Subjective ranking of concert halls substantiated through orthogonal objective parameters

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This paper studies the global subjective assessment, obtained from mean values of the results of surveys addressed to members of the audience of live concerts in Spanish auditoriums, through the mean values of the three orthogonal objective parameters (T_{mid}, $IACC_{E3}$, and LEV), expressed in just noticeable differences (JNDs), regarding the best-valued hall. Results show that a linear combination of the relative variations of orthogonal parameters can largely explain the overall perceived quality of the sample. However, the mean values of certain orthogonal parameters are not representative, which shows that an alternative approach to the problem is necessary. Various possibilities are proposed. © *2015 Acoustical Society of America*. [http://dx.doi.org/10.1121/1.4906263]

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I. INTRODUCTION

Nowadays the scientific community clearly recognizes that the quality of room acoustics is a multidimensional concept in which many physical and perceptual factors intersect. Valuable work by Beranek[1–3] provides a wealth of data including a large number of objective parameters, subjective ratings, and relationships between the two. Similarly, Ando[4] and Barron[5,6] present studies in an attempt to disentangle the relationships between objective parameters and subjective ratings. In these authors' works, as in that of most room acoustics researchers, the attempt to understand the contribution of each objective parameter in the subjective assessment of rooms is shown. The starting point is the knowledge of the dimensions of the parameter space, both in terms of objective and subjective space. This knowledge specifies which parameters are orthogonal (without statistical correlation), since the other parameters of the room could be obtained from the linear combination of said orthogonal parameters; it is even possible to obtain an overall rating of a room thereof, which in turn enables a ranking to be carried out. The knowledge gained on objective parameters that measure the quality of a room, and the values required so that the enclosure has adequate acoustics have been reflected for the last 50 years in the ISO 3382-1 (Ref. 7) standard. This standard includes all information concerning the objective acoustic parameters and their correspondence with subjective perceptions, as well as other recommendations on the values, or ranges of values, of the acoustic parameters of a room suitable for musical audition.[8]

Despite the existence of such a standard, there are still investigations to elucidate more thoroughly the keys of human response in relation to the acoustics of an enclosed space. Many pending issues still remain both from the point of view of the listener and performers,[9–11] which sometimes highlight the inadequacy of the standard in the characterization of the details received from the acoustics of the room, and even more in the comparisons with other reference rooms. Studies on the subjective assessment of halls have approached this problem by searching for perceptual factors. The greatest number of these factors were found by the Institut de Recherche et Coordination Acoustique/Musique (IRCAM) in its laboratory studies,[12,13] whereby 11 perceptual factors were established. More recently, studies by Lokki *et al.*[14,15] and Kuusinen *et al.*[16] are worthy of note, in which a virtual orchestra and recordings with this orchestra in different auditoriums are used to assess the acoustic quality of the halls. These laboratory studies using virtual methods are not exempt from criticism.[5,9] Generally these criticisms are directed at the need to confirm the results in real rooms and real concerts. Thus, for example, the factors obtained by the IRCAM were applied to listening tests and measurement parameters in concert halls and opera houses and the number of perceptual factors was reduced to eight (Kahle[17]).

The authors of this paper have been working for 10 years on the objective and subjective evaluation of concert halls, measuring acoustic parameters in theaters and auditoriums in accordance with the ISO standards, while not only substantially increasing the number of measurement points in order to achieve orthogonal parameters through statistical reduction,[18,19] but also, in parallel, collecting subjective responses from listeners during actual concerts through demonstrated and validated questionnaires.[20] This collection of data analyzed by statistics procedures has enabled models to be obtained for the relationships between objective parameters and subjective responses.[21,22] As a result of these investigations, various models have been attained of the subjective assessment of sound quality of the rooms using a reduced number of objective parameters. These models have been

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tested through their application to different contexts, such as concert halls, auditoriums, and theaters, and are similar to those obtained by Skálevik,[23] who manages to explain, with a limited number of objective parameters, much of the variance of the subjective assessment of the rooms, although these latter results seem to contrast with the fact of the multidimensionality of room acoustics. One interpretation of this apparent contradiction could be that the global perceptual assessment of halls, when comparing their acoustics, is performed considering a reduced number of factors, while their fine assessment, the *taste* of the hall (in terms of Lokki's allegory[24]), is carried out in a more complex way, since it takes multiple sensory attributes into account.

In this paper, an analysis is performed on the interest in using the average values of the orthogonal objective parameters [reverberation time, T_{mid}; early interaural cross-correlation coefficient, $\mathrm{IACC}_{\mathrm{E3}}$; and listener envelopment, LEV, which is defined[19,21] as $\mathrm{LEV} = 0.5G_{\mathrm{late}} + 10\log(1 - \mathrm{IACC}_{\mathrm{L3}})$] in the halls under study in order to explain the subjective ranking of the rooms.

II. DESCRIPTION OF DATA

Measurement campaigns were carried out in two regions of Spain, one in an eastern community, Valencia, and the other in the south, Andalusia. The methodology used in the surveys was also the same: A largely unchanged group of experts for each region, consisting of music lovers, final-year students from the music conservatory, and music teachers, was placed in locations chosen in advance so that all parts of the seating area would be covered; the experts exchanged seats during the intermissions, and these seats coincided with the positions of the microphones for the objective acoustic measurements. Written questionnaires, specially designed and verified for this purpose, were completed during or immediately after hearing a live concert of symphonic music in the official program of the concert hall. For concert-goers, the questionnaires, headed with an explanation of the aim of the research, were distributed at the entrance of the concert, and were collected at the exit.[20] The study was carried out in 16 theaters and auditoriums, from the 2 aforementioned Spanish autonomous communities: 8 halls in Valencia and 8 halls in Andalusia. These halls are related in alphabetical order, according to the acronyms assigned to their Spanish names: Auditorio de Benaguacil (AB), Auditorio Manuel de Falla (AMF), Auditorio del Palacio de Congresos de Castellón (APC), Auditorio de Ribarroja (AR), L'Auditori de Torrent (AT), Gran Teatro de Córdoba (GTC), Gran Teatro Falla (GTF), Gran Teatro de Huelva (GTH), Palau de La Música (PAM), Paraninfo de la Universidad Politécnica de Valencia (PPV), Teatro Lope de Vega (TLV), Teatro de la Maestranza (TM), Teatro Miguel de Cervantes (TMC), Teatro Principal (TP), Teatro Unión Musical (TUM), and Teatro Villamarta (TV).

In each hall, orthogonal objective parameters of acoustic quality descriptors (T_{mid}, $\mathrm{IACC}_{\mathrm{E3}}$, and LEV)[19] and other correlated acoustic parameters are determined and are spectrally averaged at each reception point; for the octave bands involved in the spectral averages, see Appendix A of the work by Giménez *et al.*[22] The spatial averaging is achieved over the spectrally averaged values for each receiver position, and all measurements are accomplished in the unoccupied room.[22] Table I shows the orthogonal parameter mean value for each room, and compares the variability of the results of these parameters in the halls, in terms of their respective just noticeable differences (JNDs) (relative 5% for T_{mid}, 0.075 for $\mathrm{IACC}_{\mathrm{E3}}$ according to the ISO standard,[7] and 1 dB for LEV parameter), with respect to the best subjectively valued room (TM) by means of question C21 of the questionnaire. These variations are calculated as

$$[\mathrm{par}] = (\mathrm{par} - \mathrm{par}_{\mathrm{best\,hall}})/\mathrm{JND}. \quad (1)$$

Question C21 of the questionnaire asked the listener: *How do you classify the acoustics of this hall overall*?, with the rating scale from 0 to 5 points.[20] The number of subjects who completed question C21 in each hall is shown in the last row of Table I. The SPSS v19.0 software[25] is used for this study.

III. SUBJECTIVE ASSESSMENT EXPLAINED BY ORTHOGONAL PARAMETERS: RESULTS AND DISCUSSION

In the work by Giménez *et al.*,[22] the agglomerate hierarchical technique and multi-dimensional scaling (MDS) analysis are performed in order to relate subjective valuations and objective parameters. These statistical procedures have provided similar results to those attained by Lokki *et al.*[14,15] under different methodological conditions (virtual orchestra, a group of assessors, attributes elicited by the experts, and assessment under laboratory conditions). By carrying out the MDS analysis on the set of subjective responses and objective parameters, it has been confirmed that, in general, objective parameters are

TABLE I. Average values of the three orthogonal acoustic parameters, mean score of question C21 of the questionnaire, normalized values of the acoustic parameters, and number of completed questionnaires for each room listed in decreasing order from question C21.

	TM	AMF	TUM	AT	PAM	GTH	TV	GTF	AB	TLV	TP	TMC	AR	APC	PPV	GTC
T_{mid} (s)	2.51	2.33	1.43	1.87	2.42	1.41	1.70	1.86	2.25	1.44	1.21	1.14	1.79	2.43	1.30	1.19
$\mathrm{IACC}_{\mathrm{E3}}$	0.47	0.39	0.33	0.32	0.41	0.35	0.39	0.45	0.33	0.44	0.41	0.46	0.40	0.39	0.33	0.44
LEV (dB)	−0.81	1.25	−1.00	0.10	0.47	−1.20	0.57	−0.30	2.13	−1.66	−2.11	−0.59	2.21	1.44	1.80	−1.76
C21	4.31	4.20	4.17	4.12	4.11	4.09	3.98	3.95	3.87	3.79	3.78	3.60	3.59	3.46	3.32	3.05
$[T_{\mathrm{mid}}]$	0.0	−1.4	−8.6	−5.1	−0.7	−8.8	−6.5	−5.2	−2.1	−8.5	−10.4	−10.9	−5.7	−0.6	−9.6	−10.5
$[\mathrm{IACC}_{\mathrm{E3}}]$	0.0	−1.1	−1.9	−2.0	−0.8	−1.6	−1.1	−0.3	−1.9	−0.4	−0.8	−0.1	−0.9	−1.1	−1.9	−0.4
[LEV]	0.0	2.1	−0.2	0.9	1.3	−0.4	1.4	0.5	2.9	−0.9	−1.3	0.2	3.0	2.3	2.6	−1.0
Subjects	89	79	23	57	31	35	61	71	140	84	87	95	112	101	118	43

not aligned with the subjective clusters of characteristics found.

In addition, since the overall assessment of halls (question C21) failed to present any good correlation with any specific acoustic parameter, a different methodology has been applied twice in order to obtain combinations of the three aforesaid orthogonal objective parameters that correlate with question C21. In Cerdá *et al.*,[21] Ando's theory of subjective preference in Beranek's version was used as reference, while in Giménez *et al.*,[22] a formula that linked the overall evaluation of the halls (C21) with the three orthogonal parameters was sought.

The existence of correlations between subjective ratings and objective parameters is interpreted by Kuusinen *et al.*[16] as a result of the greater variation of the objective parameters in the concert halls. That is, it is reasonable to assume that the ranges of these objective parameters are reflected in subjective evaluations. The variations for this sample of rooms are presented in Fig. 1, centered on zero mean and scaled by their respective JNDs. For the definitions, the octave bands involved in the spectral averages, and the JND of each parameter, see the work by Beranek,[2] the ISO standard,[7] and Appendix A of the work by Giménez *et al.*[22]

According to this criterion, the parameters with greater variability in a room are those which should be considered for a detailed analysis in the study, however in the study of correlations between objective parameters, the authors have shown that the variability of several parameters is also collected in the variability of others with which they are strongly correlated. In Fig. 1, which depicts the variability of the objective parameters, these have been grouped in accordance with the correlations observed between them, where the first parameter of the series is representative of the group with which it correlates.[19] In this way, parameters that correlate with T_{mid} are shown first. The second series is represented by IACC_{E3}, while the last series whose parameters correlate with each other is represented by the LEV parameter. As can be clearly seen, there are a number of parameters that have large variations in this case. Originally, factor analysis was used to reduce the parameters statistically. Orthogonality was obtained by applying a rotation varimax.[19] On the other hand, in the latest work,[22] statistical analysis MDS was performed and orthogonality is implicit in the fact that the parameters appear separately in different quadrants. Both statistical analysis techniques lead to the conclusion that the explanation of the variance of subjective responses can be performed with the triple objective parameters:[22] T_{mid}, IACC_{E3}, and LEV.

In the work by Giménez *et al.*,[22] multilinear regression analysis was used to obtain an expression that related the overall score of the room with these three parameters. This time, justification is sought for the fact that the subjective assessment of the rooms can be largely explained by the variance analysis of orthogonal parameters between studied rooms. To this end, the parameters of the best-appreciated hall, as indicated by question C21 of the surveys (TM), are used as a reference. The variation of the objective parameters is then measured as the difference from the value of the parameter of the best-assessed hall in terms of JNDs [see Eq. (1) and Table I]. These variations are presented in a polar diagram [Fig. 2(a)], in which values in descending order for question C21, taking the best-assessed room as the origin, are included.

As can be clearly seen, the parameters vary in different ways, but they do not follow the same trend as that of question C21. The proposed procedure is to combine the three parameters to obtain their weighted sum, which presents a similar variation to that shown for question C21. To this end, the optimization problem consists of lessening the difference between the values of the responses to question C21 and the combination of relative variations of orthogonal objective parameters, carried out by using the generalized reduced gradient algorithm.[26] The combination obtained is expressed as

$$\text{Normalized sum} = 4.3 + 0.08[T_{\mathrm{mid}}] - 0.19[\mathrm{IACC}_{E3}] - 0.18[\mathrm{LEV}]. \quad (2)$$

Figure 2(b) illustrates how this normalized sum, calculated in this way, is adjusted with very good accuracy to the average response to the C21 question. The accuracy is determined by the optimized value of the sum defining the optimization problem. The value obtained is 0.99 as the total sum of the differences. This represents a relative error of 2% in the hall with the largest discrepancy.

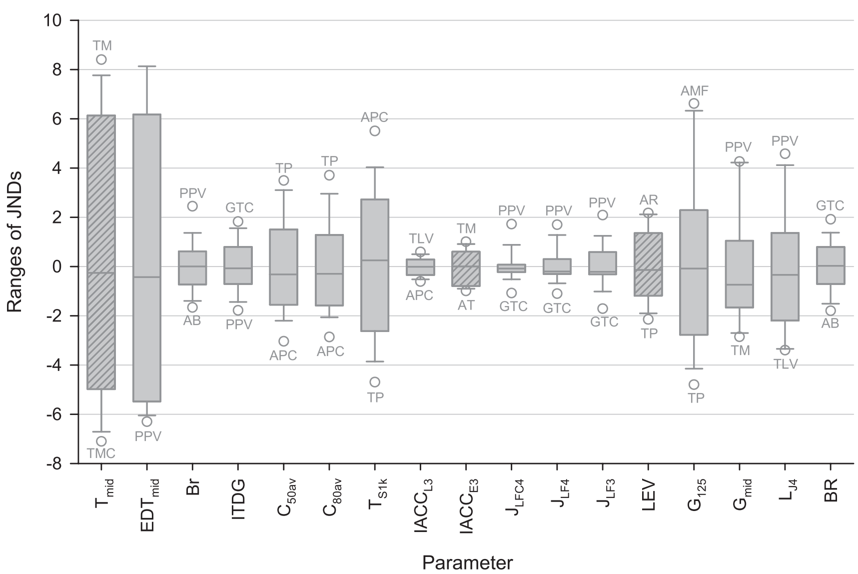

FIG. 1. The ranges of JNDs of objective acoustic parameters in the halls. Striped boxes correspond to the variation of the considered orthogonal parameters and arrangement is performed by placing behind each orthogonal parameter those with which it is associated. Dots represent those halls, identified by their acronyms, which lie outside the range.

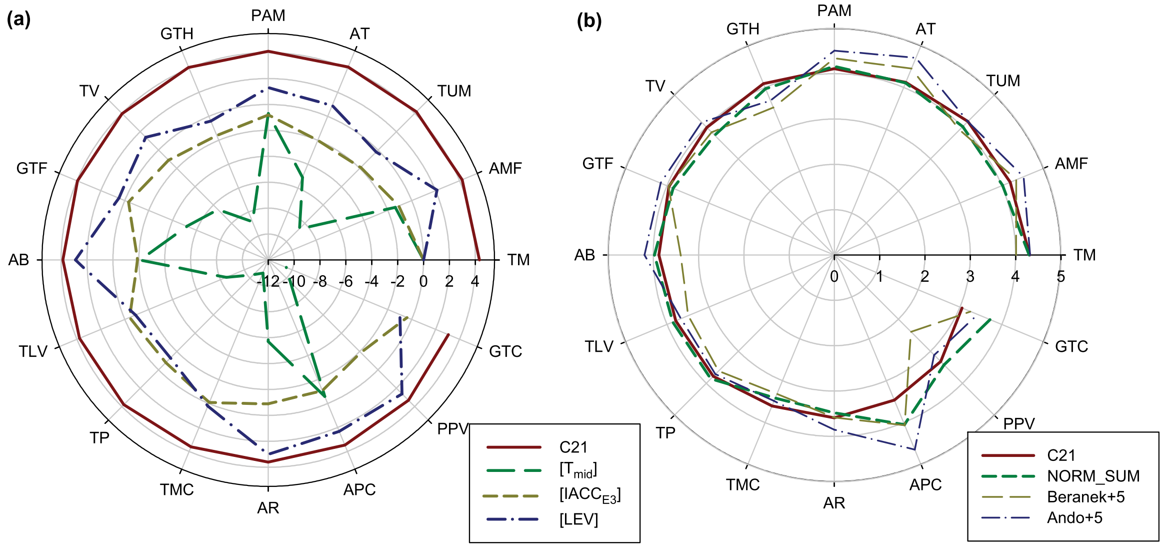

FIG. 2. (Color online) (a) Polar representation of the variations of the orthogonal acoustic parameters in terms of JND in relation to the best-assessed hall by means of question C21 from the questionnaire, which is also depicted. (b) Weighted sum for adjustment to the response to question C21, and values from Beranek's and Ando's models, normalized in the pleasantness scale of question C21.

Although there are results from renowned authors which show that, when evaluating the quality of the acoustics of a hall for classical music, two different types of evaluations exist,[15] this work is focused on the point of view of the averaged parameters. In order to obtain the explanation of the subjective response, the classic examples from Ando[6] and Beranek[2] are followed, especially the contributions of the latter author and his presentation of Ando's subjective preference model. These models have 0 as reference of quality, and provide negative results when the parameters are far from optimal values. Therefore, factors from these models have been normalized to the pleasantness scale of C21 (optimal value 5). The model presented here corresponds to a much simpler expression (linear) that provides very similar results to those obtained with Ando's preference model and with Beranek's version, as can be seen in Fig. 2(b). On adjusting C21 data and NORM_SUM by linear regression, the correlation coefficient is $r = 0.723$, whereas adjusting with Beranek + 5, the correlation coefficient becomes $r = 0.681$, and with Ando + 5, $r = 0.625$. All correlations have a p-value $= 0.01$. As shown, the combination of the variations of the orthogonal parameters provides a roughly similar arrangement. This procedure is intended to demonstrate that the use of average values of orthogonal parameters allows a good modeling of the average of the subjective responses of concertgoers.

However, the plotted graph above shows certain discrepancies that cannot be prevented with the combinations of parameters. These discrepancies have prompted the study of the representativeness of the mean values of objective parameters in each room. In Fig. 3, the percentage is shown of receptors measured in each hall that deviate from the mean value of the parameter by relatively different units of the corresponding JND. In the case of T_{mid}, it can be seen that, with scarce exceptions, there are no spatial deviations higher than one JND in the entire room. Something very different happens to the other two orthogonal parameters, IACC_{E3} and LEV. In both cases it is usual to find that variations of the parameter in the room are higher than the value which is considered as perceptually noticeable. Consequently, the average of these parameters cannot be considered representative of the room in many cases of this study sample. The two results presented here show that, although it is justified that many of the existing pieces of work on room acoustics using averages of the objective parameters have produced good scientific results, each room has its own intrinsic variation of its parameters.

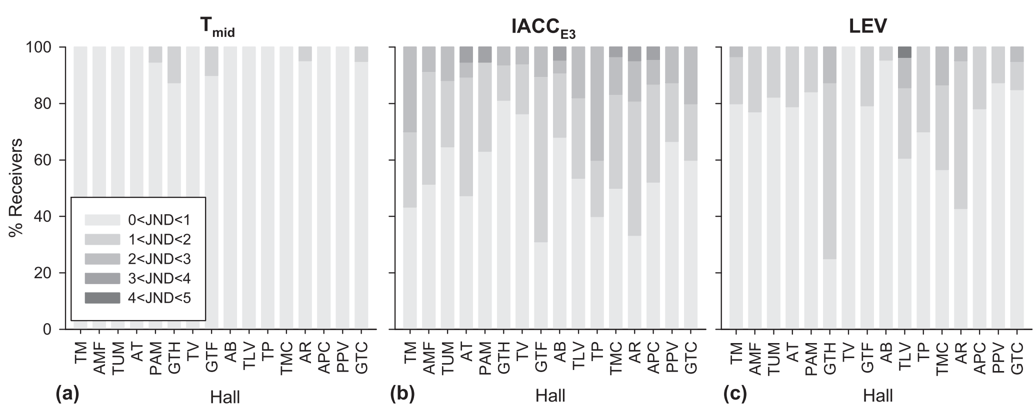

FIG. 3. Percentage of receivers that deviate from the mean value at the different intervals of JND in each hall, (a) for T_{mid}, (b) for IACC_{E3}, and (c) for LEV parameters.

The study of these variations and the establishment of laws that govern them may be the necessary approach in order to more profoundly understand the subjective response of concertgoers. One approach along these lines is that which Barron[4,5] has been carrying out in recent years to establish a curve of variation of the G parameter with the source-receiver distance as a quality element (Temporal Energy Analysis). According to the results of this work on reduction and orthogonality of the objective parameters, these studies should be carried out on the assessment of $IACC_{E3}$ and LEV: Parameters which show a significant variability in the rooms.

In addition, experimental results indicate two alternative strategies to tackle future research: The pursuit of orthogonal parameters with no spatial variations in a room; or performing statistical analyses that take into account the listening position in the room and the values of the objective parameters at that point.

IV. CONCLUSIONS

The use of ISO (Ref. 7) standards for the diagnosis and design of concert halls enables the determination of whether the room complies with the basic criteria for sound quality. The authors have worked in recent years on determining a model, from the choice of a small number of orthogonal parameters and an appropriate combination of these, to obtain an overall objective assessment of the enclosure which has a high correlation with the subjective global assessment of the room given by the listeners.[20–22]

Following this principle, a linear combination was inferred from the mean values of the orthogonal parameters that correlate strongly with the subjective global assessment of the room. In this paper, the authors show that if the average values of the objective parameters are normalized relative to the value corresponding to the best reference room in the subjective ranking of the sample, then these variations can explain the subjective ranking of the rooms from a linear combination thereof (these results are similar to the preference theory by Ando[6] and subjective preference by Beranek,[2] but with a simpler expression). The existence of differences between the model and the subjective ranking obtained is analyzed in terms of the representativeness of the mean values of the orthogonal parameters. In some cases, spatial variations are considerable, and from this fact it can be deduced that a detailed characterization of the performance space requires, in addition to the average of the objective parameters, an analysis of the variation of orthogonal parameters in each hall.[24] The combination of these two experimental results leads the authors to address studies on the relationship between subjective assessment and objective parameters in two possible ways: Either through the establishment of orthogonal parameters that are constant in the room (as in the T_{mid} case); or through the study of assessments of subjects in response to the position they occupy and the values of the parameters that concur in such a position.

ACKNOWLEDGMENTS

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