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A Factor Analysis Approach to Determining a Small Number of Parameters for Characterising Halls

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Summary
Specialist bibliographies reveal that there are many parameters for fully describing the acoustics of a hall. Are all of these parameters absolutely necessary? Although hall acoustics is a complex discipline, we can nevertheless see that many parameters measure aspects that are very similar to musical perception. Our aim in this paper is to use factor analysis to find a small number of statistically independent parameters that will enable musical performance halls to be characterised using just a few parameters. At the same time, we aim to identify other parameters that will be useful to researchers as part of a lineal combination. To achieve this, we have measured impulse responses in 17 halls and determined the most common 18 parameters. By using factor analysis, we have identified the three key factors that satisfy the required characteristics. This result confirms those obtained in an earlier study [1] of nine halls. The factors obtained strongly correlate with other classic parameters. Factor 1 correlates with reverberation time; Factor 2 correlates with the objective parameters for the impression of space; and Factor 3 correlates with parameters of strength. This last factor also correlates strongly with objective parameters for listener envelopment (LEV) [2].
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1. Introduction

Acoustic models are used when designing halls to obtain and adjust optimum values for acoustic parameters. In recent decades, researchers have made considerable efforts to obtain objective acoustic parameters (measurable) and optimum values, according to the subjective responses of listeners. However, different schools and research lines coexist and various parameters are used to measure acoustics. Therefore, we can ask: how many and which parameters are sufficient? To answer this question we need to briefly describe the various parameters that are used by highly respected researchers in the scientific community.

Since the early works of Sabine [3] that introduced reverberation time as the only design parameter, the number of parameters has been increasing. Many parameters were studied in the 1970s, but only two or three of these have been subsequently used as references by most schools. The Gottingen school [4],[5] selected as key parameters clarity, reverberation time, and the interaural cross-correlation index. Yamamoto and Suzuki [6] chose strength, clarity, and the interaural cross-correlation coefficient. Marshall and Barron [7],considered key attributes to be spatial impression, measured by the lateral energy fraction factor, as well as the interaural cross-correlation coefficient. In the following decade, Ando [8], [9] used laboratory research to develop a theory of subjective preference based on four independent parameters: listening level; delay time of the strongest reflection after the direct sound; reverberation time; and the interaural cross-correlation coefficient. Beranek, in his classic book [10], and more recent works [11],[12], [13], nominated six parameters: early decay time; strength factor; bass ratio; the time between the first direct sound and first reflection; the interaural cross-correlation coefficient; and the surface diffusivity index. This parameter is less used because of the difficulty involved in objective determination (visual inspection), while the parameter of spatial impression (the early lateral energy fraction) is currently used. Last but not least, Gade [14] used six parameters in the design of halls: reverberation time; early decay time; strength factor; clarity; the lateral energy fraction factor; and the interaural cross-correlation coefficient. Gade, in the reference quoted above, asked: *isn't one parameter enough?* If the answer is no, then we can ask: how many parameters are needed? Various researchers have analysed the parameters from a theoretical point of view [15], [16], [17], as well as using statistical analysis [11],[12], [18] and [19]. In our previ-

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Table I. a: Main typological characteristics of the halls that were studied: ID (identification of the hall): prefix C is mainly for concerts, prefix T for theatrical performances, and prefix S for conferences and multiuse.

Sala	Id	Type	Use
Auditorio de Ribarroja	C1	rectangular	theatre, opera, dance,opera and concerts
Auditorio de Benaguacil	C2	Fan shaped on two levels	Music band concerts
Auditorio de Torrent	C3	Irregular hexagonal shape, (fan shaped and inverted fan shaped)	conferences, congresses, concerts of all types, opera and dance
Palau de la música de Valencia	C4	Fan shaped central stage with upper amphitheatre, side and front boxes (shoulders)	conferences, congresses, concerts of all types, opera and dance
Sala ensayos Conservatorio	C5	rectangular	Orchestra concerts, soloist musicians, chamber orchestra and chorus
Basílica de Sant Jaume Algemesí	CH1	Rectangular absidal nave and semi-cylindrical ceiling and side corridors with square chapels and rectangular hemispheric ceilings	Religious events and organ, orchestra, chamber orchestra and chorus concerts

ous work [1], we use factor analysis as a tool to answer this question.

Factor analysis is a statistical method used to describe variability among observed variables in terms of a potentially lower number of variables called factors [20]. The observed variables are modelled as linear combinations of the potential factors, plus 'error' terms. The information gained about the interdependencies between observed variables can be later used to reduce the set of variables in a dataset. Using rotation methods, factors obtained are termed orthogonal (uncorrelated). Early works using a similar technique with physical and subjective measurements include Yamaguchi [21], and Yamamoto and Suzuki [6]. In [22], the authors made an interesting study of the statistical validity of the parameters and the use of parameters to characterise different halls. In particular, the authors showed how the hypothesis of normal distribution for parameters failed (see [23] for a recent work). From this failure, the authors question the validity of the work done to date. In our previous work [1], we had in mind this fact when we decided to make a factor analysis. We decided on the extraction of principal components method - an approach that makes no distributional assumptions [20]. This approach also fits our goal of reducing the information from many variables into a set of weighted linear combinations of those variables. In our previous study [1], nine halls of different types and sizes were studied on the assumption that they could be simply studied as enclosed three-dimensional areas, and the normally used objective parameters were studied. By means of a statistical analysis of data reduction, an orthogonal set of three factors was obtained: factors such as RT and BQI could be chosen (derived from IACCE3). However, the third factor (F3), which was a combination of G and BR, did not enable reduction to a single objective parameter and its interpretation was not very clear. As a continuance of a previous study, the aim of the current study is to confirm the results by increasing the number of halls studied and parameters measured. For this purpose, eight halls were added and the calculation was broadened to take into account other

Table I. b: Further typological characteristics of the halls: Year of opening, number of seats, number of measures (#), Volume V (m^3), reverberation time RT (s). V/seat: volume per seat. 1985*: 1500-1580 (1985) (Continuation).

Id	Year	Seats	#	V	RT (s)	V/seat
C1	1994	783	39	7830	1.79	10
C2	1960	509	31	3480	2.25	6.9
C3	1997	606	48	6430	1.87	10.6
C4	1987	1817	66	14700	2.42	8.1
C5	1880	252	12	2536	2.92	10.06
CH1	1985*	640	24	12144	5.07	19

significant parameters: ITDG, IACCl3, LFe3, and LGe4. Based on the data, a statistical analysis of data reduction was made. Firstly, Section 2 includes the halls studied and also a basic description of their acoustic features. A code is then entered to identify the main use made of the hall. The procedure and experimental devices used in the measurements are then presented, and finally, the objective parameters studied are indicated. In Section 3, the values of the objective parameters obtained for each hall studied are shown. In Section 4, the factor analysis and interpretation of the three factors obtained is presented. The study ends with the main conclusions.

2. Rooms studied, experimental device and parameters calculated

2.1. Rooms studied

This study includes different halls in the Valencia region (Spain), whose main purpose is to offer correct verbal or musical audition. A total of 17 halls, including 9 halls from the previous study and an additional 8 halls, were taken into consideration, and the additional halls were selected in accordance with the same requirements. Rooms whose type, size, age and use were not the same were chosen, based on our hypothesis that the rooms' parameters must provide all acoustical information relating thereto. Accordingly, our aim was to choose a varied selection of

Table II. a: Main typological characteristics of the halls that were studied: ID (identification of the hall): prefix C is mainly for concerts, prefix T for theatrical performances, and prefix S for conferences and multiuse (Continuation).

Sala	Id	Type	Use
Salón de Actos ETSII, UPV	S1	rectangular	conferences, congresses and soloist musician recitals
Paraninfo UPV	S2	rectangular	Conferences, congresses and soloist musician concerts; chamber orchestra and chorus
Auditorio de la Ciudad Politécnica de la Innovación, UPV	S3	Rectangular with amphitheatre on upper floor	conferences, congresses soloist musician concerts; chamber orchestra and chorus
Aula de Arte 1	S4	rectangular	Conferences, theatrical rehearsals and representations

halls and to perform a large number of measurements in all of them. A number and letter were assigned to each hall indicating the hall number and its main activity. Halls prefixed by a C are mainly used for concerts, those prefixed with T are mainly used for theatrical representations and those prefixed by S are used for conferences and are multipurpose. Their main features are listed in Table I. The volumes vary, ranging from 300 to 14700m^3. The reverberation time measured based on the response of the empty room is the average of the octaves of 500 Hz and 1 kHz and the values range from 0.7–5.1 s.). There are some halls in the group that hardly qualify as halls for symphonic performance, e.g., S4 (12 seats) and C5 and CH1, all of which have very high Gmid's. Such high values mean very loud halls, and they would usually be suitable only for small ensembles and soloists.

2.2. Procedure and experimental device

The experimental methodology was that set out by the ISO-3382 [24] and IEC 60268 [25]. The equipment was made up of a laptop PC with a professional sound card (Vxpocket v2). The two microphones used were G.R.A.S. Type 40 AK (Sensitivity at 250Hz 50 mV/ Pa, Frequency Response: 3.15 Hz-20 kHz, Upper Limit of Dynamic Range (3% Distortion): 164 dB re. 20 μPa, Lower Limit Dynamic range: 14 dB, re. 20μPa); and their corresponding supply source was GRAS 12AA and preamplifiers G.R.A.S Type 26AK (Frequency Range: 2Hz–20 kHz, Noise: A-weight :< 2.5μV). We used the multi pattern capacitor microphone AT4050/CM5 (frequency response: 20–20000 Hz, sensitivity: 15.8 mV, polar patterns: cardioids, omni directional, figure-of-eight) and the corresponding phantom supply source to determine the spatiality parameters. Finally, the binaural measures were carried out with the Head acoustic HMS III.0 (transmission range: 3 Hz-20 kHz, −3 dB/+0.1 dB; dynamic range: typ. >118 dB, max SPL 145 dB). binaural head (HEAD Acoustics).

The emission system was made up of Power amplifier M-1000 (Power output level RL = 40: 520 W + 520 W) and the dodecahedral source was Dodecahedral loundspeaker DO12 (Rated power 600 W, Sound Power > 120 dB, Frequency range: 80 Hz–6.3 kHz, directivity: nearly spherical).

We used the WinMLS program for measuring and analysis [26]. This program gives the acoustical parameters of impulse response in accordance with the ISO 3382 norm

Table II. b: Further typological characteristics of the halls: Year of opening, number of seats, number of measures (#), Volume V (m^3), reverberation time RT (s). V/seat: volume per seat. (Continuation).

Id	Year	Seats	#	V	RT	V/seat
S1	1978	142	16	434	0.68	3
S2	1978	385	24	2700	1.30	7
S3	2000	475	40	3266	1.51	6.9
S4	2000	12	6	323	1.51	27

and other recent parameters which were not included in the norm.

The impulse response of the halls was obtained by sinusoidal logarithmic sweep tests in view of the advantages this type of signal has over others. The ISO 3382 norm has been followed when working with the adequate signal/noise ratio. All measures were determined in unoccupied halls and the source was situated in the centre of the stage.

2.3. Parameters

As in the case of the previous study, all the parameters analyzed, grouped according to their fundamental subjective sensations [27], [28], [10], [29], [30] were as follows:

- Energy parameters: G, C50, C80, Ts and ITDG.
- Decay times: TR_{mid}, EDT_{mid}, BR, Br.
- Intelligibility parameters: STI, RASTI, $\%AL_{cons}$.
- Spatial parameters: $IACC_E$,$IACC_L$, LG LF_e, LFC_e.

2.3.1. Energy parameters

The Strength Factor G is a measure of the sound pressure level at a point in a hall, with an omni-directional source on stage (dodecahedral), minus the sound pressure level that would be measured at a distance of 10 m from the same sound source operating at the same power level and located in an anechoicchamber [31]. For determination of the strength of the sound at seats in a hall, the source must be calibrated. There are two methods of calibration: *Reverberation Chamber Method* and *Field Method*. In our case, we used Reverberation Chamber Method, so we can expect a difference of 1.2 dB with measures calibrated with Field Method [31]. We included in our analysis G125 and G_{mid}:

$$G_{mid} = \frac{1}{2}\left(G^{500\,\mathrm{Hz}} + G^{1\,\mathrm{kHz}}\right) \tag{1}$$

Table III. a: Main typological characteristics of the halls that were studied: ID (identification of the hall): prefix C is mainly for concerts, prefix T for theatrical performances, and prefix S for conferences and multiuse (Continuation).

Sala	Id	Type	Use
Teatro La Banda Primitiva de Lliria	T1	Fan shaped on two levels	Theatre, orchestra and music band concerts
Teatro La Unión Musical de Lliria	T2	Fan shaped on two levels	Theatre, orchestra and music band concerts
Teatro Principal de Valencia	T3	Italian theatre; horseshoe shape and boxes on different floors	Theatrical representations, orchestra and soloist concerts, opera, chorus and dance
Teatro Principal de Alicante	T4	Italian theatre; horseshoe shape and boxes on different floors	Theatrical representations, orchestra and soloist concerts, opera, chorus and dance

The averages of Clarity Factors, given by [32] were worked with:

$$C_{50} = 0.15C_{50}^{500\,\mathrm{Hz}} + 0.25C_{50}^{1\,\mathrm{kHz}} + 0.35C_{50}^{2\,\mathrm{kHz}} + 0.25C_{50}^{4\,\mathrm{kHz}}, \quad (2)$$

$$C_{80} = \frac{1}{3}\left(C_{80}^{500\,\mathrm{Hz}} + C_{80}^{1\,\mathrm{kHz}} + C_{80}^{2\,\mathrm{kHz}}\right) \quad (3)$$

The center time worked with was at 1 kHz band.

And, finally, ITDG is defined as the length of time in ms, between the arrival of the direct sound and the arrival of the first reflection [10], calculated at each measured point (without following the author's definition).

2.3.2. Decay times

Reverberation times TR30, EDT, mid values were worked with.

$$TR_{mid} = \frac{1}{2}\left(TR30^{500\,\mathrm{Hz}} + TR30^{1\,\mathrm{kHz}}\right), \quad (4)$$

$$EDT_{mid} = \frac{1}{2}\left(EDT^{500\,\mathrm{Hz}} + EDT^{1\,\mathrm{kHz}}\right). \quad (5)$$

The bass ratio (BR) and brilliance (Br) were calculated as [10]

$$BR = \frac{TR30^{125\,Hz} + TR30^{250Hz}}{TR30^{500\,Hz} + TR30^{1KHz}}, \quad (6)$$

$$Br = \frac{TR30^{2\,\mathrm{kHz}} + TR30^{4\,\mathrm{kHz}}}{TR30^{500\,\mathrm{Hz}} + TR30^{1\,\mathrm{kHz}}}. \quad (7)$$

2.3.3. Intelligibility parameters

STI and RASTI from the original versions [33] were worked with. These are based on weighted sums of modulation transfer function (MTF) values. STI is calculated as the weighted sum of modulation transfer indices MTI, one for each octave frequency band from 125 Hz through 8 kHz (where each MTI value is derived from MTF values over 14 different modulation frequencies) taking into account auditory effects according to IEC 60268-16. The RASTI is calculated as the weighted sum of MTI's over the 500 and 2000 Hz octave bands, where the MTI values are derived from MTF values over 4 and 5 different modulation frequencies respectively [33]. %Alcons, were determined by the Farrell Becker empirical formula [34]

$$\%Al_{cons} = 170.5045\mathrm{e}^{-5.419(STI)}. \quad (8)$$

Table III. b: Further typological characteristics of the halls: Year of opening, number of seats, number of measures (#), Volume V (m^3), reverberation time RT (s). V/seat: volume per seat. (Continuation).

Id	Year	Seats	#	V	RT	V/seat
T1	1951 (1992)	967	81	5314	1.35	5.5
T2	1951 (1992)	967	45	6287	1.43	7.3
T3	1832 (1991)	1224	53	6986	1.50	5.7
T4	1905–1915	1102	39	4539	1.21	4.1

2.3.4. Spatiality parameters

Following [35], early and late IACC were worked with as

$$IACC_{E3} = \frac{1}{3}\left(IACC_E^{500\,\mathrm{Hz}} + IACC_E^{1\,\mathrm{kHz}} + IACC_E^{2\,\mathrm{kHz}}\right), \quad (9)$$

$$IACC_{L3} = \frac{1}{3}\left(IACC_L^{500\,\mathrm{Hz}} + IACC_L^{1\,\mathrm{kHz}} + IACC_L^{2\,\mathrm{kHz}}\right). \quad (10)$$

The early lateral energy fraction (LF), the early lateral energy fraction cosine (LFC) and late lateral strength (LG)worked with average,

$$LF_{E3} = \frac{1}{3}\left(LF_E^{500\,\mathrm{Hz}} + LF_E^{1\,\mathrm{kHz}} + LF_E^{2\,\mathrm{kHz}}\right), \quad (11)$$

$$LF_{E4} = \frac{1}{4}\left(LF_E^{125\,\mathrm{Hz}} + LF_E^{250\,\mathrm{Hz}} + LF_E^{500\,\mathrm{Hz}} + LF_E^{1\,\mathrm{kHz}}\right), \quad (12)$$

$$LFC_{E4} = \frac{1}{4}\left(LFC_E^{125\,\mathrm{Hz}} + LFC_E^{250\,\mathrm{Hz}} + LFC_E^{500\,\mathrm{Hz}} + LFC_E^{1\,\mathrm{kHz}}\right), \quad (13)$$

$$LG_{E4} = \frac{1}{4}\left(LG_E^{125\,\mathrm{Hz}} + LG_E^{250\,\mathrm{Hz}} + LG_E^{500\,\mathrm{Hz}} + LG_E^{1\,\mathrm{kHz}}\right). \quad (14)$$

3. Results and discussion

Get the correlations between different parameters is a work that different authors have already done. The aim is to work with a small number of parameters when classifying and designing rooms. As result, different schools use

Table IV. a: Main typological characteristics of the halls that were studied: ID (identification of the hall): prefix C is mainly for concerts, prefix T for theatrical performances, and prefix S for conferences and multiuse (Continuation).

Sala	Id	Type	Use
Auditorio de Castellón	T5		Conferences, congresses, concerts of all types, opera and dance
Teatro de Paterna	T6	Rectangular with amphitheatre on upper floor	Theatrical representations, orchestra and soloist concerts, opera, chorus and dance
Teatro Serrano de Gandía	T7	Fan-shaped with amphitheatre	Theatrical representations, orchestra and soloist concerts

different sets of independent parameters. We propose a data reduction procedure by means of factor analysis. Any analysis of these features requires an appropriate number of data to have statistical value. Accordingly, numerous measurements were made in each hall, many more than those required as a minimum in accordance with the ISO 3382 (in total, combining all the measures in each room, we have 308 measurements, see Tables I–IV). The statistical analysis was performed using the program SPSS 13.0 [36]. The mean values obtained in each room and for each parameter are shown in Tables V and VI.

3.1. Factor analysis: Reduction of data

The main applications of factor analysis are the reduction in the number of variables and the detection of a structure in the relationship between variables. The factor analysis performed consisted of extracting the principal components, by analyzing the correlations matrix, for eigenvalues over one. The process was completed by rotating the factors by means of the varimax procedure. By this procedure, three factors accounting for 78 % of the variance were obtained. Table VII shows the components obtained in accordance with the parameters studied and their correlations. In the following sections we analyze the three factors obtained.

3.1.1. Factor 1: Reverberation-intelligibility-clarity objective parameters factor

This factor include the following parameters: Brilliance (Br), $IACC_{l3}$, ITDG, $\%AL_{cons}$, STI, EDTmid, C50avg, RASTI, C80avg, RT_{mid}, and $Ts1kHz$ which are reverberation, intelligibility and clarity factors (scores for both verbal and musical audition). This factor correlates with RT_{mid}.

$$F_1 = 2.09 - 1.15 RTmid, (0.94). \qquad (15)$$

Previously, the result obtained was:

$$F_1 = 3.94 - 2.57 RTmid, (0.93). \qquad (16)$$

As can be observed, there is an improvement in the correlation coefficient. This result suggests that Factor 1 is essentially the reverberation time in the hall studied. This result is confirmed by the statistical analysis of linear regression with all the parameters and the excellent correlation between Factor 1 and RT_{mid} shown in Figure 1.

Table VI. b: Further typological characteristics of the halls: Year of opening, number of seats, number of measures (#), Volume V (m^3), reverberation time RT (s). V/seat: volume per seat. (Continuation).

Id	Year	Seats	#	V	RT	V/seat
T5	2004	1200	51	14850	2.43	12.4
T6	1928 (2000)	566	25	2700	1.61	4.8
T7	1921 (2006)	604	12	5064	1.42	7.7

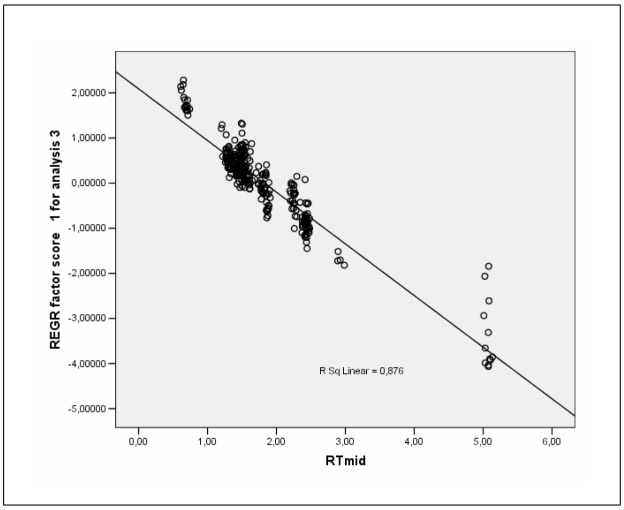

Figure 1. Linear regression between the values of Factor 1 versus RT_{mid} (r = -0.94).

Obviously, it can be shown that Factor 1 correlates with any of the parameters it includes, to a higher or lesser degree. For example, it can be observed that it correlates with $C80_{avg}$ by means of the following relation and the results shown in Figure 2.

$$F_1 = -0.63 + 0.32 C80_{avg}, (0.97). \qquad (17)$$

It should be pointed out that of the new parameters calculated in this paper that were not determined in the previous one, this factor includes ITDG and $IACC_{L3}$,although the latter has little statistical significance. This is interesting since ITDG is considered to be statistically independent by most of the scientific community [29],[10]. Accordingly, it should be noted that correlation with RT_{mid} is low, i.e. of 0.62. However, it should also be pointed out that this has been determined in all measured points (which as shown is a high number) and not a single point in accordance with

Table V. Mean values of the objective parameters.

id	Br	BR	$IACC_{E3}$	$IACC_{L3}$	$\%AL_{cons}$	RASTI	STI	Ts1kHz	$C80_{avg}$	$C50_{avg}$
C1	0.91	1.08	0.40	0.13	9	0.54	0.55	103	1.98	−0.27
C2	0.74	0.78	0.33	0.14	9	0.50	0.55	124	1.02	−1.25
C3	0.90	1.22	0.32	0.13	11	0.50	0.50	106	0.92	−0.97
C4	0.80	1.01	0.41	0.18	14	0.45	0.47	131	−0.08	−2.39
C5	0.84	0.93	0.29	0.12	18	0.36	0.41	207	−3.50	−5.17
CH1	0.71	0.96	0.35	0.10	29	0.29	0.34	362	−6.81	−7.91
S1	1.47	0.79	0.29	0.18	4	0.70	0.70	45	7.68	3.61
S2	1.06	0.85	0.33	0.17	7	0.57	0.59	81	2.75	−0.32
S3	0.88	0.76	0.28	0.19	7	0.55	0.58	87	2.18	−0.68
S4	1.10	0.68	0.33	0.14	9	0.50	0.54	112	0.44	−2.24
T1	0.84	1.32	0.38	0.17	7	0.60	0.61	61	4.46	1.71
T2	0.77	1.22	0.33	0.15	7	0.57	0.58	74	3.32	1.06
T3	0.85	1.06	0.49	0.19	6	0.60	0.62	64	3.99	2.65
T4	0.92	1.22	0.41	0.17	6	0.62	0.64	55	5.34	2.75
T5	0.90	0.86	0.39	0.11	14	0.43	0.46	157	−1.23	−3.78
T6	0.88	1.45	0.41	0.15	8	0.57	0.57	74	2.97	1.24
T7	0.87	1.57	0.48	0.15	6	0.60	0.61	63	4.36	1.68

Table VI. Mean values of the objective parameters (continuation).

id	EDT_{mid}	RT_{mid}	ITDG	G125	G_{mid}	LG_{E4}	LF_{e3}	LF_{E4}	LFC_{E4}
C1	1.62	1.79	23	6.03	9.72	−1.53	0.22	0.19	0.25
C2	1.85	2.25	29	9.40	9.13	2.14	0.21	0.18	0.25
C3	1.87	1.87	24	7.44	4.91	−0.63	0.24	0.19	0.25
C4	2.25	2.42	29	7.12	5.69	−0.56	0.27	0.21	0.25
C5	2.93	2.92	26	15.68	14.29	10.80	0.25	0.23	0.30
CH1	5.08	5.07	76	13.38	12.12	6.61	0.19	0.17	0.22
S1	0.56	0.68	14.46	9.00	10.89	−1.02	0.30	0.25	0.29
S2	1.12	1.30	12	16.10	9.78	3.11	0.33	0.28	0.34
S3	1.22	1.51	18	8.74	8.12	1.12	0.28	0.22	0.27
S4	1.48	1.51	2	−1.70	18.46	8.96	0.22	0.23	0.28
T1	1.15	1.35	22	5.07	3.81	−5.21	0.23	0.17	0.23
T2	1.35	1.43	17	7.16	4.34	−2.28	0.21	0.17	0.24
T3	1.51	1.50	9	4.16	2.44	−5.55	0.14	0.14	0.19
T4	1.16	1.21	21	5.10	3.80	−4.79	0.23	0.21	0.24
T5	2.30	2.43	23	6.92	6.30	0.05	0.26	0.21	0.26
T6	1.47	1.61	23	5.18	4.27	−2.98	0.21	0.18	0.23
T7	1.26	1.42	19	6.79	6.15	−2.63	0.18	0.14	0.20

the Beranek procedure [10]. The fact that ITDG and reverberation times are correlated, might be simply because they would both tend to increase with increasing room volume. This new result may be due to the larger range of room volumes included in the current study and which is larger than in most previous work.

For $IACC_{L3}$, Factor 1 is obviously the factor including it with most correlation, but the correlation with RT_{mid} is very low (0.46). Since its inclusion in Factor 1 seems to be statistically forced, the factor analysis was repeated obligating the algorithm to extract 5 factors. In this case, the fourth factor obtained contains exclusively $IACC_{L3}$ and the fifth factor ITDG. This fact is not a good thing, since a factor with a single parameter can result from an abnormal variation of it, as occurs with the $IACC_{L3}$ parameter that presents almost the same value for the majority of the halls, as shown by Beranek [31] and the results of Table V.

In our opinion, although these parameters are included within the reverberation-intelligibility-clarity factor, it is evident that more research is required to confirm whether they could be considered to be another orthogonal factors.

3.1.2. Factor 2: Spatiality objective parameters factor

The spatiality parameters studied appear in this factor: LF_{E4}, LFC_{E4}, LF_{e3} and $IACC_{E3}$. Its dependence is:

$$\begin{aligned} F_2 &= -1.61 + 2.25LF_{E4} + 4.96LFC_{E4} \\ &\quad + 2.80LF_{E3} - 2.05IACC_{E3}, (0.99). \end{aligned} \qquad (18)$$

In our previous study, the dependence obtained was

$$\begin{aligned} F_2 &= 0.77 - 2.92LFE4 - 6.28LFC_{E4} \\ &\quad + 3.73IACC_{E3}.(0.98) \end{aligned} \qquad (19)$$

Table VII. Grouping of the parameters studied in three factors in accordance with the reduction of variables method (factor analysis) with varimax rotation. The parameters integrated in each factor and with their correlation coefficient are marked in bold. (There is an * next to the parameters not taken into consideration in the first study).

Param	F1	F2	F3
ITDG	**-0.621**	-0.085	0.027
LFe4	0.04	**0.909**	0.175
LFCe4	0.009	**0.944**	0.144
LFe3*	0.025	**0.89**	0.141
G125*	0.006	0.035	**0.805**
Gmid	-0.139	0.022	**0.868**
LGe4*	-0.498	0.33	**0.683**
RTmid	**-0.936**	-0.132	0.108
EDTmid	**-0.916**	-0.202	0.1
C50avg	**0.896**	-0.246	-0.134
C80avg	**0.966**	-0.064	-0.08
Ts1kHz	**-0.946**	-0.012	0.228
STI	**0.96**	-0.095	0.026
RASTI	**0.961**	-0.079	-0.039
ALcons	**-0.956**	0.02	0.097
IACCe3	0.114	**-0.771**	-0.045
IACCL3*	**0.46**	-0.138	0.064
BR	0.053	-0.238	**-0.692**
Brilliance	**0.548**	0.24	0.488

It can be observed that there is a sign change, a slight improvement in the correlation and finally, the LF_{E3} not previously included, now appears in this factor.

The equation now obtained can be reduced to a simpler expression if the statistical relations between LF_{E4}, LFC_{E4} and LF_{E3} are used. We have obtained

$$LF_{E4} = 0.79 LFC_{E4} (0.98) \tag{20}$$

and

$$LF_{E3} = 1.18 LF_{E4} (0.99), \tag{21}$$

then

$$F_2 = 3.66 + 9.35 LFC_{E4} + 2.05 BQI, (0.99) \tag{22}$$

where BQI is Beranek's binaural quality index $BQI = 1 - IACC_{E3}$ [10]. According to [35] and [37] a relation between the two parameters included in Factor 2 is expected to exist, of the type

$$LFC = \frac{BQI}{k}. \tag{23}$$

As shown in Figure 3, there is a high statistical correlation between BQI and LFC_{E4}. Thus k=2.55; while in the previous study a value of 2.71 was obtained with a lower correlation (0.72),

$$LFC_{E4} = \frac{BQI}{2.55}, (0.87) \tag{24}$$

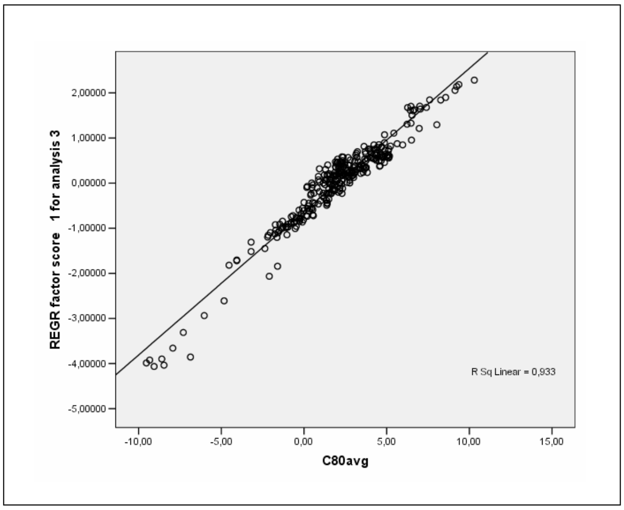

Figure 2. Linear regression between the values of Factor 1 versus $C80_{avg}$ (r = 0.96).

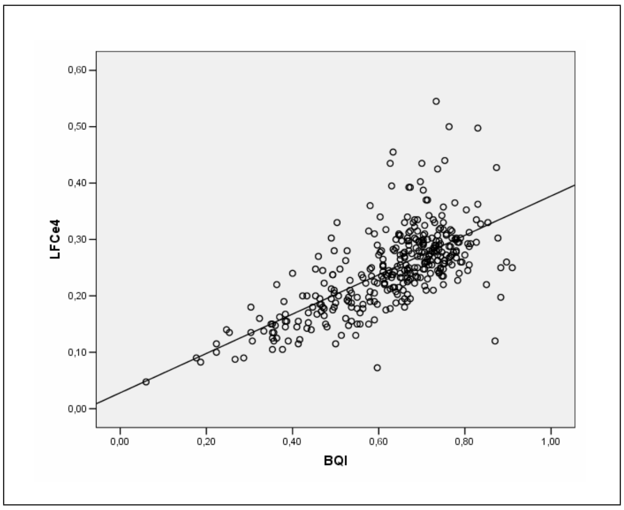

Figure 3. Linear regression between the values of BQI and LFCe4. (r = 0.88).

This result suggests that the Factor 2 obtained corresponds to a spatiality impression parameter [12]. If the correlation of Factor 2 with LFC_{E4} is studied, the result is (see Figure 4)

$$F_2 = -3.30 + 13.05 LFC_{E4} (0.94). \tag{25}$$

If expressed on the basis of BQI (see Figure 5), the result is

$$F_2 = -3.66 + 5.77 BQI (0.77). \tag{26}$$

By comparing these two results, it can be confirmed that Factor 2 is essentially LFC_{E4}.

The lower correlation found here than is usually reported, is an interesting result and ought to be investigated a little more as to why it has the lowest correlation for high values of BQI (see Figure 3).

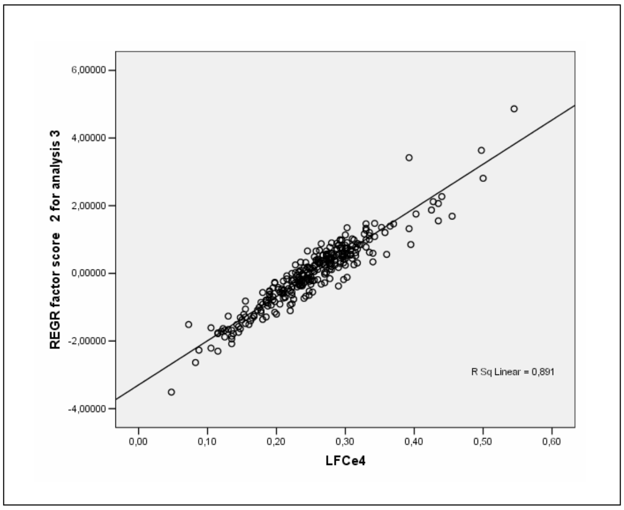

Figure 4. Linear regression between the values of Factor 2 versus LFCe4 (r = 0.95).

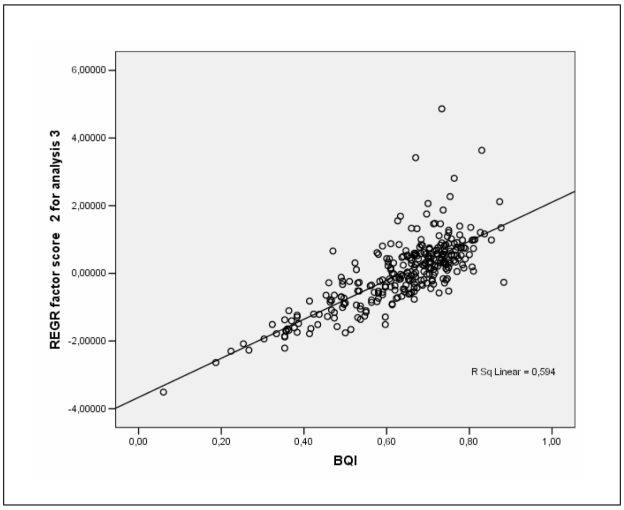

Figure 5. Linear regression between the values of Factor 2 versus BQI (r = 0.77).

3.1.3. Factor3: Strength, warmth: objective listener envelopment parameter factor

$G125$, G_{mid} , LG_{E4} and BR are involved in this factor. The first measures the strength of the hall. These parameters particularly depend on the position [37], [38],[39], [12]. Moreover, it seems that the way in which it decreases with distance is an important fact in design [40],[2]. LG, which was not included in the previous study, is related to the sensation of being surrounded by sound [41], [12], [42], [2]. BR measures the ratio of low frequency to mid-frequency decay times (warmth) and it is near constant in the halls. These parameters are references for the quality of a hall, as intuitively the listener wants a concert hall that is rich in bass [12], and has certain strength[40]. Since these parameters appear in the same factor, it can be assumed, as in the case of the other two factors, that they have something statistically in common and that they may be related to general acoustical quality in halls. The relationship between Factor 3 and these three parameters is

$$F_3 = -0.55 + 0.102G125 + 0.143G_{mid} - 0.016LG_{E4} - 1.31BR(0.98). \tag{27}$$

In the previous study, the result was

$$F_3 = 1.19 + 0.17G_{mid} - 2.21BR(0.98). \tag{28}$$

If the relation of F_3 to any of the parameters it includes is studied, the graphs shown in Figures 6, 7, 8, 9 are obtained. It can be observed that the correlation with G_{mid} and G125 are rather good. Therefore, Factor 3 could simply be reduced to these parameters. However, in the previous study it was already stated that if this reduction were to be made, significant information regarding Factor 3 would be lost. This factor, calculated with the four parameters it includes, takes positive values for halls with poor acoustical conditions; and negative values in halls with higher sound quality (scored better by listeners). This implies that for this factor, the reduction to a single parameter, as in the case of Factor 1 and Factor 2, does not appear to be adequate.

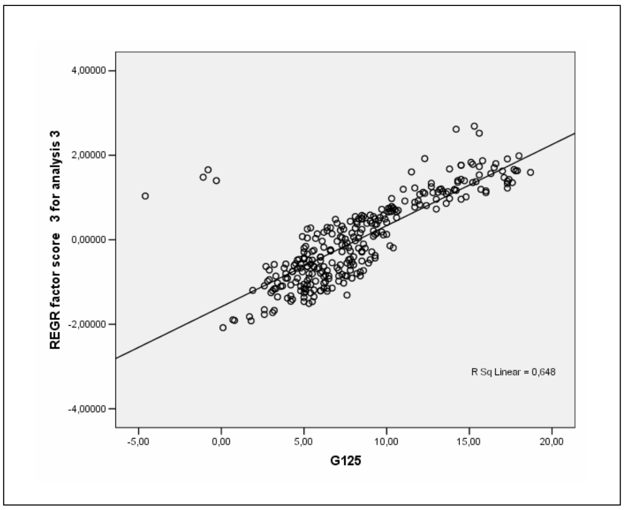

Figure 6. Linear regression between the values of Factor 3 and G125 (0.81).

The parameters added in this study, appearing in Factor 3, together with G_{mid} and BR is late lateral strength(LG), a parameter associated with the 'listener's surround sound' (LEV) [41] and G125, a parameter related to the adequacy of bass perception (strength of bass as heard in a concert hall) [39], [2], [43]. Many attempts have been made to objectively determine the listener envelopment (LEV). Based on the formulas of [2], we have found a manner to calculate the listener's surround sound using an expression correlating with the formula presented in [2] related to the perception of this surround sound. The calculation is as follows: G_{late} is calculated using the values of G and C_{80}.

$$G_{late} = G - 10\log(1 + \log^{-1} C_{80}/10) \tag{29}$$

and

$$LEV_{calc} = 0.5G_{late} + 10\log(1 - IACC_l). \tag{30}$$

Accordingly, the LEV_{calc} obtained is given in Table VIII.

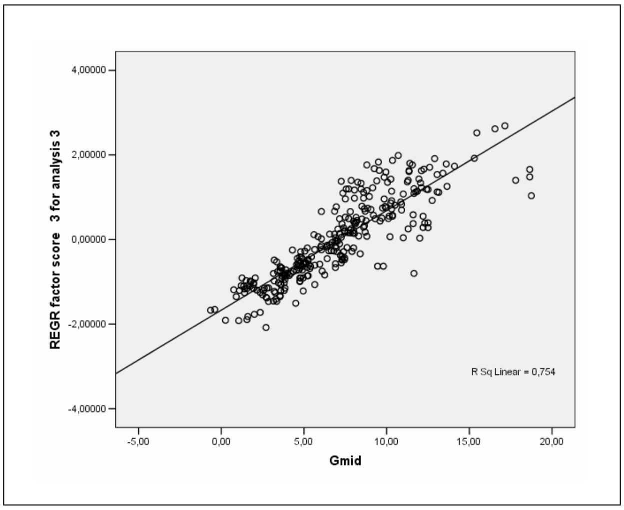

Figure 7. Linear regression between the values of Factor 3 and with Gmid (0,86).

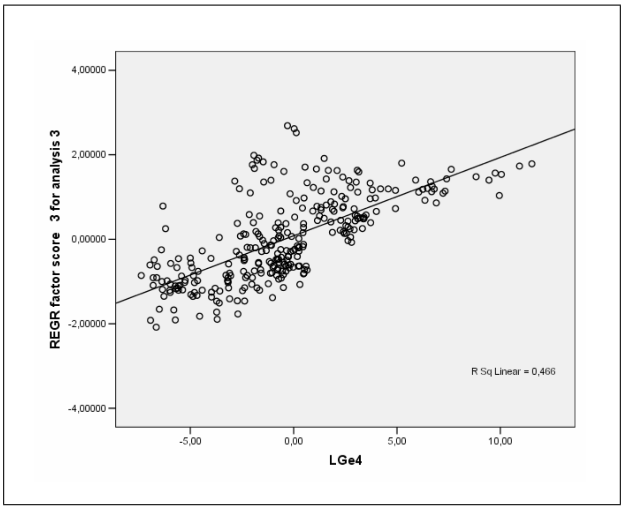

Figure 8. Linear regression between the values of Factor 3 and LGe4 (0.69).

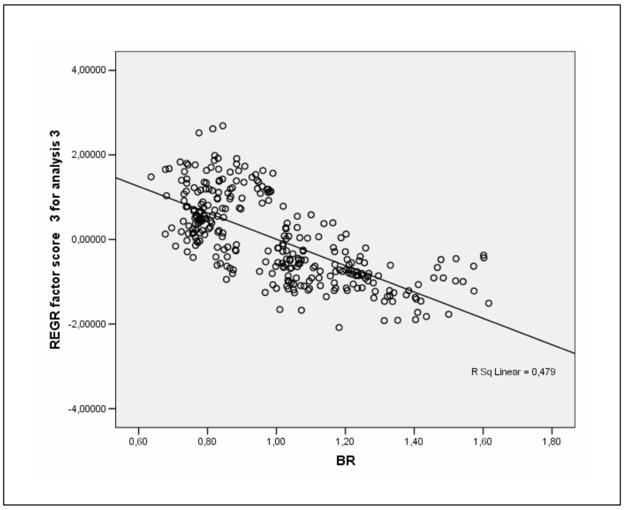

Figure 9. Linear regression between the values of Factor 3 and BR (0.69).

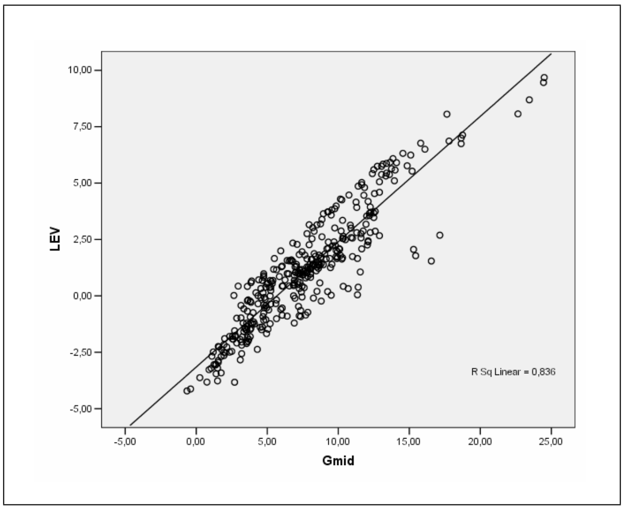

Figure 10. Correlation between LEV_{calc} (determined by the formula 30) and G_{mid}.

Table VIII. Mean LEV_{calc} scores in the halls studied.

ID	LEV_{calc}	ID	LEV_{calc}	ID	LEV_{calc}
C1	2.21	S1	0.37	T3	−2.42
C2	2.13	S2	1.80	T4	−2.11
C3	0.10	S3	1.01	T5	1.44
C4	0.47	S4	6.94	T6	−0.94
C5	5.81	T1	−1.78	T7	−0.47
CH1	5.18	T2	−1.00		

To determine a new calculation formula, we examined the correlation of LEV_{calc} with each of the parameters that appears in Factor 3. The Figures 10 and 11 show that an excellent correlation exists between LEV_{calc} and G_{mid}, LEV_{calc} and LG_{E4}. In this way, the expression obtained to determine LEV is

$$LEV_{proposed} = -1.71 + 0.358 G_{mid} + 0.241 LG_{E4} (0.95). \quad (31)$$

This correlation, as well as the functional relation obtained, can be seen in Figure 12. We consider this to be a significant result, since objectively determining LEV is currently of special interest [2]. Moreover, upon relating $LEV_{proposed}$ to the Factor 3 obtained, it is concluded that LEV is an orthogonal parameter with the parameters of intelligibility-clarity (Factor 1) and with the parameters of spatiality impression (Factor 2). In other words, according to the results obtained, the studied impulse responses are characterised by their objective reverberation, spatiality impression objective parameter, and surround sound objective parameter (listener envelopment determined from G_{mid} and LG_{E4}). This is verified by searching for the LEV correlations with all the parameters calculated, as can be observed in Table IX.

3.1.4. A comment on the results

The results from this study provide, from a statistical standpoint, answers to Gade's question: isn't one objective parameter enough? Furthermore, although the results

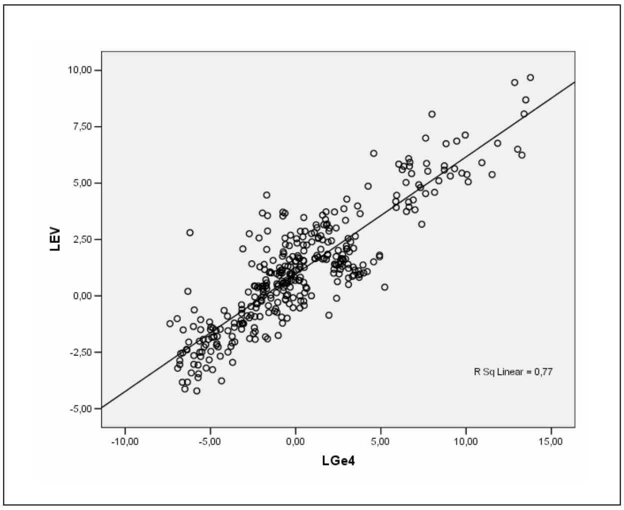

Figure 11. Correlation between LEV_{calc} (determined by the formula 30) and LG_{E4}.

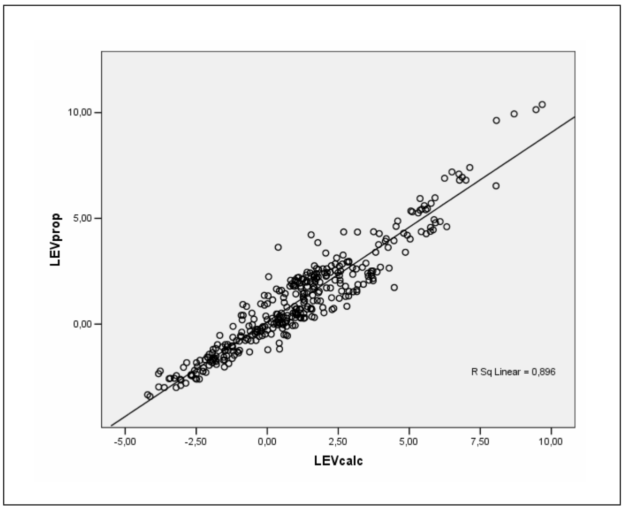

Figure 12. Correlation between LEV_{calc} (determined by the formula 30) and $LEV_{proposed}$ (determined by the formula 31).

Table IX. Coefficients of the correlation of LEV_{calc} with each of the parameters calculated.

Correlations	LEV_{calc}	Correlations	LEV_{calc}
G_{mid}	**0.91**	LF_{E3}	0.06
LG_{E4}	**0.88**	$IACC_{E3}$	−0.10
Ts1kHz	0.56	Brilliance	−0.14
EDT_{mid}	0.51	$IACC_{L3}$	−0.28
RT_{mid}	0.51	BR	−0.30
$\% AL_{cons}$	0.50	STI	−0.53
G125	0.45	RASTI	−0.56
ITDG	0.27	$C50_{avg}$	−0.57
LFC_{E4}	0.11	$C80_{avg}$	−0.58
LF_{E4}	0.09		

cannot serve as an experimental basis because chance may have intervened, they agree with the minimum number of parameters that Gade postulates [14]:

It should also be mentioned that the objective parameters related to the three subjectively different aspects: reverberance/clarity, loudness and spaciousness show low mutual correlation when measured in different seats or in different halls. In other words, they behave as orthogonal factors and do not monitor the same properties of the sound fields. Consequently, it is obviously necessary to apply one objective parameter for each of these subjective aspects.

4. Conclusions

This research, following the work method and based on the premises established in our previous study [1], that characterizing halls from their IR's, independently of the purpose for which they were designed, can be performed by means of a set of orthogonal parameters, has been corroborated through the inclusion of new halls (a total of 17) and new parameters. Based on the measures (308 points), a statistical data reduction process was performed by means of Factor Analysis. Our previous results were verified since three factors were obtained and we can explain them by a similar interpretation.

Factor 1 includes reverberation, intelligibility and clarity parameters. This factor correlates well with the RT_{mid} and the other decay time parameters and intelligibility parameters. For simplification purposes, it can be said that Factor 1 is determined by RT_{mid}. Additionally, this factor includes two new parameters that were not calculated in the previous study: ITDG, $IACC_{L3}$. These two parameters, in a similar way to Brilliance, show low correlation with RT_{mid} or Factor 1. However, of the three obtained it is with this factor with which they correlate the most. In order to determine if they alone could tie together a factor, the factor analysis was forced to obtain five factors. In this case, a fourth factor appears, which is formed exclusively by $IACC_{L3}$, as well as a fifth factor, formed by the ITDG. This means that the study needs to continue to be broadened in order to be able to affirm that these parameters alone form a factor, or otherwise, are related to RT_{mid}.

Factor 2 includes all the spatiality objective parameters studied: LF_{E4}, LFC_{E4}, LF_{E3}, $IACC_{E3}$. In this study also included is LF_{E3}, a parameter that was not calculated in the previous study. The relationships between these four parameters enable Factor 2 to be reduced to a single parameter: LFC_{E4}. Since the relationship between LFC_{E4} and BQI currently continues to be researched, this relationship was calculated and the results were as follows: $LFC_{E4} = \frac{BQI}{2.55}$ (0.87). It is important to point out that the procedure for measuring these two parameters is completely different.

Factor 3 includes G125, G_{mid}, BR and LG_{E4}, i.e. strength, warmth and lateral late strength. In this study this factor includes a new parameter LG_{E4} and this led us to seek a more complete interpretation of Factor 3 that done in previos work [1]. Following the guidelines of Beranek [2], we have obtained the LEV_{calc} and we have verified that it correlates with Factor 3. Consequently, our interpretation of this Factor is that it relates to objective listener envelopment parameter. Also, it allows for LEV to be calculated simply on the basis of two parameters (G_{mid},LG_{E4}) and, in view of this relationship, this result may serve as a guide to delve into the features involved in listener envelopment: a combination of strength and lateral late strength.

Consequently, it can be concluded that, statistically, the objective characterization of the halls is determined by their reverberation, spatiality, and sensation of envelopment objective parameters. It's very important to note what data analysis reveals is not a hierarchy of the fundamental subjective sensations in room acoustics, but, maybe, insight into the structure of impulse responses in rooms.

These three factors that this study comes down to are very sensible: RT_{mid}, LFC_{E4} (BQI) and G_{mid} (LG_{E4}). Here are some comments, all in favor of the results of this paper:

- RT_{mid} is known to be important to musicians. In design, this parameter is considered of primary importance.
- LFC_{E4} (and BQI) are important. They are determined by early lateral reflections in a hall and such reflections give "Apparent Source Width" broadening. In design, early lateral reflections are an important consideration.
- G_{mid} serves two purposes. It is directly related to envelopment: in the best halls envelopment is high. But, it is also related to loudness, and a hall must not be too loud for the kind of music played. For symphonic concert halls, the value should lie between 2 and 6 dB. In seven of the halls in Table VI, the values for G_{mid} lie between 9 and 18 dB. These large values are suitable for smaller performing groups. Again, in design, G_{mid} is an important consideration.

Acknowledgments

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