SOME RESULTS ON THE OBJECTIVE CHARACTERISATION OF ROOM ACOUSTICAL QUALITY IN BOTH LABORATORY AND REAL ENVIRONMENTS

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1. INTRODUCTION

During the last few years the room acoustics group at IRCAM has studied the perceptive factors governing human perception of room acoustics (Jullien et al. 89). In a laboratory environment acoustical criteria were varied independently and subjects performed non-verbal dissimilarity judgments. A set of 11 independent factors with their corresponding objective criteria was established and their sensitivities were estimated. Using these results and an a posteriori verbal description a structured questionnaire was designed for this complementary study of the human perception of room acoustics in a natural environment. A series of measurements and listening tests was carried out in several European halls, some of which were chosen for their longstanding reputation for excellent acoustics, so as to create a reference database. The halls fall into the following categories : concert halls for symphonic repertoire (Philharmonie Berlin, Concertgebouw Amsterdam, Salle Pleyel Paris), operas (Teatro alla Scala Milan, Opéra Palais Garnier Paris, Théâtre des Champs-Elysées Paris) and small auditoria (300-500 places) for mixed use from chamber music to conferences (Auditorium du Louvre Paris, Auditorium du Musée d'Orsay Paris, Carré Magique in Lannion/Brittany). In this paper we briefly report on the set of the perceptive factors that has been found in laboratory experimentation and on some preliminary findings from the analysis of the questionnaires and the correlations with the objective measurements in the studied halls.

2. THE PERCEPTIVE FACTORS DERIVED FROM LABORATORY STUDIES

The original aim

The original aim of these studies was to check if commonly used acoustical criteria were relevant in the perceptive field. Mainly : Acoustical Level, Clarity Index, Reverberation Time, Lateral Efficiency. For that purpose, we carried out listening tests at IRCAM with artificial sound fields where the values of some acoustical criteria were carefully controlled.

The experimentation

The tests were carried out in an anechoïc chamber. The musical signal was processed to reconstruct controlled first reflections and reverberation. The whole apparatus allowed to control the time arrivals, the levels, the frequency balance and the directions for the added first reflections and reverberation.

Only the level of the direct sound was controlled. Anechoïc monophonic recordings, available at IRCAM, were diffused through a single loudspeaker, in front of the listener. Eight other loudspeakers were used to diffuse the added first reflections and the reverberation (figure 1). A simpler apparatus, using headphones, was used when the spatial parameters of the tested sound fields were kept constant.

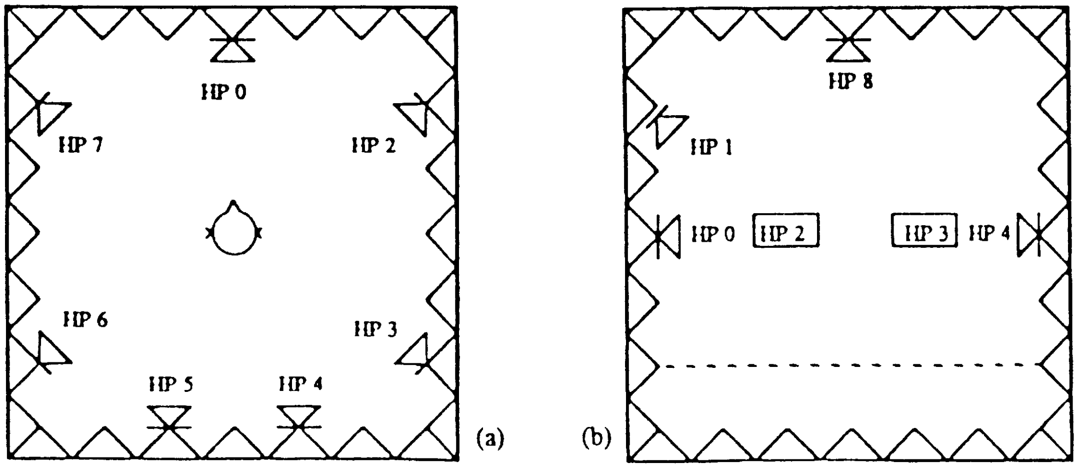


Fig. 1 Loud-speakers system set in the anechoïc chamber
a) horizontal cut   b) vertical cut

For a given test, a set of artificial sound fields (9 different configurations on average) was selected. Most often, very few acoustical criteria were varied (2 or 3) while the others were kept constant. The listeners (12 on average for each test) had to estimate a perceived dissimilarity between a pair of configurations for all the possible pairs in the set of the tested sound fields.

A total of 16 different tests were organised. Ten of them were dedicated to the study of the time distribution of the acoustical energy; four others to the spatial distribution; two to colorations due to the frequency dependance of the acoustical level and the reverberation time.

The analysis
For each test, these dissimilarity judgments were analysed by the INDSCAL procedure which provides a multidimensional scaling of the dissimilarities. The tested configurations are projected in a perceptive space where the distances among the configurations correspond to the dissimilarity judgments. The different axes of the proposed space are the perceptive factors that we have to interpret.

Some specific tools had to be developed in order to determine, for each test, the relevant number of the perceptive factors (an input parameter of INDSCAL analysis) that should be kept to explain with good accuracy the dissimilarity judgments. Then, cumulating all the axes given by INDSCAL for the 16 different tests, we obtained 52 axes that we tried to understand.

To understand a perceptive factor (id est one of the axes given by INDSCAL), we computed its correlation with objective criteria. Some of these criteria were used to select the tested configurations, some were taken from the literature, some were specially designed.
When a criterion could explain a perceptive factor, it was possible to derive a sensitivity on that criterion so that the variance on the perceptive factor could be predicted by the objective variance on the criterion.
The key point of this work was to find a minimal set of objective criteria with the following important properties :

-for one test, the different axes should be interpreted by different criteria ;
-the perceived variance of one axis should fit the predicted one by the criterion ;
-it should not be possible to eleminate one criterion without decreasing drastically the fitting for one of the INDSCAL axis.

The results
For the 9 tests dedicated to the study of the temporal distribution of the energy, INDSCAL gave a total of 31 axes. It was possible to explain all these axes by only 4 acoustical criteria (F1, rt, Rev, D2, see below). For the 4 tests dedicated to the spatial distribution (14 axes) we had to add only one criterion (the lateral efficiency) and we had to modify the definition of the former criteria to take into account the spatial distribution. For the tests dedicated to the study of the coloration, specific criteria had to be designed but each of them explains only one axis over all the tests and cannot be considered with the same confidence as the previous ones.
Most of the proposed criteria have temporal and spatial ponderations. Only some indications are given here to allow a general understanding of the criteria. For instance, Es (early sound) is very closed to the proposal of Lochner & Burger (Lochner, Burger, 1958) with a spatial ponderation (measured with a cardioïde microphone).

Factors	Criteria	Sensitivity	Proposed Name
F1	Es dB early sound	24/dB	strength
F2	rt s derived from reverberation time	170/s	reverberance
F3	Rev dB derived from late sound	21/dB	room effect
F4	D2 dB derived from the integrated decay curve	55/dB	"clarity"
F5	lef	350	lateral efficiency
F6	Lim (ms) early center time	3/ms	echo sensitivity
F7	Drf (dB) direct sound over early energy	11/dB	transparency
F8	drtHF rt slope for high frequencies	360/oct	liveness
F9	drtLF rt slope for low frequency	180/oct	intimacy
F10	dF1HF early energy slope for high frequency	60/dB/oct	brilliance
F11	dF1LF early energy slope for low frequency	60/dB/oct	warmth

In order to give an idea of the performance of the criteria and of the confidence one can have in them, we give for each of the criteria : the mean correlation with the explained axes, the number of the explained axes and the total variance explained by this criterion over all the tests.

Criterion	Correlation	Number of Axes	Total Variance
Es	0.75	13	368
rt	0.77	7	453
Rev	0.84	13	383
D2	0.69	9	98
lef	0.82	3	17
Lim	0.66	2	19
Drf	0.90	1	2
drtHF	0.89	1	34
drtLF	0.90	1	18
dE1HF	0.97	1	29
dE1LF	0.82	1	12

Discussion

One can remark that, among the criteria used to construct the artificial sound fields, only the reverberation time (and with some modifications) was retained. Neither the Total Energy nor the Clarity Index seemed to correspond to perceptive factors.

The results emphasized the importance of early energy; not only for "strength" perception but also for coloration effects. It is worthwhile stressing that the early energy depends more on the disposition of the audience around the orchestra rather than on the room characteristics.

Moreover, the preference judgments (not documented in this paper but obtained simultaneously with the dissimilarity judgments) indicate preference for a high "strength" and a very low "room effect" measured by the late energy. Might it be linked to the use of artificial sound fields? The reverberation time does not seem to have the same impact on average preference judgments and should be more dependant on individual preferences with different styles of music.

However, the first reflections between 40ms and 80ms seem to produce contradictory effects. On the one hand they increase (partially) the "strength" and also the "clarity" by accelerating the sound decay, on the other hand they decrease the "transparency" and could lead to "echo perception".

Having this set of objective criteria, we wanted to test their usefullness in real halls in order to derive a complete measurement procedure for characterizing room acoustical quality : where do we have to place the measurement sources, what directivity should we use for those sources, how is it possible to derive an objective characterisation of the orchestral balance ...

3. PROTOCOL FOR MEASUREMENTS AND LISTENING TESTS IN STUDIED HALLS

Objective acoustic measurements were taken in the halls according to a detailed measurement protocol : a grid with a spacing of four meters between parallel lines was superimposed onto the plan of the hall. Up to nine source positions and 25 receiver positions were chosen, according to the size of the hall, and the impulse response was measured for each source/receiver couple. To simulate the complex directivity of musical instruments the impulse response was measured for different source orientations (in front, behind, above and to right and left), using a directive loudspeaker. In order to take into account a spatial weighting of the reflections, an omnidirectional, a cardioid and a "figure 8" microphones were used. The seat numbers corresponding to the receiver positions were noted and a listening test organized. Two concerts with a program corresponding as far as possible to the standard use of the hall were chosen. The listeners (8 to 12) were mainly trained musicians and/or acousticians. Each listener completed one questionnaire for each piece of music and changed seats during the interval(s) (Warusfel, Jullien, 92).

4. THE QUESTIONNAIRE

The questionnaire was designed using the 11 perceptive factors (verbalised a posteriori) arising from the laboratory experiments. It was further found that excesses of colorations lead to defects. To avoid pejorative terms in the questions regarding colorations, the detection of defects was separated. Two terms ("dynamics" and "subjective dimension of the hall") frequently occuring in the literature but not issued from the laboratory tests were equally added.

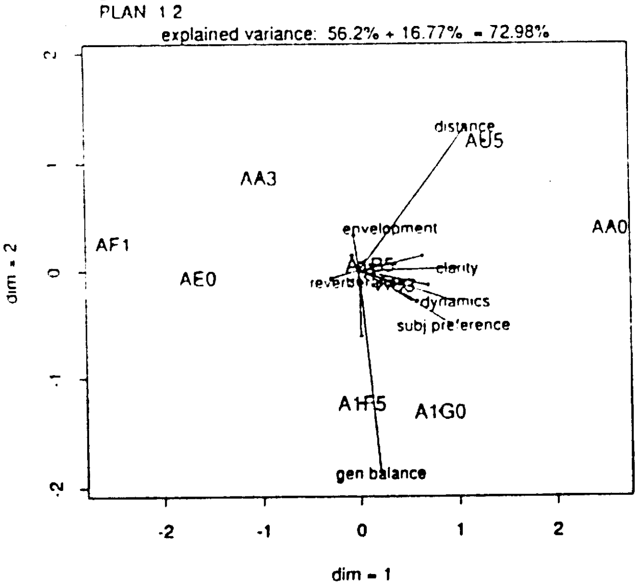
Special care was taken to treat the question of balance. In general, in the laboratory tests, monophonic or stereophonic direct sounds are used, presenting a major shortcoming when compared to a real concert situation. Therefore, several questions were asked, one about the equilibrium between soloist(s) and the orchestra, especially for operas, another about the general impression of balance, and finally the questions concerning the perception of the sources that had been asked globally were detailed for each instrumental section. The last page of the questionnaire was reserved for judgments of subjective preference. Control questions concerning the appreciation of the piece of music and the interpretation were added to check dependencies of the responses on the musical context.

5. PRELIMINARY RESULTS AND DISCUSSION

Whereas in laboratory tests each parameter can be controlled independently, in a natural environment different acoustic criteria and hence the corresponding perceptive factors are strongly correlated. To at least partially overcome this problem, halls with differing geometry and for different types of use were chosen. In the laboratory the number of tests, where each time a small number of criteria varies, can be multiplied. Furthermore, the long-term performance of auditory memory is relatively poor, so non-instantaneous changes will lead to a loss of the fine structure of human perception. Hence in-site tests will mainly reveal the principal parameters subjects used to evaluate differences in the acoustics of a room. However, detection of contradictions, detailed analyses of each hall and the analysis of the residue of the correlations should lead to clarify the dependencies among the different factors and the correlations with objective measurements.

5.1 Analysis of a single hall.
Fig. 2 shows a plan of the first two axes of a principal component analysis (PCA) of the Concertgebouw Amsterdam (the places where coded as follows : a prefix for elevation, a letter from A to G for distance and a number from 0 to 5 indicating the distance from the central axis). A PCA can be analysed in two different ways : the axes show the distances between the different objects (listening locations), the arrows are the projections of the variables into the plane, the length is determined by the covariance of the variables with the axes. The first axis (explaining more than half of the variance) differentiates the front and the rear of the main floor, the second axis the places on the balcony (indicated by the prefix 1) and the stalls, especially the place U5 in the choir seats behind the orchestra. Looking at the arrows one can easily discern the questions spanning out this plane: the subjective distance and the general impression of balance. Between these two variables lies the arrow representing subjective preference, strongly correlated for this hall with the subjective impressions of dynamics and clarity (correlations of 95% and 88%, respectively).

Fig. 2: PCA of the Concertgebouw Amsterdam



5.2 Analysis of all halls confounded
Figs 3 and 4 show the first three axes of a PCA of all halls confounded (the cloud of listening locations has been indicated by the stars, each star representing one place, for a better legibility of the graph). The plan 13 (representing the first and the third axes) resembles the plan 12 of the PCA of the Concertgebouw : the slightly opposed couple of subjective distance and general balance limiting the fan-shape of the other variables including subjective preference, dynamics and clarity. The plan 12 shows the variable

reverberation used by the listeners to distinguish the halls. One interesting point can be noted looking at the couple clarity/reverberation : the projections onto the first axis (strongly linked to the subjective preference) are pointing in the same direction, indicating that a big subjective reverberation does not exclude a good clarity, the projection onto the second axis are in opposite directions.

Fig. 3: PCA of all halls confounded

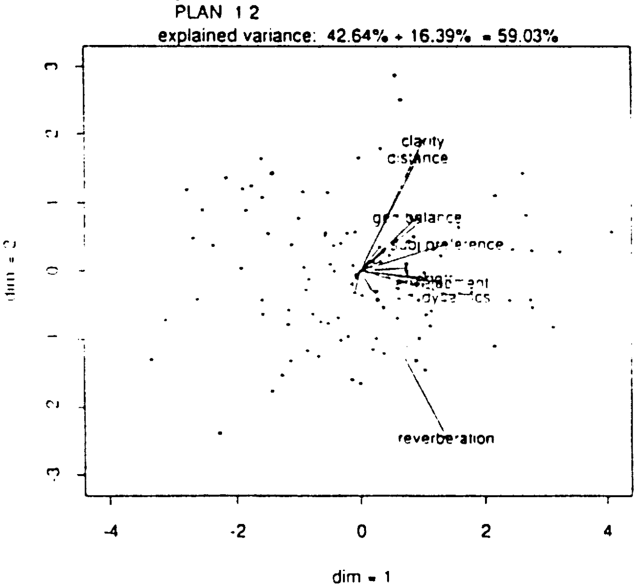
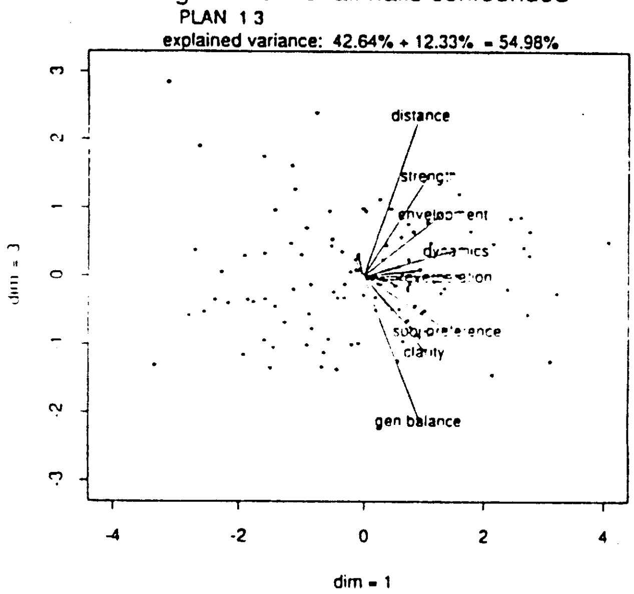


Fig. 4: PCA of all halls confounded



5.3 Correlations with objective criteria

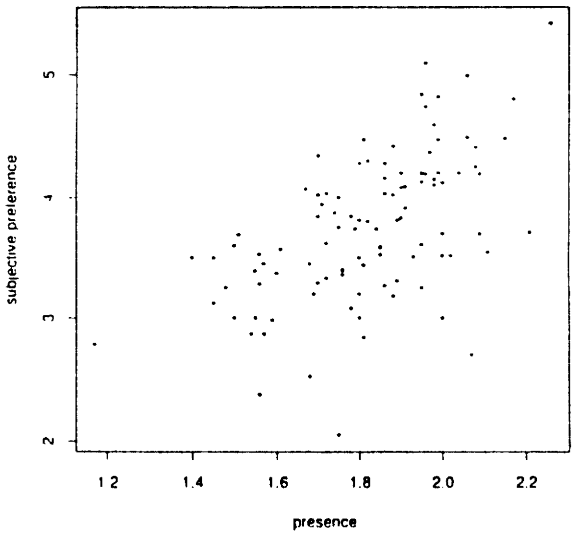
Detailed analysis for each hall has not been perfomed yet, so only partial results, derived from analysis with all halls confounded, are presented here. The subjective distance is well correlated with the arrival time of the direct sound, i.e. the geometrical distance (correlation of 70%). The subjective reverberation is best correlated with the reverberation time at mid-frequencies (average 500 Hz/1000 Hz) with a correlation coefficient of 65%. On the contrary no single objective criterion is well correlated with subjective preference or clarity. Especially, no correlation could be found between the ratio of early energy to late energy C80 and the subjective impression of clarity. A high value for the variable DirE (enlarged direct sound: integration of the energy in the time range 0-40 ms and half the energy in the time range 40-80 ms, measured using a cardioid microphone) is preferred. In general, longer reverberation times are liked.

5.4 Correlations with objective measurements: the need for a detailed measurement protocol

As an example for the difficulties in correlating objective measurements with subjective listening tests, an example of the listening test in the Philharmonie in Berlin is given. In this hall, the orchestra is on all sides surrounded by the public. This results in a smaller average distance between the public and the orchestra, but might lead to problems due to the directivities of the instruments. The subjects were listening to three different works, the concerto for piano and orchestra by Brahms, a ballet music (for big chamber orchestra) by Schubert and orchestral pieces by Berg. The judgments of the places behind the orchestra were different for the concerto for piano and orchestra. Here the strong directivity of the piano leads to a decrease of the clarity and to a deterioration of the (spatial and spectral) balance. For the perceptive factor sound strength the best correlation with objective measurements were obtained when an omnidirectional source was considered (reconstituted by adding the different orientations of the loudspeaker). For other factors like the contrast, depending on a clear perception of the attacks, correlations with the measurements with the loudspeaker at the place of the piano and in frontal direction turned out to give the best results.

5.5. Subjective preference
Plots of the subjective preference vs. variables like presence, clarity, intimacy or liveness exhibit a general characteristics : low scores of a perceptive factor prevent high rating of subjective preference whereas for high scores of a perceptive factor low scores of subjective preference do occur (Fig. 5). This behaviour corresponds to a necessary but not sufficient condition. For other factors like subjective distance and general balance, a linear model for the dependency with the subjective preference seems to fit better.

Fig. 5: Plot of presence vs. subjective preference



6. CONCLUSION

With the help of the structured questionnaire, subjects were clearly able to distinguish different listening locations. When all halls are confounded the analysis reveals a few strongly varying parameters. For these, the correspondences between perceptive factors and objective variables are very strong. However the large database will allow more detailed analyses : (a) investigating different source locations and orientations, their sum and differences, and (b) analysing independently each hall with respect to either responses to questions or objective criteria. This will help finding further links between the subjective and the objective domain.

7. REFERENCES

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