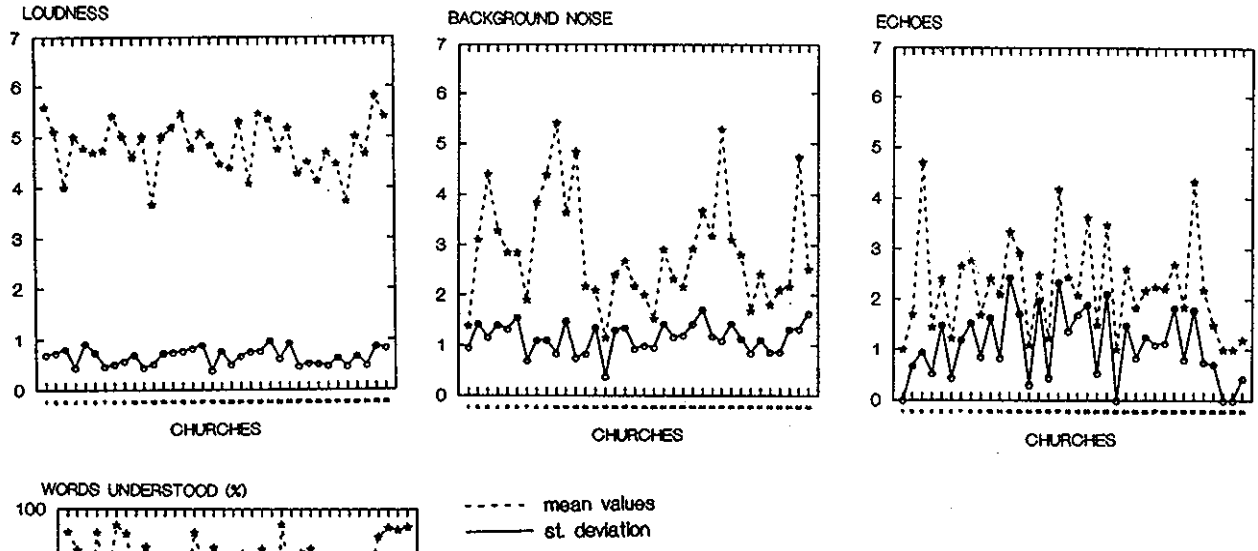

Figure 2 - Standard deviation compared with mean values for each church (the *x* axis shows the 36 churches numbered *1* to *36* from left to right) for selected subjective criteria.

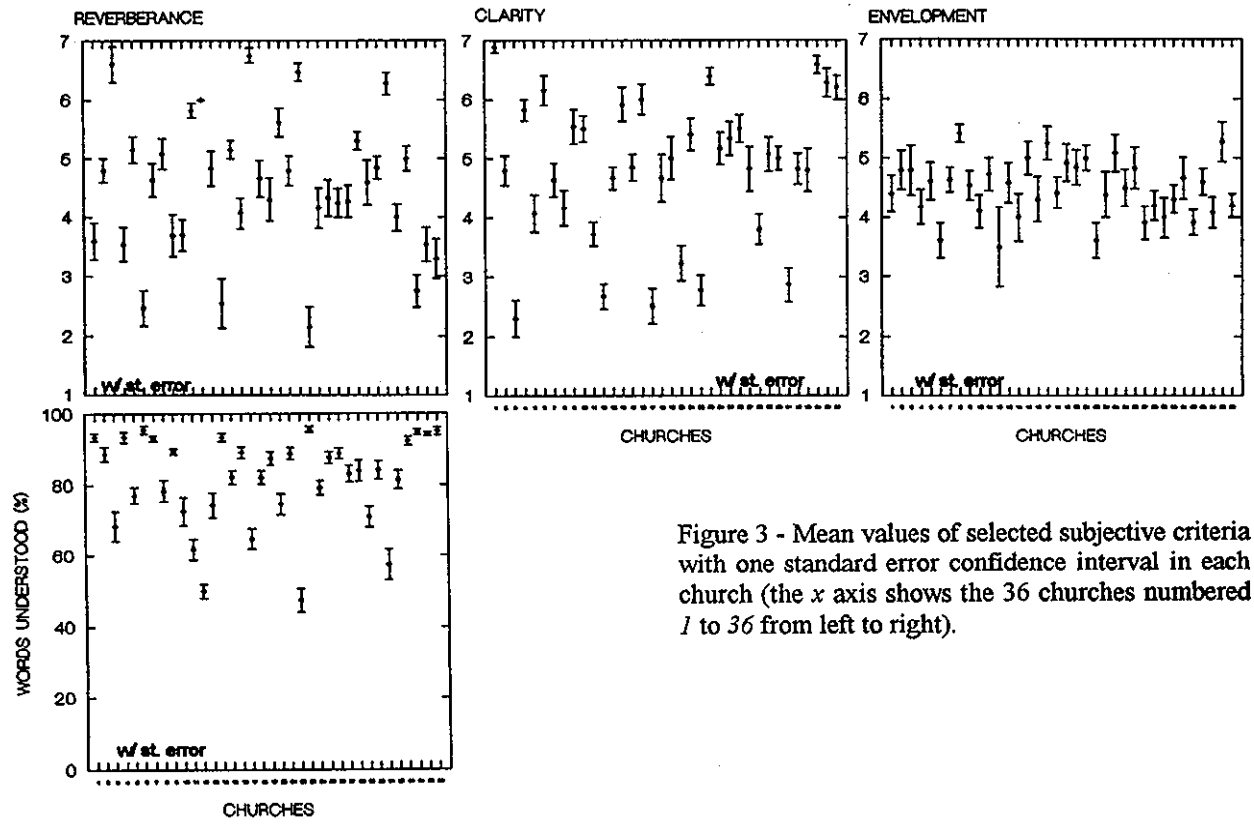

Figure 3 - Mean values of selected subjective criteria with one standard error confidence interval in each church (the *x* axis shows the 36 churches numbered *1* to *36* from left to right).