ACOUSTIC QUALITY OF THEATRES: CORRELATION BETWEEN EXPERIMENTAL MEASURES AND SUBJECTIVE EVALUATIONS

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Total number of pages of this manuscript: 30 + 2 original pictures.

0. ABSTRACT

This paper deals with the psychoacoustic correlations between physical parameters and subjective aspects of perception.

Many acoustic describers have been measured experimentally in eight Italian theatres and halls, among which the Milanese Teatro Alla Scala and the Teatri Comunali in Bologna and Florence. A questionnaire was distributed, gathering almost 200 contributions from international musicians, such as Riccardo Chailly, Severino Gazzelloni, Claudio Scimone and Uto Ughi. The results have been compared and statistically analyzed, yelding interesting correlations.

1. INTRODUCTION

The aim of this research is the definition of the physical and acoustic describers capable of representing the characteristics of the sound field which are responsible for the audience's psycho-subjective feeling of "acoustic comfort" in theatres. Their definition forms the basis of any intervention of acoustic design.

The problem was dealt with following these fundamental points:

- experimental measurements of the *Impulse Response* (stage - audience) in a number of well-known Italian theatres;
- setting up a one page questionnaire based on compared analysis techniques, using a numerical scale connecting pairs of opposed subjective describers; this made it possible to gather almost 200 fully compiled questionnaires employing highly qualified listeners, internationally renowned musicians, musicologists and music critics;
- statistical analysis of objective and subjective data, using techniques of multiple regression.

From the results obtained, it is possible to hypothesize the realization of a simple mathematical model which would make it possible to estimate the subjective quality evaluation from the objective parameters. Such a subjective evaluation is very important in order to foresee the effects of architectural interventions on theatres, so that the necessary collaboration between musicians and music critics on the one hand, and acoustic designers on the other, can be established.

2. THE STATE OF THE ART

The psycho-acoustic study of concert halls has developed contemporarily in two directions: through the study of electro-acoustic simulations of the sound field and through questionnaires regarding existing halls.

Cremer *et al.* (1982) have discussed the possibility of formulating questionnaires for music pieces similar to those used for the study of speech intelligibility. Such questionnaires could include, for example, the ability to recognize the instruments used, or the transcription of short sections of music pieces through "music dictations", but this would have limited the number of those able to answer such questions to a circle of professionals and, above all, it would not have completely resolved the problem: in fact, contrary to conference halls, here the need for clarity and "musical intelligibility" does not have absolute priority (Izenour, 1977); think about how the pianist, using the pedal of substain, obtains the effect of sound fusion, and increases the expressiveness of typically romantic melodies.

Often, non-acoustic phenomena such as the view from the occupied seat, the comfort of the seat itself, the thermoigrometric comfort of the environment, etc., can also influence the overall judgment (Farina, 1986).

In order to obtain satisfying results, it is necessary to have access to a fairly large number of questionnaires, whose questions should refer to situations close in terms of time, and under the same conditions, apart from one single varied parameter.

Furthermore, studying the acoustic conditions of different concert halls necessarily implies a time interval of days, or even years. Even the acoustic signal, being variable, will obtain a different judgment. Finally, the position of the listener in the hall will also influence the judgment.

In general, by expressing the individual judgment through a number x_k , it will be possible to calculate the average value of various judgments, using the formula:

$$\overline{x} = \frac{1}{n} \times \sum_{k=1}^{n} x_k \qquad (1)$$

making sure to check, in the case of comparisons between different halls, that the dispersion in the subjective judgments, i.e. the variance, will not exceed the difference with average values.

2.1. Electro-acoustic simulations

The method of sound field electroacoustic simulations is based on the recording of music pieces using a binaural instrument (artificial head), made in various halls, and then reproposed to the subjects in an anechoic room. This technique, which is very fast, was used in the Göttingen and Berlin Schools (Wettschureck, 1975 and Damaske, Wagener, 1969). In the first case, anechoic musical pieces were used, reproduced in theatres using a loudspeaker, and recorded using an artificial head, and later reproposed through 2 loudspeakers in an anechoic room. In the second case, a recording was made of the same music piece interpreted by the same orchestra in different points of the halls analyzed, using an artificial head, and then reproposed through stereo headphones.

The continuous use of loudspeakers both during recording in the test room, and during reproduction in an anechoic room provokes a signal distortion and objective modifications of the sound field.

The use of stereo headphones, however, over-amplifies the impression of space and of being surrounded by the sound field.

Together with these experiences, a number of electro-acoustic simulation techniques have been developed, in order to facilitate the comparison between the various sound signals. With these techniques, it is possible to vary continuously just one acoustic parameter. For example, Y. Ando (1985), in formulating his well-known theory, based himself on comparative studies made on electro-acoustically simulated fields, from which he drew the independence of 4 basic parameters, which are: sound level, ITDG, reverberation time and IACC. They were based exclusively on the simulation of the effect induced by direct sound and by the first two reflections, on a small number of subjects.

The sound field simulations allow extremely fast modifications to the system, and so they facilitate the study of correlation through the comparison of signals: a negative judgment can lead to an immediate modification of the environment and it is possible to analyze directly the influence that it has on the overall judgment. Furthermore, it is possible to simulate the environmental changes which can take place in the halls during the musical performance.

A.C.Gade's research (1989) has moved in this direction, continuing the study carried out by Barron and Marshall (1981). However, the great versatility given by the electro-acoustic synthesis presents a number of limitations, linked to the necessary simplification of the description of the acoustic phenomenon:

- very limited number of first reflections (maximum 4 or 5);
- very "poor" temporal and spacial description of the field;
- limited sound quality and fidelity, therefore the sound and timbre of the musical instruments are altered;
- limited energy input: at the moment it reproduces no more than half of the total reflected energy;
- need, in every case, to have good digital instruments, as well as a suitable environment to reproduce the signal (anechoic chamber).

These limits have pushed A.C. Gade to differentiate electro-acoustic simulations according to whether the research was addressed to single solo interpreters or to groups of orchestra musicians.

Recently, one of the authors (Farina, 1993) developed a new auralization system capable of removing all the limitations listed above. At the moment this system is under test: a number of subjects will judge the similarity of digitally auralized music signals with binaural music directly recorded in some concert halls.

2.2. Experiments in Existing Halls

In the last years the tendency has been to carry out, in conjugation with the studies using electro-acoustic simulations, similar studies on existing halls.

This can accomplished in two ways: the first is a direct listening experience in existing halls, using a panel of selected subjects; the second is to employ binaural music recordings made in the halls, with an orchestra or with loudspeakers fed by anechoic music.

At the same time, it is possible to make accurate objective measurements of the most important physical parameters, using modern digital signal processing techniques (Cocchi *et al.*,1992). In this field the authors developed a measurement system giving a direct reading of Ando's preference indexes (Cocchi, Farina, 1988); with this system, many ancient Italian theatres were studied in past years (Cocchi, 1992).

With this method it is possible to maintain a real acoustic quality of the analyzed signals, in so far as none of the components, either spectral or temporal, is modified. However, the comparison between the different sound messages is rather complex, since it is not possible to make a comparison with only one parameter having undergone a continuous variation.

The possibility to carry out psycho-subjective research on the acoustic quality of real environments have been possible using the following method:

1) Structural changes relative to only one room, modifying some of its aspects, i.e:

- volume, through the introduction or removal of dividing panels which allow the creation of new rooms, of variable sizes;
- shape, by modifying, with the use of adequate instruments, the position of the walls, thus changing, by rotating the surfaces, the path of the reflected sound waves;
- sound absorbtion, changing the original characteristics, by introducing or removing sound-absorbing, diffusing or reflecting materials (Farina, Barabaschi, 1990).

2) Comparative analysis on different rooms, through the creation of relevant questionnaires, on the basis of a number of reference pieces, addressed to a large number of musicians and/or qualified personnel.

2.2.1. Structural modifications

In the case of structural modifications of the environment, the difficulties concern mainly logistical factors, unless they are supported by an adequate architectural design of the theatre, as, for example, in the case of the "Espace de Projection" at the IRCAM in Paris.

In fact, such difficulties encourage this methodology when interventions in the above-mentioned halls have to be made due to other needs, and indeed the questionnaires are usually used in the case of a general restructuring of the building, which would involve an important variation particularly of its sound-absorbing characteristics (e.g. Teatro Comunale in Florence).

The first example of this kind was carried out by W.C. Sabine himself (1929), when he established the reverberation time preferred by a small group of musicians from a local music conservatory; he used some stuffed cushions as sound-absorbing units to modify the reverberation time in the hall.

2.2.2. Comparative Analysis

In the case of comparative analysis on various halls, many of these problems have been overcome. The main limitations specifically concern:

- the reliability of the answers, which are often given after an interval of many years with respect to the performance to which they refer;
- the musical reference, that is the obvious impossibility to repeat the same conditions and the same musical piece on which the subjective evaluation has to be given.

The psycho-subjective research of acoustic quality through questionnaires regarding existing halls has developed throughout this century, and it was the first to be carried out in order to define the most appropriate acoustic describers capable of defining the acoustic quality of a given environment.

F.R. Watson (1927) was the first to try to obtain a relation between optimum reverberation time and volume of the hall, basing himself on the calculation of RT in 6 halls "considered good by public opinion".

In 1952, Parkin (1952) carried out the study of 12 English Concert Halls, by sending a written questionnaire to 170 music experts (the majority of whom were not musicians, since he considered the opinion of musicians different from that of music critics and other spectators in general. Unfortunately, only 42 of them were sent back, so their evaluations seem to have little correlation. In fact, the questionnaires asked for a general opinion on the quality of the halls, without going into details, and such opinion was expressed with only 3 possibilities ("Good", "Fair", "Bad").

The result even appears to prove a lack of correlation with the reverberation time, since the three most popular halls had a RT of 1.6, 1.1 and 2.2 sec..

The most representative example of this practice is that given by L. Beranek (1962). He described 54 Opera Houses and Concert Halls, after visiting each one personally, and for each hall he asked 23 conductors and 21 music critics (among whom were Sir John Barbirolli and Bruno Walter) to describe various different aspects of the sound perception, through the choice of various terms chosen among those close to music terminology, such as "warmth", "intimacy", etc..

Beranek showed how reverberation time was not able to give an exhaustive description of the acoustic characteristics of indoor environments, and with this aim introduced new describers (e.g. the ITDG). At the same time he gave a different weight to each parameter without previously carrying out a statistical study to determine its value. For instance, he gave 40 points to the ITDG, and only 15 (out of 100) to the reverberation time in the middle frequencies.

2.2.3. Wilkens'study.

Wilkens (1972, 1977) carried out a preliminary study of the terminology to be used in the questionnaire.

His research, which followed the example of other researchers (Hawkes, Douglas), was based on pairs of opposite terms, and interviewed people had to write their answers marking a point on a scale of values whose extremes were the opposite terms. At first, he gathered all the descriptive terms he was able to find in music literature, and later also the terms used in the normal, everyday language of musicians; at the end of the preliminary analysis, he selected 90 pairs of parameters.

In the following phase, he tried to reduce that large number of acquired terms, paying special attention to the selection that was to be made. Some important aspects of perception could be ignored or not be given enough importance.

All of the terms considered irrelevant for the description of acoustic perception were excluded from the questionnaire, as were the terms whose meaning was unclear or ambiguous. Also the words which suggest a physical state ("resounding"), and those synonymous of other pairs already included, were avoided.

Wilkens established the presence of two different types of musical taste; however, he was unable to associate a particular musical taste with a precise category of listeners.

At the end of his work, Wilkens noticed how the great majority of the interviewees coincided in expressing a given opinion in relation to a particular question connected with phisical properties (for example, in defining a hall "clear", or "strong"), but giving a different weight to their own judgment to obtain the overall subjective preference.

2.3. Numerical techniques of correlations

The techniques still used today are of two types: the technique of comparative judgments and that of the factor analysis. Both techniques make reference to a wide theory of the statistical evaluation of quality, i.e. of the "multidimensional analysis of quality".

2.3.1 Multidimensional analysis of acoustic quality

It is based on the hypothesis that the individuals are able to express with continuity their own preference, expressed through parameters, factors or dimensions. At the end of the analysis procedure, the signals on which opinions were given are represented in an n-dimensional space through points, whose distance expresses, through given relations, the difference found between the initial stimuli.

After carrying out a series of acoustic measurements of the environment, an attempt is made at identifying the n-dimensions in terms of physical parameters, which are finally represented through projections on orthogonal plans, so as to simplify their interpretation.

2.3.2. Comparative evaluation

In the technique of "Comparative Evaluation" the individuals taking part in the survey are asked to express a simple judgment of similarity or preference.

In the first case, the individuals are asked to express a judgment of similarity between the proposed stimuli, expressing it in a scale of values, e.g. from 1 (min.) to 9 (max.). The results of the survey are represented in a matrix, in which the element X represents the judgment of similarity between the i-th and the j-th signals.

In the second case, the interviewees simply have to express a preference between two signals, choosing the one which they believe to be the best.

Later, the results can be represented in a matrix, i.e. using only two parameters (0 and 1) in which, for instance, X = 0 if the i-th signal is preferred to the j-th signal. The score obtained by each signal can be calculated by simply adding how many times it has been preferred by the interviewee. The preference matrix will be formed by the rows corresponding to the proposed signals, and by the columns relating to the subjects.

In order to correlate the subjective results to the numerical value of the objective parameters used in the description of the physical characteristics of the system's acoustic field, the parameters themselves are introduced as variables depending on the factors obtained.

This becomes possible by looking for the matrix relation between the factors and the objective parameters. The matrix of the weights thus obtained can be calculated through the solution of a linear system, since the matrixes of the factors and that of the parameters are already determined. At the end of the study, it is possible to represent the results thus obtained through the projections on orthogonal plans of the r-dimensional space of preferences.

2.3.3. Factor analysis

The factor analysis is a global theory of statistic analysis, which can be applied to any discipline (Harmann, 1968). By "factor", we mean an independent aspect, physical or not, which affects the judgment.

The technique can be used indifferently both for the analysis of physical-objective parameters and for the study of psycho-subjective judgments.

The aim of the procedure consists in expressing the matrix of the initial data, $[D]_{n\times N}$, in the product of two other matrixes, $[W]_{n\times m}$ and $[F]_{m\times N}$ respectively, named "weight matrix" and "factor matrix". The data matrix is constituted by the physical values (rows) in correspondence with measurement points (columns), or by judgment given in questionnaires (rows) in correspondence with measurement points (columns), of various halls.

The solution to the algorithm is obtained through a mathematical calculation, and in the case in which $n<m$, the problem does not present an univocal solution, so it is necessary to act according to approximations, using the method of least squares.

Wilkens' study represents a typical example of factor analysis applied to the study of the subjective aspects of the acoustic characteristics of rooms.

He expressed the obtained results through the orthogonal projections of the three dimensional space of preferences ($m=3$) which he had obtained. Actually, the factor analysis has a number of limits, which regard:

- the working capacity of data management;
- the risk of dispersing a large part of such data;
- the difficulty of interpreting the results obtained.

Furthermore, the use and interpretation of the results are not particularly easy, since the existing correlation between subjective judgements and physical parameters is not immediately clear.

3. MEASUREMENT PROCEDURE

The procedure followed during the phase of data acquisition and computation can be summed up in the following points:

- recording of the reflectogram of the hall, carried out using an impulsive source (pistol-shot), on D.A.T. digital recorder by means of binaural microphones;
- play back of the recorded reflectograms and calculation of the Impulse Response of the hall using a two-channel FFT analyzer;
- evaluation of the sound-level distribution meant as the sum of the contribution made by the direct wave of a theoretical point source with a power level of L_w=100 dB and the reverberation contribution made by the environment (measured);

- calculation of Reverberation Time (T15 and T30) from the pistol-shots of the hall, by means of a third-octave real time analyser with Schroeder's backward integration;
- calculation of the E.D.T. through Schroeder's backward integration of the Impulse Responses using software on a PC ("MLSSA");
- calculation of the normalised Inter-Aural Cross-Correlation between the right and left impulse response using software on a PC;
- calculation of the mean value between left and right impulse response of some physical describers (Clarity, Center Time, RASTI) using software ("MLSSA");
- introduction of the data relating to the type of musical signal proposed (t_e);
- calculation of the ANDO preference index using software.

For the Sala Europa and the Teatro Comunale of Bologna, the calculation of the Impulse Response was also carried out through the cross-correlation of the MLS pseudo-random signal.

The procedure can be summarised in the following points:

- generation of the MLS pseudo-random signal through the MLSSA board installed on a TOSHIBA 3200 portable computer and emission in the room through a specific acoustic transducer (amplifier and omnidirectional loudspeaker);
- simultaneous sampling of the acoustic signal in the room through binaural microphones connected to the PC board via a wireless transmitter;
- real-time calculation of the Impulse Response through cross-correlation carried out using Hadamard's algorythm.

In the phases following the calculation of the Impulse Response, the procedure used for the Sala Europa and the Teatro Comunale remains the same as that used for the other examples.

It was verified that the sound spectrum emitted by the omnidirectional loudspesker is similar to that emitted by the pistol-shot by directly listening the impulse responses files.

3.1. Experimental results

Measurements for acoustic qualification have been carried out in the following theatres:

- Teatro Alla Scala in Milano;

- Teatro Verdi in Firenze;
- Teatro La Pergola in Firenze;
- Teatro Comunale in Firenze;
- Sala Ridotto del Comunale in Firenze;
- Sala Poggio Imperiale in Firenze;
- Sala Europa in Bologna;
- Teatro Comunale in Bologna;

For each of these, 12 wide-band acoustic parameters were measured, which were:

- Reverberation Time (R.T.) [s]
- Early Decay Time (E.D.T.) [s]
- Center time (Ts) [ms]
- Initial Time Delay Gap (I.T.D.G.) [ms]
- Clarity (C80) [dB]
- Inter Aural Cross Correlation (I.A.C.C.)
- Sound Pressure Level (SPL) [dB]
- Equivalent reflection amplitude (Aeq)
- Rapid Speech Trasmission Index (RASTI)
- Clarity (C50) [dB]
- Early/Late ratio (C5) [dB]
- Reverberant/Direct ratio (R/D)[dB]

For each room analyzed, a single number for each objective parameter was found by averaging first between the left and right channels (in the case of monoaural describers) and later between the different measurement points.

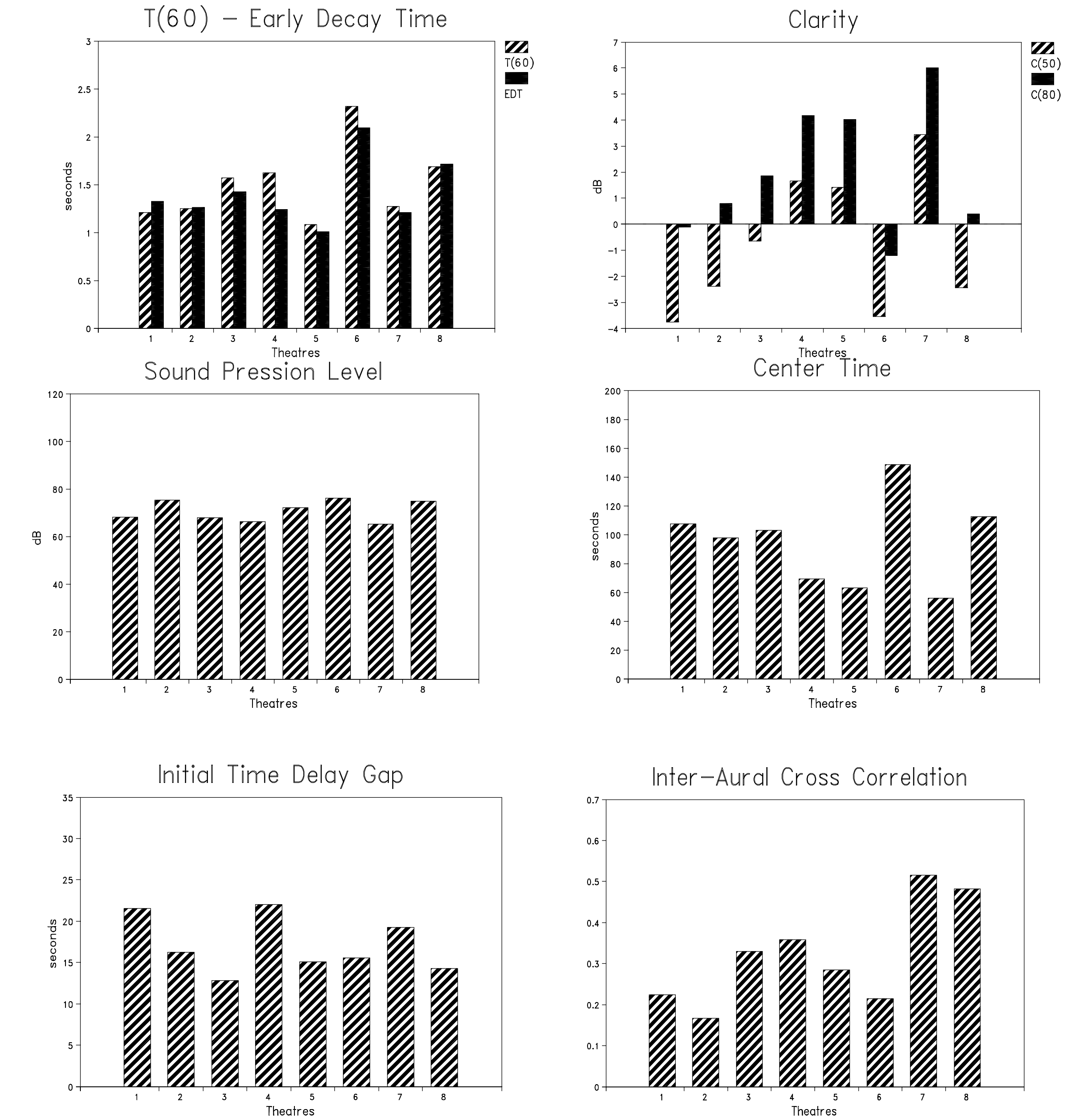
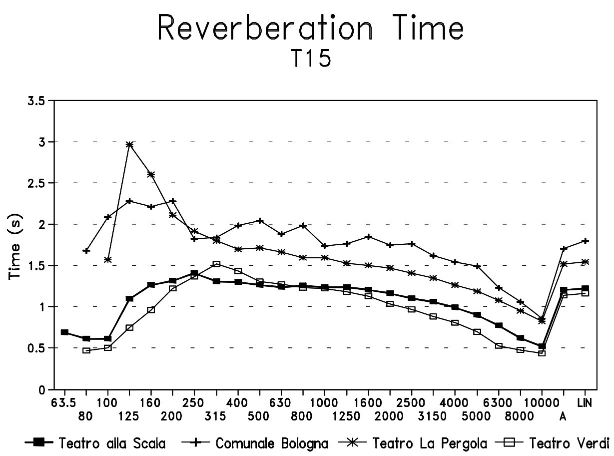


Figure 1: Acoustic parameters measured in 8 italian theatres, as listed in Table 1.

The reverberation time T15 was also measured in 1/3 octave bands:



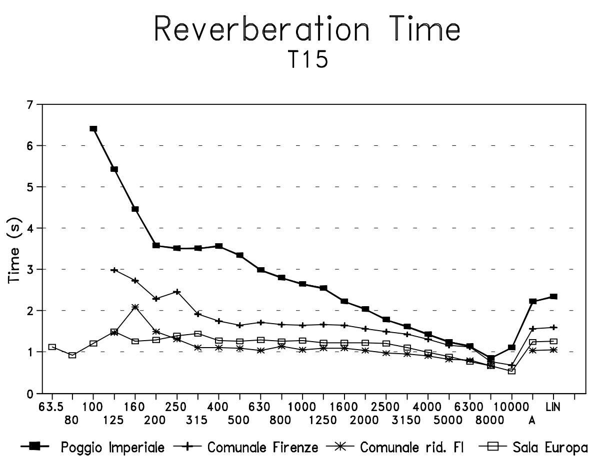


Figure 2: Reverberation time measured in 8 italian theatres, as listed in Table 1.

Later, the preference indexes were calculated according to the formulation proposed by Ando.

The Global Preference S_t is given by:

$$S_t = -\sum_{i=1}^{4} w_i \times |x_i|^{\frac{2}{3}} \quad (2)$$

where is: x = normalised parameter

w = weight coefficient.

The preference index according to Ando was calculated in relation to a piece by Wagner (t_e = 40 ms). In the case of the Theatre "alla Scala" in Milan, the analysis was carried out on 48 different positions and also on pieces by Haydn (t_e = 65 ms) and Gibbons (t_e = 127 ms).

In the largest halls (Teatro alla Scala, Comunale in Florence and Bologna, Verdi) the preference was penalised by the large dimension of the buildings: this has meant a lower value of the sound level preference index. The smaller halls, on the contrary (Ridotto del Comunale, Poggio Imperiale), present difficulties due to the excessive reverberation of the environment and the lower musical clarity and intelligibility. The Theatre "Alla Pergola", due to its smaller size, is the most suitable for musical events in general ("loud","clear"), and symphonic in particular, while the Teatro alla Scala and the Comunale in Bologna appear to be more suitable for opera (RASTI quite high), the Sala Europa for the spoken word (designed for conferences and debates), the Sala poggio Imperiale for chamber music (high sound level and reverberation). The Teatro Comunale of Florence was the most penalised from an acoustic view point, while the Teatro Verdi and the Ridotto del Comunale are on the whole quite versatile.

		T(60)	EDT	Ts	ITDG	C(80)	IACC	SPL	Aeq	Rasti	C(50)	C(5)	R/D	S_t
Theatre 1	SCALA	1.209	1.323	107.46	21.52	-0.11	0.22	68.1	1.00	0.50	-3.76	-13.7	-0.09	-1.8
Theatre 2	PERGOLA	1.251	1.259	97.89	16.26	0.80	0.17	75.2	3.05	0.52	-2.38	-13.6	9.22	-0.6
Theatre 3	VERDI	1.570	1.422	102.89	12.78	1.85	0.33	67.8	1.94	0.52	-0.64	-7.7	5.65	-1.9
Theatre 4	COMUNALE FI	1.624	1.242	69.23	21.99	4.17	0.36	66.3	1.25	0.60	1.66	-4.1	1.72	-2.1
Theatre 5	COM. RID. FI	1.080	1.010	62.96	15.09	4.01	0.28	72.2	1.56	0.61	1.41	-6.3	3.73	-1.1
Theatre 6	POGGIO IMP.	2.316	2.092	148.64	15.58	-1.21	0.21	76.1	2.83	0.39	-3.54	-10.3	8.95	-1.2
Theatre 7	SALA EUROPA	1.269	1.207	56.06	19.27	6.00	0.51	65.2	1.28	0.63	3.44	-6.5	1.71	-2.5
Theatre 8	COMUNALE BO	1.685	1.712	112.60	14.25	0.38	0.48	74.8	2.28	0.47	-2.45	-7.2	6.54	-1.1

Table 1: Table summarising the average values of the measured parameters for each Theatre.

4. SUBJECTIVE EVALUATION

4.1. Setting up the Questionaire

In setting up the questionaire, Wilkens' work was taken into consideration, using the terminology to be analysed; in fact, his questionaire is the most complete, although it contained a large number of descriptive words.

The different pairs, in Italian, German and English, are randomly sorted between the left and the right side, in order to avoid the risk of associating one side of the questionaire to a particular quality judgement.

The questionaire was distributed among the components of the "Orchestra Teatro alla Scala di Milano". The aim was to judge the readiness of those musicians to answer the different questions and, if necessary, modify or improve them.

Finally, when the completed questionaires had been returned, the opinions were analyzed. It came out that certain questions had been generally answered in the same way, thus showing a correlation among them, while other pairs of terms had been met with a certain level of skepticism ("random" responses).

Due to these observations, the need to simplify the raw data along with the need expressed by the musicians to be able to complete the questionaire quickly, the text was re-written.

4.2. Final version

In the following version of the questionaire, some pairs of terms were deleted, for instance "small-large"; other pairs were re-defined, for instance the pair "undeutlich-deutlich" was re-defined "impastato-definito", the meaning of which was certainly closer to the musical field; other terms were reduced to one single pair, since they appeared very close in meaning: an example is the pair "rund-spitz" and "stumpf-scharf", in English "rounded-pointed" and "blunt-sharp", which, in Italian, became "rotondo-spigoloso".

Finally, in the margin of the questionaire, under the space reserved for the overall judgement, there was a summary of the characteristics of the person completing the questionaire.

Pairs of words with almost identical meaning were included, but were well separated and inverted, such as "vigourous-attenuated" and "weak-strong", in order to check the reliability of the questionaires.

The questionaire was then distributed among artists and musicians of international fame, asking the interpreters to express themselves only in the case of personal performances in the theatres proposed, whilst in the case of technicians and/or music critics, they were asked to give their opinion only if they were familiar with the hall in question.

They were all asked to pay attention to the effect produced by the theatre on a general musical piece.

Fig.5 a,b: a) The first version of the questionaire, completed by C. Scimone

b) The final version of the questionaire, completed by L. Alberti

4.3.: List of Artists

In total, a few hundred questionaires were distributed; three orchestras answered them, among which two "permanent" orchestras, which were:

-the "permanent" orchestra of the "Teatro alla Scala di Milano" (23 musicians);

- the permanent orchestra of the "Teatro Comunale di Bologna" (56 musicians);

- orchestra of the "Accademia S.Cecilia di Roma" (12 musicians).

A number of musicians expressed themselves only on one theatre, while others have worked in several theatres.

Among those who have given their contribution, we would like to mention: M° Alberti, M° Benini, M° Chailly, M° Gazzelloni, M° Scimone, M° Ughi.

Among the people with different qualifications, there were: the Stage Director of the Teatro alla Scala di Milano, some music critics, a music archiver and artistic consultant, two music organisers, two theatre agents, three sound engineers, etc.

A total of 192 questionnaires were analyzed.

5. ELABORATIONS

5.1 Data analysis

The questionnaires referred to the eight theatres analyzed in par.3.

Therefore, the data obtained belonged to two matrixes measuring 192x14 (subjective data) and 8x12 (objective data) respectively.

Within the "subjective data" matrix (192x14), the average values attributed by the interviewees to the individual terms of the questionnaire for each hall were calculated, thus obtaining a reduced matrix 8x14. It should be noted that some interviewees suggested intermediate answers to the values proposed, and in such cases the decimal values proposed were input as valid data.

5.2. Statistical Calculation Procedure

For each pair of objective/subjective data, the linear regression between the 192 subjective answers and the corresponding objective values and the relative correlation coefficients were calculated. In fact, according to Y. Ando, each subjective parameter is a function of only one objective describer, and not of a linear combination of different parameters; therefore, as a basic hypothesis, it was thought to use these results in order to simplify the calculation algorythm, and, if needed, to check later its reliability.

The linear regression line can be expressed in the following formula:

$$Y_{sogg} = A \times X_{ogg} + B \tag{3}$$

in which X_{ogg} = objective parameter

Y_{sogg} = subjective parameter

Coefficient A is calculated with the method of the least squares, according to the following algorythm:

$$A = \frac{n \times \sum_{i=1}^{n} X_{i\,ogg} \times Y_{i\,sogg} - \sum_{i=1}^{n} X_{i\,ogg} \times \sum_{i=1}^{n} Y_{i\,sogg}}{n \times \sum_{i=1}^{n} X_{i}^{2}{}_{ogg} - \left(\sum_{i=1}^{n} X_{i\,ogg} \right)^2} \tag{4}$$

while coefficient B was calculated with the formula:

$$B = \frac{\sum_{i=1}^{n} X_{i}^{2}{}_{ogg} \times Y_{i\,sogg} - \sum_{i=1}^{n} X_{i\,ogg} \times \sum_{i=1}^{n} X_{i\,ogg} \times Y_{i\,sogg}}{n \times \sum_{i=1}^{n} X_{i}^{2}{}_{ogg} - \left(\sum_{i=1}^{n} X_{i\,ogg} \right)^2} \tag{5}$$

The linear regression coefficien "r" is expressed by:

$$r = \frac{n \times \sum_{i=1}^{n} X_{i\,ogg} \times Y_{i\,sogg} - \sum_{i=1}^{n} X_{i\,ogg} \times \sum_{i=1}^{n} Y_{i\,sogg}}{\left[\left(\sum_{i=1}^{n} X_{i}^{2}{}_{ogg} - \sum_{i=1}^{n} X_{i\,ogg} \times \sum_{i=1}^{n} X_{i\,ogg} \right) \times \left(\sum_{i=1}^{n} Y_{i}^{2}{}_{sogg} - \sum_{i=1}^{n} Y_{i\,sogg} \times \sum_{i=1}^{n} Y_{i\,sogg} \right) \right]^{\frac{1}{2}}} \tag{6}$$

it represents the degree of approximation obtained in the calculation of the regression. It should be noted that it is always:

$$r \in [-1,1] \tag{7}$$

i.e., "r" represents a positive or negative number, which indicates the correlation of the different input data with the regression line.

The standard deviation was also calculated, in order to have a figure of the dispersion of the data analyzed.

5.3. Results

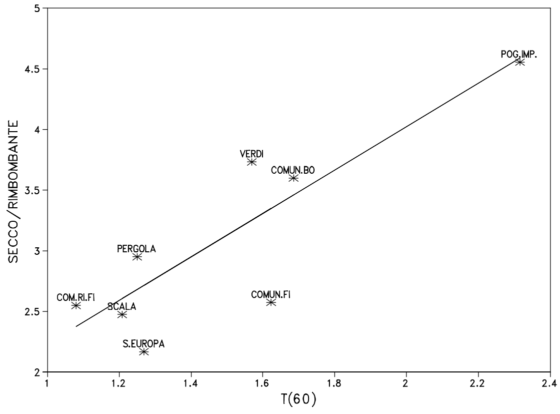
At the end of the calculation procedure, three 14x12 data matrixes were constituted, for the coefficients "A" and "B" of the linear regression line, and for the linear regression coefficients "r" respectively.

Parameters	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Question n 1	-0.10	-0.23	-0.31	0.28	0.34	0.03	-0.41	-0.37	0.33	0.31	0.15	-0.35
Question n. 2	-0.16	-0.07	-0.03	0.04	-0.05	-0.06	0.10	0.03	0.01	-0.08	-0.12	0.01
Question n 3	-0.15	-0.20	-0.25	0.35	0.22	0.03	-0.35	-0.40	0.26	0.18	0.06	-0.40
Question n 4	-0.14	-0.24	-0.30	0.17	0.32	0.02	-0.34	-0.29	0.31	0.29	0.12	-0.27
Question n 5	-0.08	-0.14	-0.20	0.34	0.20	0.00	-0.31	-0.35	0.21	0.16	0.06	-0.35
Question n 6	-0.20	-0.22	-0.20	0.22	0.18	-0.03	-0.31	-0.29	0.22	0.14	-0.02	-0.29
Question n 7	-0.30	-0.36	-0.30	0.31	0.24	-0.14	-0.40	-0.38	0.34	0.18	-0.04	-0.38
Question n 8	-0.25	-0.25	-0.20	0.17	0.14	-0.09	-0.20	-0.19	0.22	0.10	-0.07	-0.20
Question n 9	-0.11	-0.17	-0.24	0.08	0.26	0.07	-0.24	-0.22	0.25	0.25	0.13	-0.20
Question n 10	0.35	0.36	0.29	-0.34	-0.19	0.17	-0.27	0.29	-0.31	-0.12	0.11	0.31
Question n 11	0.22	0.31	0.30	-0.30	-0.28	0.12	0.34	0.27	-0.33	-0.23	0.03	0.28
Question n 12	-0.07	-0.05	-0.08	-0.06	0.06	0.07	0.02	-0.02	0.06	0.06	0.6	-0.01
Question n 13	-0.18	-0.09	-0.02	0.16	-0.04	-0.05	-0.10	-0.17	0.03	-0.08	-0.15	-0.19
Question n 14	0.26	0.33	0.27	-0.31	-0.23	0.20	0.34	0.28	-0.31	-0.18	0.10	0.30

Table 2: Linear regression coefficient "r".

A plot was made of the resulting regression line, superposed to the average values of the responses to the questionaires, subdivided for each of the 8 theatres analysed.

It should be stressed how the average value of the subjective parameters of each of the theatres does not represent a parameter of equal weight as the representation of the correlations, in so far as the number of questionnaires is very different for each theatre. The questionnaires relating to the Teatro Comunale di Bologna and to the Teatro alla Scala di Milano represent about 54% of the total number of questionaires, while the data available for the Sala Europa di Bologna and the Sala Concerti di Poggio Imperiale in Florence were only 7% of the total number (14 out of 192)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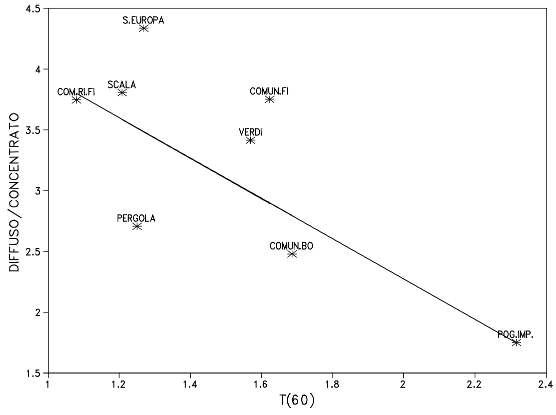
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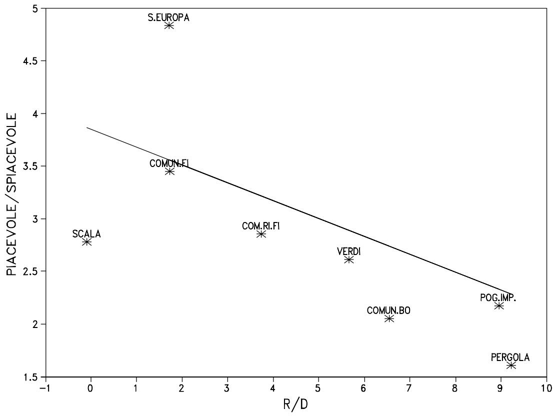
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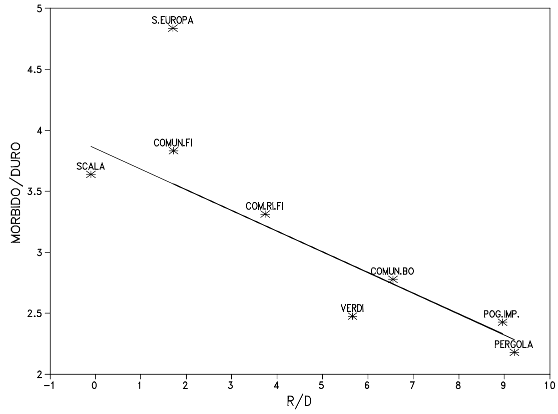
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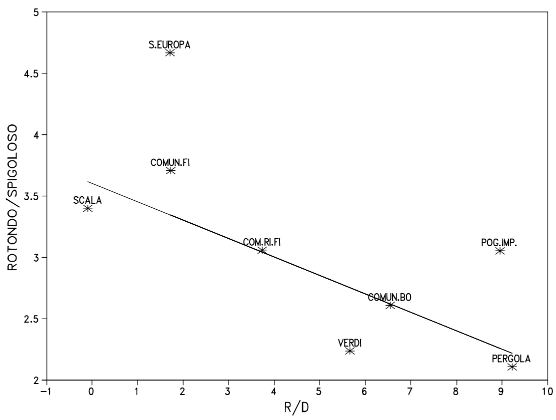
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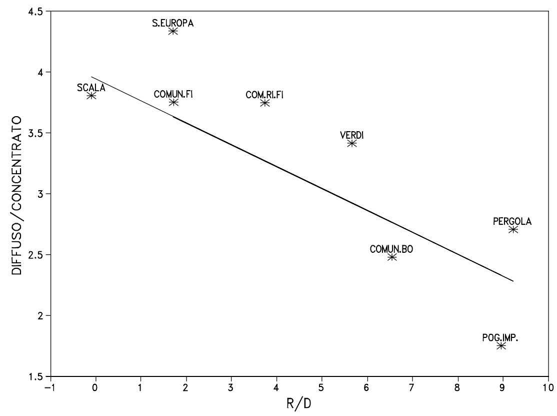
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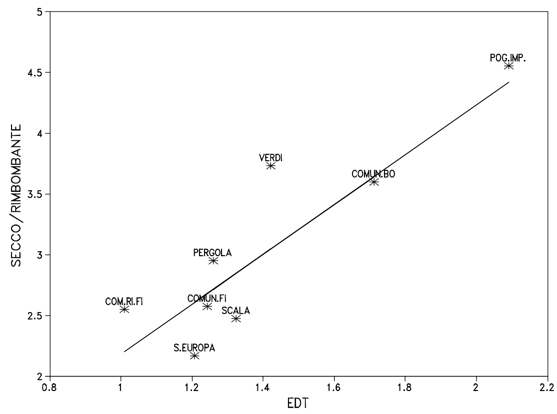
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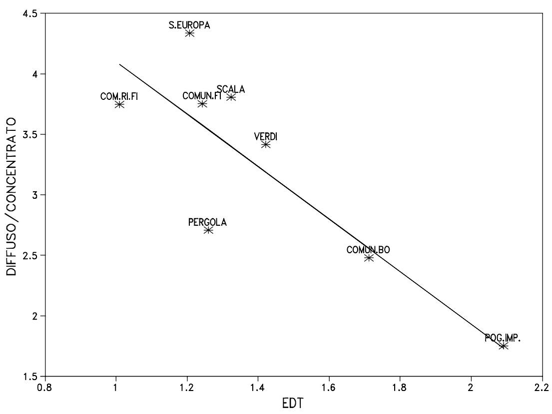
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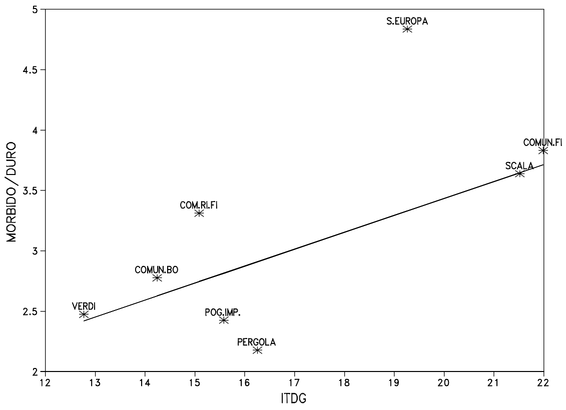
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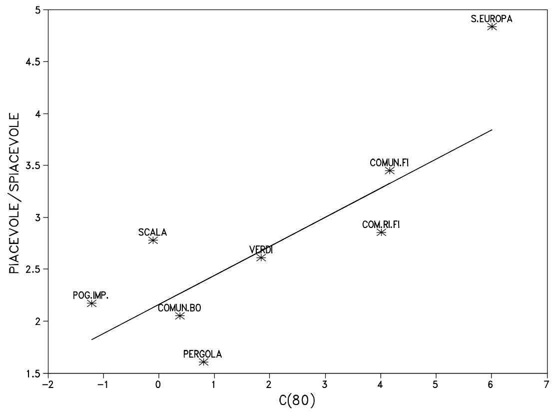
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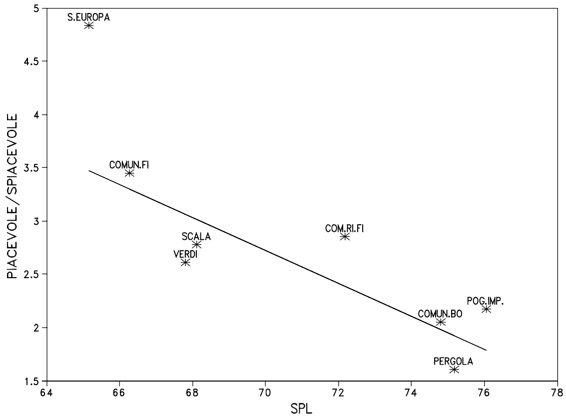
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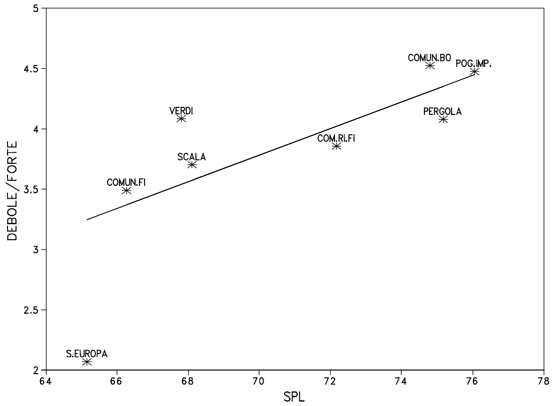
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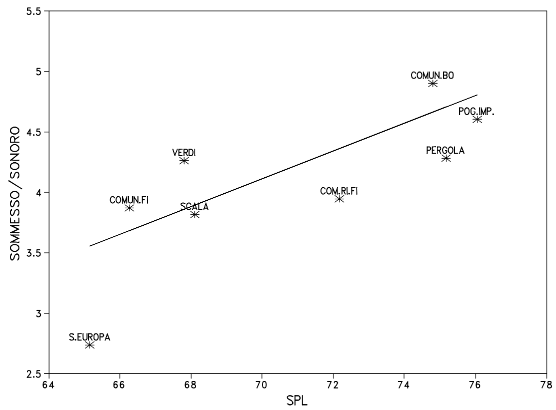
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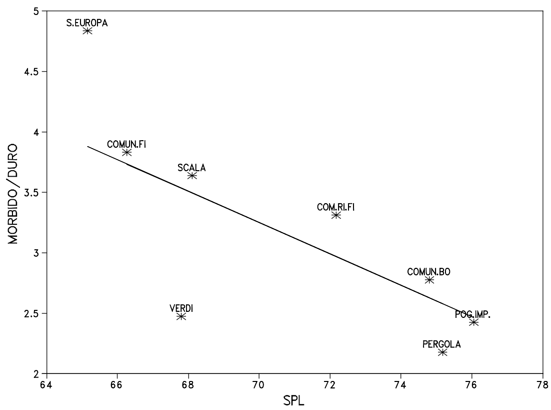
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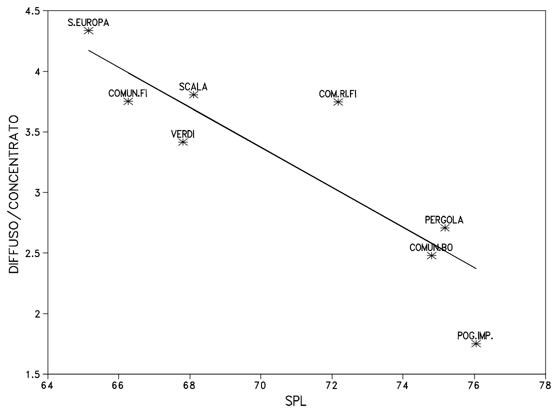
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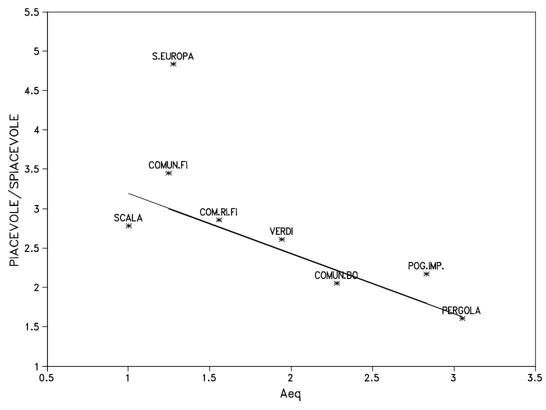
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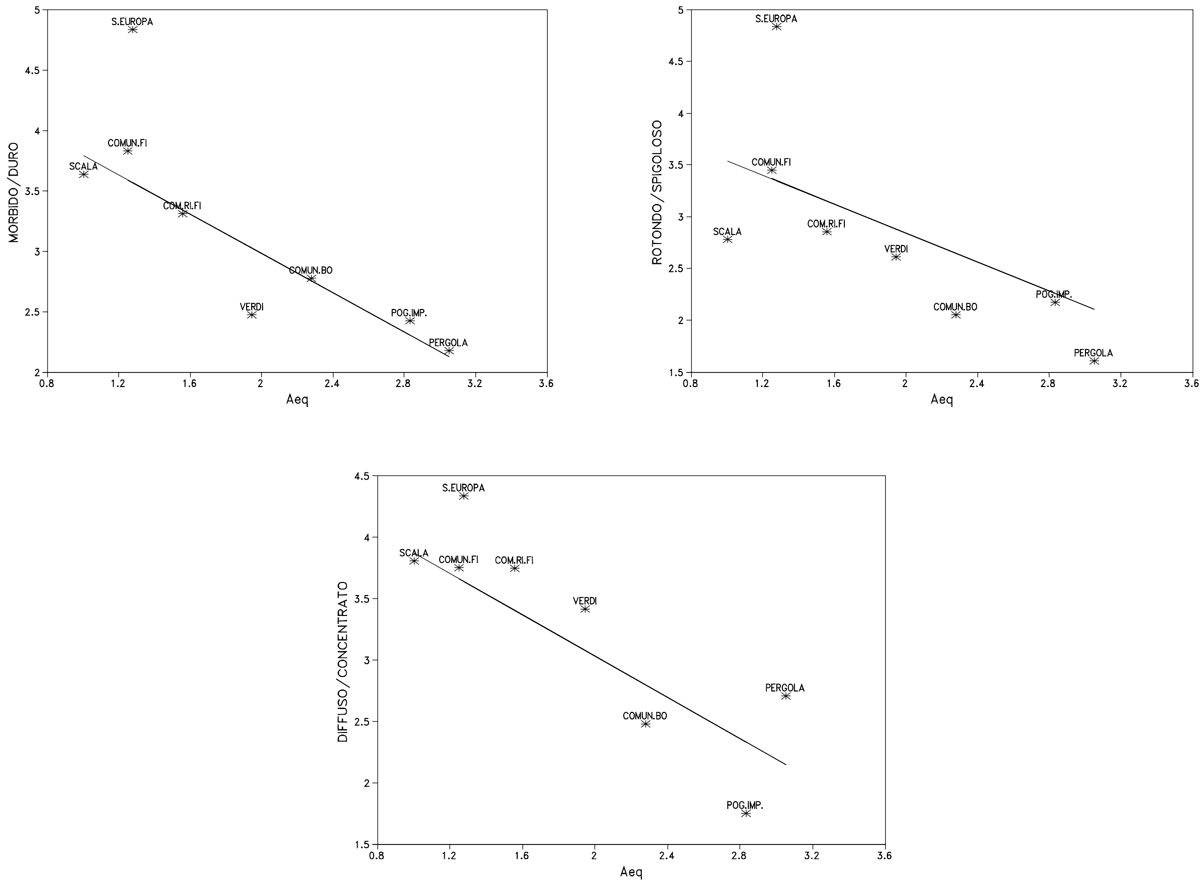

Figure 4: 19 correlation plots

5.4. <u>Discussion of Results</u>

From the result of the comparative study between the various pairs of parameters, from the calculation of the linear regression and from the calculation of the correlation coefficients, the following conclusions can be drawn:

1) some pairs of questions proposed appear to be strongly correlated; furthermore, some terms have been seen to be sufficiently correlated to specific physical describers, while others appear to be practically independent from them. This result was quite obvious, and represents a check of the basic hypotheses. If the opposite should have emerged, the whole of the questionnaires would have been considered hardly reliable. However, this result makes it possible to attribute a value to the study carried out;

2) the initial hypothesis of linear proportionality between objective parameters and subjective judgments is fundamentally acceptable, even though for the time being it has not been possible

to check the possible existence of other types of links between the various parameters. Obviously, the curve which offers the greatest correlation between the different objective parameters and the subjective preference relating to them will probably be a "Gaussian", i.e. of the type:

$$\phi(x) = \frac{1}{\sqrt{2\pi}} \exp\left[-\frac{(x-\overline{x})^2}{2\sigma^2} \right] \qquad (8)$$

in which: $\overline{x}$ = average value

σ = variance

since it is foreseeable that an optimum value of the objective parameters exist, and that it represents the maximum of the function. In the case in which the parameter represents a value different from the optimum value, the function will decrease.

In the hypothesis of rather "dispersed" data (and in fact this is one of the reasons why more than one theatre were analyzed), it is predictable that the optimum value be within the totality of the acquired data, and therefore the linear regression will not necessarily be the curve which best correlate the set of data analyzed with the subjective preference

With regard to point 1, it should be noted that:

a) pairs n.3 and n.5 are strongly correlated in a positive sense, i.e. they can be considered equivalent. The same applies to pairs n.6, n.11 and n.14. Pairs n.8 and n.10 are inversely correlated, i.e. the increase of one pair induces the decrease in the other one;

b) not all the objective parameters represent in the same way the subjective judgments of the acoustic quality of the hall. Some of them are strongly related to some particular questions, while others seem to be totally useless.

Some acoustic parameters are strongly correlated (but this was already implicit in their definition). For example, "R/D" is by definition very similar to A_{eq}, and C(50) is very similar to C(80).

The reverberation time is strongly correlated with the EDT, a practically analogous parameter, but the latter is more strongly correlated with the subjective judgments. This result too reflects what has already been checked by Jordan (1974), and can be considered a further check of the results obtained. In future writings of questionnaires, only one describer will be chosen among these parameters.

The RASTI does not seem to be related to a particular pair of subjective terms, and this result can be interpreted in relation to the type of research carried out. In fact, the attention was put particularly on musical signals and not on the comprehensibility of the spoken word, so it is correct that the quality of the perception of the musical signal should not be related to intelligibility.

The intensity of the direct wave, indicated with C(5), is weakly linked to the pairs of words in this questionnaire. Actually, this parameter is not strictly linked to the study of acoustic qualification, therefore the result is acceptable.

The greatest relation is represented by the sound level, negatively related to the pair of general qualification "pleasant-unpleasant". This leads us to suppose that the theatres analyzed are characterized by an unsatisfactory sound-level, because it is too low. However, as stated above, when the subjective parameter is "preference" the linear regression should be substituted with other correlation techniques.

The two parameters "Ts" and "ITDG" are not particularly related to the pairs analyzed, or rather, being related to most pairs, they do not seem to be related to one particular pair, in spite of a relation with the whole of the questions asked.

The IACC, on the other hand, is the most interesting case which has come out of this analysis. In fact, it is the parameter which has least relation with the questions asked.

Actually, the reason for this result is found in the formulation of the questionnaire. As has already been analyzed, the questionnaire proposed by Wilkens lacks terms which describe the spaciousness of the sound field. This intrinsic limitation of the questionnaire has lead to a result apparently in expectable.

The acoustic parameters correlated to the pairs of subjective parameters are:

1.a) E.D.T. with *Diffuse-Concentrated* and with *Dry-Reverberant*: r = -0.36, r = +0.36;

1.b) R.T. with *Diffuse-Concentrated* and with *Dry-Reverberant*: r = -0.30, r = +0.35;

2) I.T.D.G. with *Soft-Hard*: r = +0.35;

3) C(80) with *Pleasant-Unpleasant*: r = +0.34;

4) S.P.L. with *Pleasant-Unpleasant*, with *Soft-Hard*, with *Diffuse-Concentrated,* with *Weak-Strong* and with *Soft-Loud*: r = -0.41, r = -0.35, r = -0.40, r = +0.34, r = +0.34;

5.a) A_{eq} with *Pleasant-Unpleasant,* with *Soft-Hard,* with *Rounded-Pointed,* with *Diffuse-Concentrated*: r = -0.37, r = -0.40, r = -0.35, r = -0.38;

5.b) R/D with *Pleasant-Unpleasant,* with *Soft-Hard,* with *Rounded-Pointed,* with *Diffuse-Concentrated*: r = -0.35, r = -0.40, r = -0.35, r = -0.38.

At point 1 the correlation between EDT and *Dry-Reverberant* needs no explanation. The result is fairly obvious also for the other pair: to the increase in EDT corresponds an increase in the feeling of a diffuse sound field.

For point 2, the increase in ITDG provokes an increase in the hardness of the sound, as has been verified by other authors.

In situation 3, there is an obvious wish for sound field clarity, and this result is due to the specific profession of the interviewees, most of which are music interpreters and members of orchestras.

The remaining points illustrate more complex situations.

In point 4, a demand for greater loudness of the halls under study is shown. Being all these rooms too dull, it is clear how the increase in the level is a pleasant effect, how it produces a greater diffusion of the sound field, which is also more loud and strong; unexcectedly, it becomes also softer. This last effect seems to be unjustifiable; however, a linguistic bias is possible: the italian word "morbido" does not have any implication of "weakness", as the english translation "soft" has instead.

In point 5 it can be seen how the increase of the reverberant component of the sound field is strictly linked to a pleasant feeling, to a greater diffusion of loudness, and how the resulting sound appears to be soft and rounded. These results show the contemporary demand for sound clarity and diffusion.

At the end of this analysis, it was possible to write a reduced questionnaire, more suitable to statistic elaborations and easier to complete.

6. CONCLUSIONS

6.1. Proposal for a New Reduced Questionnaire

The questionnaire which will be proposed is necessary in order to carry out, following the criteria used up to this point, more specific research, based on statistics, in the field of acoustics and architecture, with the aim of making more immediate the measurement and the optimization of few physical describers, managing to foresee which will be the general preference obtained in a theatre by varying certain characteristics. The proposed questionnaire is organized using the following terms:

1	piacevole (pleasant)	spiacevole (unpleasant)
2	impastato (unclear)	definito (clear)
3	morbido (soft)	duro (hard)
4	avvolgente (diffuse, involving)	concentrato (concentrated)
5	secco (dry)	rimbombante (reverberant)
6	acuti accentuati (treble emphasized)	acuti non accentuati (treble not emph.)
7	bassi accentuati (bass emphasized)	bassi non accentuati (bass not emph.)
8	sommesso (soft)	sonoro (loud)

The first term represents a word referring to the general quality. The second is independent, so it is not possible to link it to other terms.

Pairs 3, 5 and 8 seems to be the closest to music terminology among all the correlated terms.

Words 6 and 7 represent the response in frequency of the halls being studied and, since they do not seem to be correlated, it has been decided to keep both. The lack of correlation is obviously due to the fact that frequency dependent objective parameters was included in the investigation.

Pair n.4 has been added, closer to binaural describers such as IACC, and which had been left out of Wilkens' questionnaire.

There will still be in the margin a summary of the position occupied by the interviewee, with an indication of his qualification.

6.2. Future Developments

Improvements are possible (and foreworded) in both the physical parameters measure and in the questionnaires compilation.

Some physical parameters that have shown no correlation with subjective responses shall be disergarded, while new others can be inserted. Particularly, the frequency dependence of the most correlated parameters shall be evaluated, by measurements in at least 5 octave bands.

In the case of future elaborations, it will be possible to acquire, through the use of the above-mentioned reduced questionnaire, a great number of responses on a particular theatre, for example the Teatro Comunale di Bologna, managing to map out step-by-step the calculated values of the acoustic parameters and the personal judgments of the interviewees, in order to express according to the statistical theory of factor analysis each subjective parameter as a linear combination of the others, in function of their own weight, and therefore the different subjective parameters in weighted terms (i.e., with their corresponding factor) according to the physical describers which have proved to be more important.

The procedure which can be followed can be simplified thanks to a smaller number of variables present, as a result of the reduction of the questionnaire.

It will be possible to define the existing relation between each pair of words ("dependent") and the pair of general reference ("pleasant-unpleasant"), as a linear combination between the pairs of the questionnaire and the relative weights, determined through the algorithm of the problem to the eighenvalues, calculation procedure of which is standardized (there is specific software capable of make this).

So, by carefully selecting the terms with a limited correlation coefficient (e.g. less than 0.3 or 0.4), it will be possible to express the degree of "pleasantness" through the algebraic sum of only certain terms, multiplying them by their weight factor.

By calculating the correlation coefficients between the various acoustic parameters, which have proved to be independent, and the various pairs of terms, the "degree of pleasantness" will in turn be expressed in physical-acoustic terms.

At the end of the study, it will be possible to know the real degree of favor of a hall, as soon as the values given by the specific physical describers are known.

ACKNOWLEDGEMENTS

The author wishes to thank Prof. Luciano Rocco for the support of this study; Luisa Sulsenti Fornaciari and Giovanni Farolfi for their collaboration in measurements made in Florence and Milan theatres; Massimo Garai for his collaboration during measurements in Teatro Comunale of Bologna.

Work partially supported by the Ministry for University and Scientific Research (MURST 40%).

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