Concert hall acoustics assessment with individually elicited attributes

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Concert hall acoustics was evaluated with a descriptive sensory analysis method by employing an individual vocabulary development technique. The goal was to obtain sensory profiles of three concert halls by eliciting perceptual attributes for evaluation and comparison of the halls. The stimuli were gathered by playing back anechoic symphony music from 34 loudspeakers on stage in each concert hall and recording the sound field with a microphone array. Four musical programs were processed for multichannel 3D sound reproduction in the actual listening test. Twenty screened assessors developed their individual set of attributes and performed a comparative evaluation of nine seats, three in each hall. The results contain the distinctive groups of elicited attributes and show good agreement within assessors, even though they applied individual attributes when rating the samples. It was also found that loudness and distance gave the strongest perceptual direction to the principal component basis. In addition, the study revealed that the perception of reverberance is related to the size of the space or to the enveloping reverberance, depending on the assessor.
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I. INTRODUCTION

Subjective comparison of concert halls is not an easy task since preferred acoustics depends on a number of elements. The music, the conductor, and the performance of the orchestra greatly contribute to the listening experience, and the contribution of the auditorium acoustics itself is hard to isolate with perceptual studies. Traditionally, concert hall evaluation studies have been implemented with questionnaires or by comparing recordings or simulations with the attributes usually defined by the researchers. The majority of these studies have applied objective measurements to determine preference judgments or discrimination tests to assess the perceptual differences between stimuli.

In other scientific disciplines, sensory analysis is applied to study perceptual differences between stimuli. Sensory evaluation, and descriptive testing specifically, requires panels of human assessors who rank and rate the products using their senses. By applying advanced statistical techniques to the analysis of the subjective data, it is possible to reveal the perceptual differences of the products under test. For example, sensory analysis is a common practice in food science.[1]

Similarly, the perception of concert hall acoustics is complex and multidimensional by nature. Individuals have different tastes and preferences, such that the descriptions of perceptual attributes of halls can be ambiguous. In this study, a sensory evaluation method is applied to concert hall acoustics assessment to gain a deeper understanding of the perceptual criteria applied to the rating of three concert halls. The contribution of this paper is to link sensory evaluation and auditorium acoustics. The final goal is to deliver a better understanding of concert hall acoustics, which aspects are perceived and considered important and how perception could be measured when assessors can simultaneously compare different listening positions and concert halls.

II. BACKGROUND

A. Concert hall acoustics evaluation

Concert hall acoustics has been investigated for over 100 years. Since the pioneering work of Sabine,[2] scientists have tried to understand why some halls sound better than others and what are the perceptual attributes that contribute to the general opinion of "good" acoustics. The obvious method of gathering information has been interviews of conductors, musicians, and the public audience. Beranek[3] has done an enormous number of interviews, based on which he has been able to rank the most popular concert halls in the world. Formal questionnaires have been utilized in several other studies, e.g., by Hawkes and Douglas,[4] Barron,[5] and Kahle,[6] who all used more or less expert listeners in evaluating halls *in situ* by listening to the real performances of orchestras.

While *in situ* listening to concerts produces the most reliable and natural perception, the problem of comparison between halls cannot undoubtedly be solved. The data analysis of structured questionnaires is difficult, sometimes even impossible, due to delayed comparisons, simultaneous variation of large number of parameters, nonidentical stimuli and the mood of subjects.[7] Kürer *et al.*[8] and Schroeder *et al.*[9] (studies summarized by Cremer and Müller[10]) were among the first researchers who made the instant comparison of concert halls possible by applying binaural technology. In addition, Schroeder *et al.*[9] enabled the comparison of halls with spatial sound reproduction in laboratory conditions by

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exciting halls with anechoic recordings, played back by two loudspeakers on the stage. Later, room acoustics simulation was used to understand the descriptive attributes.[11,12] Soulodre and Bradley[13] convolved measured impulse responses with anechoic signals to create controlled stimuli for listening tests. The problem in all of these studies has been that one or two sources on the stage do not represent well a real symphony orchestra.

The aim in this study is to overcome several drawbacks of earlier subjective concert hall evaluation studies. As indicated by Kahle and Jullien,[7] the different subjective responses can depend on the acoustics, the musical piece, the subject, and the position in a hall. Here such issues have been carefully considered by recording an orchestra of loudspeakers in three concert halls in several listening positions with a state-of-the-art spatial sound recording technique. The recordings are then reproduced in a laboratory environment, enabling a simultaneous comparison of all samples.

B. Descriptive sensory evaluation

Descriptive analysis (DA) techniques are based on the quantitative description of a set of stimuli; many different methods exist to develop perceptual attributes and rating scales. Bech and Zacharov[14] reviewed such methods and their application in the field of audio quality evaluation. Generally, DA employs consensus vocabulary techniques in which a panel of assessors develops a set of attributes and agrees on their definitions. Panel discussions are laborious and time consuming,[14] and thus, problematic in practice. Individual vocabulary techniques have been developed to reduce time and resource requirements. Each assessor creates her own set of attributes for the evaluation of stimuli in these techniques. The use of individual attributes solves the issue of predefined attribute interpretation. Such techniques require advanced statistical procedures to extract a common language of the assessors. Individual vocabulary techniques include Free-choice profiling,[15,16] the Repertory grid technique,[17] the Flash profile,[18] and Individual vocabulary profiling (IVP).[19]

In Free-choice profiling, expert assessors create their individual attributes and scale anchors. The overall assumption is that every assessor is able to verbalize his/her perception well and is able to rate stimuli consistently without any training. The Repertory grid technique introduces the triplets of stimuli to the assessors whose task is to identify one sample of the triplet that differs the most from others. The difference is then verbalized and further descriptions are requested for identifying the similarity between two similar samples. In this method, attributes are produced by the bipolar nature of the descriptors, which become the end-points of a scale used; thus, this method enables the classification of the opinions of assessors. The Flash profile was invented to overcome the time consuming nature of a standard DA procedure. The whole procedure is divided into four phases: (1) generation of an individual list of attributes by focusing on the attributes that allow for discrimination of the stimuli; (2) refining the attributes and possibly adding new ones using the pooled list of attributes from all assessors; (3) rank ordering of stimuli with the elicited discriminative attributes; and (4) repetition of phase three. The Flash profile differs from free-choice profiling by focusing on discriminating attributes that are used to rank all stimuli. The Flash profile has also been shown to be a reliable method giving results almost identical to the laborious conventional descriptive analysis.[20]

The individual vocabulary techniques have been recently applied with success to the studies of spatial sound reproduction[14,21,22] and the perceptual evaluation of multimedia loudspeakers.[23] Therefore, they might be well suited for the evaluation of complex and multidimensional stimuli, such as recordings of a symphony orchestra in a concert hall. The use of individual attributes solves the problem of predefined attribute interpretation, and as such, they are considered for the description of the acoustical properties of concert halls.

III. METHOD

An IVP method,[19] adapted and modified from the Flash profile,[18] was applied in the subjective evaluation of concert hall acoustics. In IVP each assessor develops his own set of attributes for the evaluation. The implemented concert hall acoustics evaluation method consisted of four separate listening sessions for each assessor. Each session lasted a maximum of 2 h depending on the performance of the assessor. The first two sessions were designed for the attribute elicitation and development process. In the third session assessors rehearsed the usage of their attributes and scales in a complete evaluation of the stimuli, which simulated the real test situation in the final session.

All of the assessors spoke Finnish as their mother tongue; therefore, it was natural to use the Finnish language in attribute elicitation. The instructions emphasized finding precise and reliable attributes and avoiding affective terms, such as preference or acceptance. They were asked to search for any perceptually interesting aspects of the sounds to ensure a proper familiarization to the audio material. This strategy was considered very important because affective terms are based on subjective preference, which might bias the perceptual measurement. In addition, the attributes employed should discriminate between the stimuli, have little or no overlap with other terms, and be singular terms, rather than a combination of several terms. In the second session, the assessors were free to add or discard words if they found several words describing the same aspect in the sound samples. In addition, they were instructed to select the most appropriate and descriptive words in their list. The goal was to condense into the 4 to 6 most descriptive attributes which could be used to discriminate these audio samples. The assessors also defined for each attribute respective bipolar anchor labels for the continuous scales. In addition, they wrote down brief descriptions of the respective perceptual aspects. This was carried out under the supervision of the experimenter to ensure that the developed attributes were descriptive and non hedonic although the experimenter gave as little advice as possible to prevent any bias.

The third session consisted of a simulation of the sensory profiling task. The assessors completed the assessment with their own attributes and definitions. They were also instructed to recheck their attribute list once more and after completing the task, they were able to make final modifications, or even add or remove attributes. Most often none or only minor adjustments were made. In the final session, the assessors completed the sensory profiling task with their own attributes. The presentation order of the nine samples in each window (corresponding to a particular attribute-music pair) was fully randomized. For example, if the assessor had developed 5 attributes, the whole evaluation consisted of 20 (5 attributes times 4 musical excerpts) sets of 9 samples. It was strongly advised that the assessors would take at least one short break to maintain an adequate concentration and performance level.

A. Assessors

The assessors were selected with a screening procedure consisting of an online questionnaire, a pure-tone audiometric test, a test for vocabulary skills, and a triangle test for the discriminative skills of audio stimuli. The screening procedure was developed to meet the requirements of assessing audio stimuli with elicited attributes.

Forty-seven candidates filled in the online questionnaire. They were mainly students of acoustics, psychology, and musicology. Thirty-one of them were considered to have discriminative listening skills and musical background. They participated in the discrimination tests, and their hearing thresholds were evaluated by the criterion that a threshold was not to exceed 15 dB in any frequency band, except one, which was not to exceed 20 dB. The applied discrimination test was a triangular AAB forced-choice test. The candidates were presented the sample triads, and for each triad, the task was to decide which sample differed from the others. The triads of the same sample-pair were presented several times to reject the null hypothesis of guessing. Finally, 20 candidates (9 males and 11 females) of age from 21 to 51 years were selected as assessors. They were not expert assessors by definition, but they were considered to be experienced assessors.[14] The detailed description of the screening process and the performance of the assessors in the final tests are presented in detail by Kuusinen *et al*.[24]

B. Apparatus and stimuli

The attribute elicitation and final rating of stimuli were performed in a dark anechoic chamber. The spatial sound reproduction system consisted of 16 Genelec 8030 loudspeakers in a 3D layout (see Sec. IV). The assessors controlled the playback of stimuli with a small touch screen device, which displayed the graphical user interface shown in Fig. 1. With a stylus, the assessor chose the stimuli to be played. He was able to set the start and end positions of a shorter loop and to move the sliders to give ratings. The continuous scales had values from 0 to 120, so that between anchors there were 100 points. The assessors were encouraged to use the full scale.

A very important feature in individual vocabulary profiling is that the assessor should be able to evaluate stimuli simultaneously. This is hard to achieve because multiple sound samples cannot be listened to simultaneously. However, by playing samples in parallel and enabling real-time switching between them, the assessors could perform a detailed comparison of several stimuli. The simultaneous comparison of concert halls requires a special way to record stimuli, as explained in the next section.

IV. RECORDING CONCERT HALLS WITH A LOUDSPEAKER ORCHESTRA

The studied concert halls were recorded by exciting the halls with an enhanced version of the loudspeaker orchestra reported by Pätynen *et al*.[25] In each receiver position, the sound was captured using a multi-microphone technique that further enabled multichannel 3D sound reproduction. The entire signal processing chain is depicted in Fig. 2.

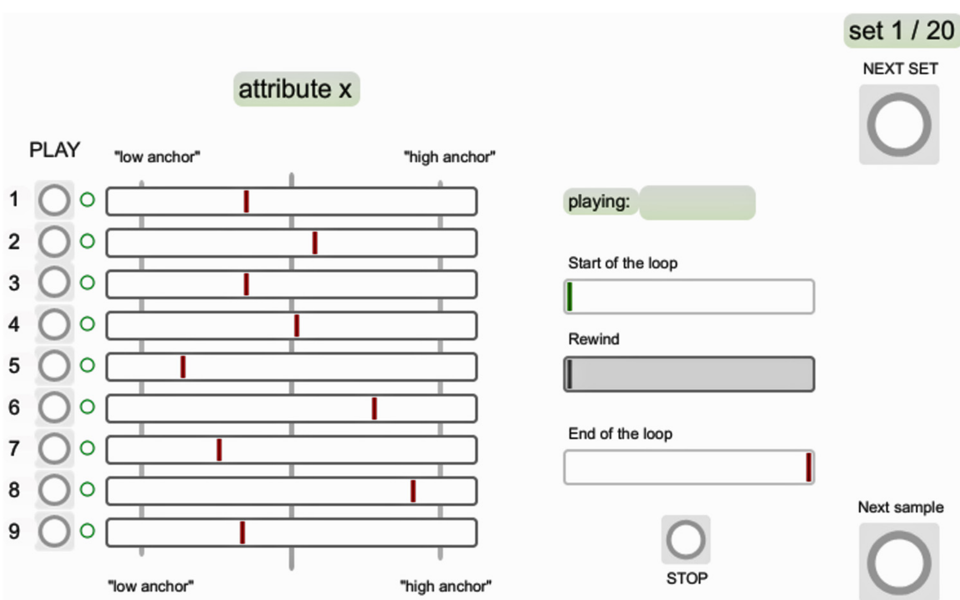

FIG. 1. (Color online) Applied graphical user interface (original Finnish texts translated to English).

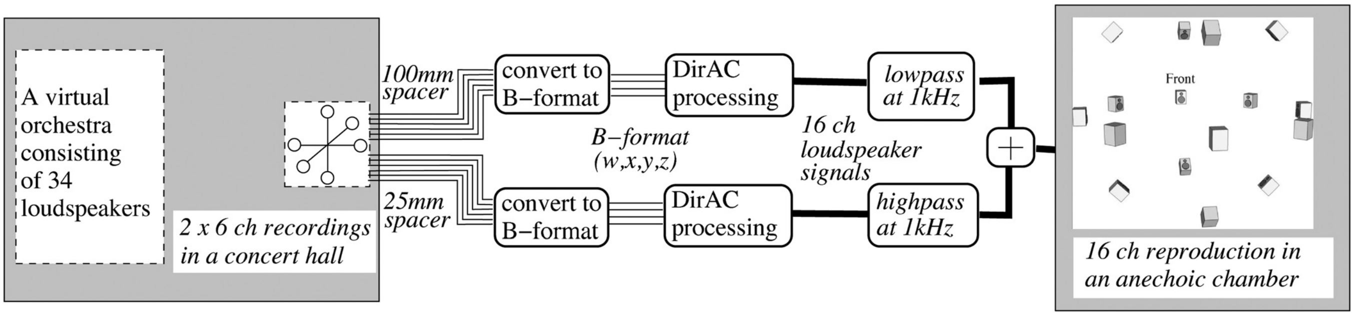

FIG. 2. Signal processing chain to obtain comparable stimuli for the subjective evaluation. The loudspeaker orchestra is recorded with 6 microphones twice, with 25 mm spacer and 100 mm spacer. Both six microphone signals are converted to B-format signals that are processed with DirAC for rendering sound with 16 loudspeakers in an anechoic chamber.

A. Signal processing for 3D spatial sound reproduction

The recording equipment consisted of 34 active loudspeakers, 6 microphones, and a rack of D/A converters connected to a MacBook Pro computer with a digital audio interface (RME Digiface). Each musical piece was recorded at each receiver position twice with a six-channel GRAS vector intensity probe (type 50 VI-1). The first recording was performed with a 100-mm spacer, and the second one, with a 25-mm spacer. The use of two spacers enabled the computation of better figure-of-eight microphone signals at a wider frequency range[26] when six omnidirectional signals are converted to a first order B-format signal, which consists of omnidirectional W and three figure-of-eight signals X, Y, and Z (see Fig. 2). All microphones were calibrated with the B&K 4231 calibrator. Each loudspeaker on the stage was calibrated in each hall by measuring 85 dBA at 1 m distance when the loudspeaker emitted bandpass (200–1000 Hz) white noise.

The B-format signals were processed with directional audio coding (DirAC)[27] to create 3D spatial sound reproduction. It has been proven[28] that DirAC produces better perceptual quality in loudspeaker listening than other available techniques, such as Ambisonics,[29] using the same microphone input. DirAC performs a time-frequency analysis of the B-format signal and computes the sound intensity and diffuseness estimates in each time-frequency block. Based on this information, figure-of-eight signals were used during the reproduction with a defined loudspeaker array. In this case, the loudspeaker array consisted of 16 loudspeakers in a 3D setup, as depicted in Fig. 2 and in Fig. 7(b) in Vilkamo *et al*.[28]

B. Loudspeaker orchestra

The layout of the loudspeaker orchestra, consisting of 34 active loudspeakers (Genelec models 1029A, 8030, 1032A), is presented in Fig. 3. These were chosen because they do not need external amplifiers and they have well behaving power response. The loudspeakers were pointing toward the position of the conductor, except loudspeaker 24, at the soloist position, and loudspeakers 19 and 20 (French horns), with the main sound radiation direction toward the back. In addition, the extra loudspeakers for string instruments were lying on their backs on the floor, thus emitting high frequencies to the upper hemisphere. This arrangement was chosen to compensate for the difference between the string instrument and loudspeaker radiation patterns. Otherwise, the technical details were the same as in the original loudspeaker orchestra.[25]

1. Anechoic music

The loudspeaker orchestra emitted anechoic music to excite each hall identically. The recording of anechoic symphony music has been reported earlier by Pätynen *et al*.[30] Moreover, the details of the signal processing needed to create a natural sounding loudspeaker orchestra have been reported by Lokki and Pätynen.[31] The musical excerpts played during the listening tests were as follows.

(1) W. A. Mozart (1756–1791), An aria of Donna Elvira from the opera *Don Giovanni*, Act II, Scene III, bars 1–15, 26.0 s.
(2) L. van Beethoven (1770–1827), Symphony no. 7, movement I, bars 12–18, 23.5 s.
(3) A. Bruckner (1824–1896), Symphony no. 8, movement II, bars 41–61, 29.0 s.

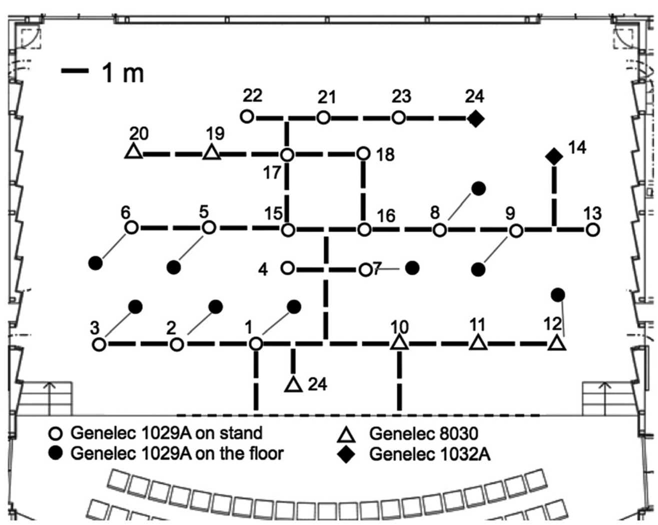

FIG. 3. Layout of the loudspeaker orchestra on the stage of a concert hall.

(4) G. Mahler (1860–1911), Symphony no. 1, movement IV, bars 71–86, 17.5 s.

These four short passages of music represent different eras of classical music and the size of the orchestra varies between them. Mozart's aria represents the classical style and has a vocal soloist. The introduction of Beethoven's 7th symphony has big chords in the beginning and many string crescendos. Bruckner and Mahler are great examples of works that require large orchestras. However, the musical texture of Bruckner's music is quite conventional while that of Mahler is very complex.

The signals of individual instruments were played from the loudspeaker channels according to Table I. To have more natural sounding string sections, each string instrument recording was individually processed with small delays (up to 70 ms) and slight pitch shifting (up to 14% of a semitone). For example, six slightly varying copies of one first violin recording were made. When these copies were reproduced from spatially separated loudspeakers according to Table I, a reasonable first violin section was achieved.

2. Concert halls and recording positions

The concert halls measured (plans in Fig. 4) were not a selection of world famous concert halls, but they were available, and they each have a characteristic sound. Two of them are quite small in volume, but the stage is large enough for a symphony orchestra. The Sello hall has 397 seats in an ascending audience area and no balcony. The hall of Konservatorio has 470 seats, 354 on the main floor and 116 on the balcony. The third hall, Tapiola, is a medium-sized hall with 690 seats, 510 on the main floor and 180 on the balcony. It is the permanent venue of the Espoo city orchestra. The recording tour was realized in June 2009, during four consecutive days.

In each hall, the recordings were made in 5 to 8 positions. Five of them were "equal" positions, meaning that their distances to the loudspeakers were exactly the same. This fact was verified by measuring the distance with a laser meter to four defined loudspeakers. However, for the listening test, three positions from each hall were selected to have a diverse selection of positions in each hall to be compared. The chosen positions are illustrated in Fig. 4; they were R1, R4, and R5 in Sello; R1, R4, and R6 (on the balcony) in Konservatorio; and R4, R6 (on the balcony), and R8 in Tapiola. In each hall, there was one position (R4) at an equal distance from the loudspeaker orchestra, as shown in Fig. 4.

V. RESULTS

Twenty assessors completed the individual vocabulary profiling and each of them elicited four, five, or six attributes. Each attribute was applied to rate all four musical signals, resulting of 16, 20, or 24 sets of evaluations in randomized order. Each set contained nine samples (recording positions), as shown in Fig. 1. As the numbers of attributes vary between assessors, the total number of collected attributes was 102. Because one attribute was applied for all

TABLE I. Distribution of instrument tracks for the loudspeaker channels (CH, see Fig. 3 the positioning of channels on the stage). A Roman numeral means a part of the particular instrument and an Arabic numeral denotes how many delayed and pitch shifted copies of the same recording has been used for string instruments.

CH	Instrument	Mozart	Beethoven	Bruckner	Mahler
1	I violins (vl1)	2	4	4 + 1 vl2	4
2	I violins	2	4	4 + 1 vl2	4
3	I violins	2	4	4 + 2 vl2	4
4	II violins (vl2)	3	4 + 1 vl1	4 + 1 vl1 + 1 vla	4 + 1 vl1
5	II violins	2 + 1 vl1	4 + 1 vl1	4 + 1 vl1 + 1 vla	5 + 1 vl1
6	II violins	2 + 1 vl1	4 + 2 vl1	4 + 2 vl1	5 + 2 vl1
7	violas (vla)	1	2	2	2
8	violas	2	4	3	3
9	violas	2	4	3	3 + 1 vc
10	cellos (vlc)	1	2	3	2
11	cellos	2	4	2	2
12	cellos	2	4	3	3
13	contrabasses (cb)	2	2	3	4
14	contrabasses	2	2	3	4
15	flutes (fl)	I + 1 vla	I,II	I,III + II ob	I,III + II,IV ob + 1 vl2
16	oboes (ob)	0 + 1 vla	I,II	I,III + II fl	I,III + II fl + 2 vla
17	clarinets (cl)	I	I,II	I,III + II bsn	I,III + II bsn
18	bassoons (bsn)	I	I,II	I,III + II cl	I,III + II,IV cl
19	French horns	I	I	I, III, V, IV	I, III, V, IV
20	French horns	II	II	II, IV, VI, VIII	II, IV, VI
21	trumpets (tr)	0	I	I,III + II trb	I,II,III
22	trombones (trb)	0	0 + II tr	I,III + II tr	I + IV tr + II timp
23	timpani (timp)/ tuba (tb)	0/0	0/0	0/I	0/0 + II,III trb
24	soprano/percussions/timpani	1/0/0	0/0/timp	0/0/timp	0/I,II/I + I tb

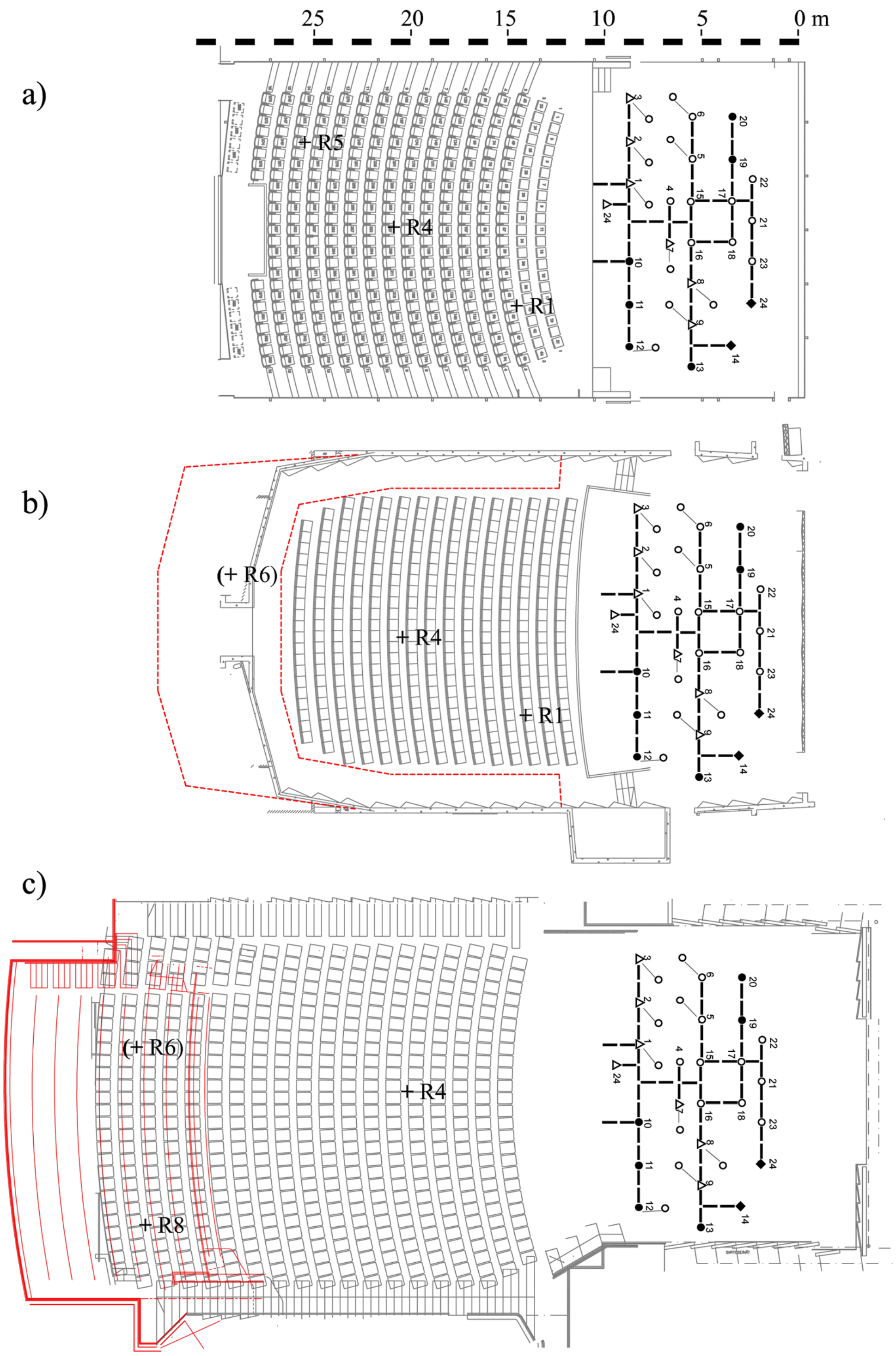

FIG. 4. (Color online) Halls and recording positions, (a) Sello, (b) Konservatorio, and (c) Tapiola.

signals, it is possible to see how attributes are grouped within the entire data set. Therefore, a data matrix, illustrated in Fig. 5, containing 36 rows and 102 columns was created. Most of the assessors used the whole scale from 0 to 120 in evaluation, but in a few cases the extreme values were not used. For that reason, the columns of the data matrix were scaled and centered for the following analysis. The centering was done by subtracting the column means of data matrix from their corresponding columns and scaling was performed by dividing the centered columns of data matrix by their root-mean-square.

A. Clusters of attributes

The first task in the analysis was to classify elicited attributes into collective categories. The clustering could be done manually based on the short description of each attribute. However, automatic clustering would reveal the real structure of the data. Therefore, hierarchical agglomerative clustering based on Euclidean distances, and in conjunction with Ward's minimum variance method,[32] was applied to the entire data set. The colored dendrogram in Fig. 6(a) shows that data are grouped into seven clusters. The main

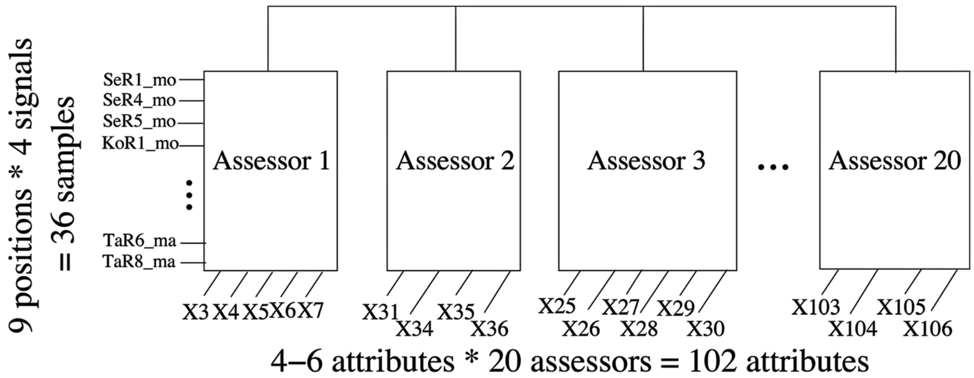

FIG. 5. The rows of data matrix consist of 4 signals × 9 receiver positions (3 positions in 3 halls). 102 columns contain 4–6 attributes by 20 assessors.

cluster is still manually divided into three subgroups based on the definitions of the individual attributes. All elicited attributes are collected in Table II, and the nine found groups are labeled based on the individual attributes and their definitions. The original attributes in Finnish language are listed by Kuusinen *et al.*,[24] and the attributes in Table II are translated by the authors of this article. Although the translation is carefully made, there is a risk that attributes elicited in one language could lose some important information when translated into other languages.[33]

Before looking in more detail at the formed groups some other method should be used to confirm the grouping of attributes. The hierarchical clustering method may produce misleading results, by producing a hierarchy whether the objects are or are not hierarchically interrelated.[34] A powerful visualization method for grouping studies is a distance matrix showing the Euclidian distances of attributes. The order of attribute groups was changed for better visualization (see Fig. 6(b)). Now, attribute groups form few squares along the diagonal, i.e., they are close to each other.

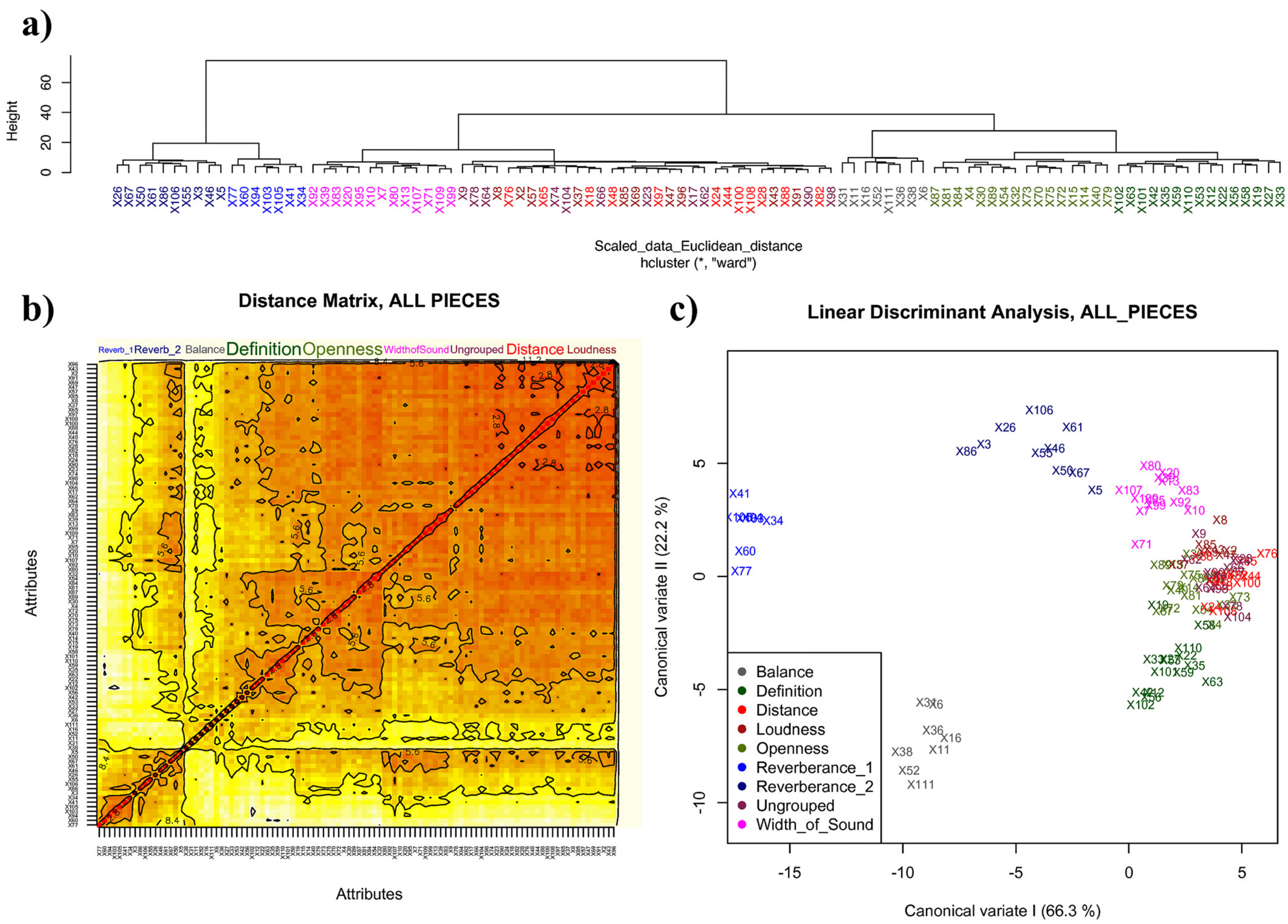

FIG. 6. (Color online) Grouping of attributes is based on hierarchical clustering and validated with distance matrix and linear discriminant analysis. (a) Hierarchical clustering with Ward's method based on Euclidean distances. (b) Distance matrix for all data, the color scale goes from dark (short Euclidean distance) to white (long Euclidean distance) (c) The results of linear discriminant analysis to confirm the grouping of hierarchical clustering.

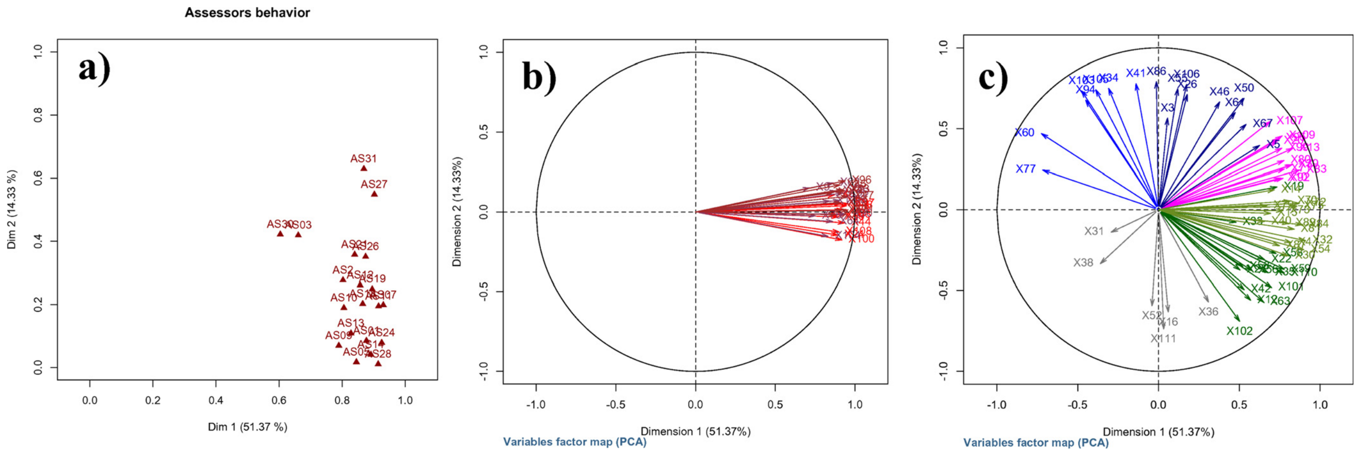

FIG. 7. (Color online) Loadings of individual attributes on the two main axis of the MFA space. (a) The behavior of assessors. (b) Loading of main cluster attributes to two main dimensions. (c) Loading of the rest of the attributes to two main dimensions.

However, it can also be seen that some attributes correlate quite well, although they are clustered in different groups. Another powerful method is Linear Discriminant Analysis (LDA), which minimizes the intragroup variance and maximizes the ratio of the intergroup variance to the intragroup variance by searching for a linear combination of descriptors. In other words, LDA visualizes, in this case, 36-dimensional data, so that the groups are separated as well as possible into a two-dimensional plot. Figure 6(c) confirms the clustering results, showing that found clusters are reasonable. In addition, LDA suggests that the clusters can be approximately presented in a two-dimensional space, since the first two canonical variates sum up to 88.5%.

The formed groups each consist of 7 to 16 individual attributes each (see Table II). First, the minor branch of the dendrogram has two groups, named Reverberance_1 and Reverberance_2. They clearly differ from other groups, and the LDA analysis shows that the division of reverberance attributes into two groups is clear. Based on the individual attributes, it could be stated that Reverberance_1 is related to the size of the space. Individual attributes can be translated as the reverberance, reverb, and size of the space. In contrast, Reverberance_2 seems to be related to enveloping reverberation since four nonreverberation attributes are broadness, envelopment, width, and bass.

Balance clearly differs from other groups as suggested by LDA. Based on attribute descriptions Balance is evenly related to the timbre (balance between low and high frequencies) or to the localization/direction (left-right balance). LDA further suggests that two more groups, namely, Width of Sound and Definition, differ from the main cluster because individual attributes form nonoverlapping separate groups. Width of Sound has a variety of individual attributes. Some of them are related to source width, some others to broadness, envelopment, and how the sound is filling the space. Timbre-related attributes, such as balance or bass, are also indicated by three assessors. Definition could be described as the clarity or separability of instruments or

TABLE II. All collected 102 attributes grouped in 9 subgroups.

Group	Individual attributes (translated to English)	N
Reverberance_1 (size of the space)	reverberance (X41), reverberant (X77), reverb (X34), sonority (X103), amount of reverb (X94), drr (X60), size of the space (X105)	7
Reverberance_2 (envelopment)	reverberance (X26, X3, X67, X86), reverberation (X50), broadness (X55), reverb (X106), envelopment (X61), width (X46), emphasis on bass (X5)	10
Width of Sound (bass)	width of sound (X39), wide (X13), wideness (X95, X80), width (X92), sense of space (X10), 3-dimensional (X20), focused sound (X107), envelopment (X83), naturalness (x7), bass (X109), balance between warm and cold (X71), amount of bass (X99)	13
Loudness	loudness (X37, X2, X43, X96, X69), full-flavored (X8, X85), dynamics (X57), volume (X47), approach of sound (X91)	10
Distance	distance (X82, X24, X28, X48, X44, X88, X100, X108, X97), distant (X76), closeness (X18, X65)	12
Ungrouped	spread of sound (X17), breadth (X74), neutral (X78), brightness (X66), liveness (X64), muddy (X98), stand out (X9), intimacy (X90), eq (X62), sharpness (X104), width of sound (X23)	11
Balance	balance (X31), directed (X52), symmetry (X11), brightness (X38, X36), balanced (X6, X111), clearness (X16)	8
Openness	soulless (X15), naturalness (X14, X73), openness (X84), depth (X70), clearness (X30, X75, X89), pronounced (X79), presence (X81), definition (X87), discrimination (X40), distance of source (X32), intensity (X72), closeness (X4, X54)	16
Definition (separability, clarity)	definition (X27, X35, X102, X53), distinctness (X59), clarity (X58), localizability (X63, X101), treble (X110), transparency (X22), tone color (X56, X33), precise (X12), softness (X42), texture (X19)	15

melodies. In addition, localization- and timbre-related attributes are mentioned, mainly about the high frequency content of the signals (clarity).

Finally, the largest cluster is formed with Loudness, Distance, Ungrouped, and Openness, although the hierarchical clustering separates the last one. Although assessors seem to have rated samples similarly according to Loudness or Distance attributes, they are considered two separate groups. The Loudness group contains individual attributes that are all related to loudness and dynamics. The Distance group has individual attributes, such as distance and closeness. Ungrouped cannot really be separated from Loudness and Distance. Openness can be described by the ability of music to breath freely, or the degree of airiness is the music. In addition, a few assessors describe the separability of instruments. Interestingly, a few distance-related attributes are also in this group confirming the closeness of the Openness cluster to the main cluster.

B. Sensory profiles

The collected 102 individual attributes describe the perceptual characteristics based on which the assessors were able to discriminate between samples. Such a list of attributes is very interesting information for acousticians. The grouping of individual attributes is an interpretation of the authors of this article to study the halls more generally. For example, based on this grouping and these samples the sensory profiles of the studied concert halls can be formed, as presented in Fig. 8. These sensory profiles show the listening test data for each recording position as an average of individual attributes within a group.

Figure 8(a) illustrates the sensory profiles of positions in the Konservatorio hall. The front position R1 is rated the highest with all perceptual dimensions except Reverberance 1 and Reverberance 2. In contrast, the far position on the balcony (R6) is in the totally reverberant field giving low ratings for Definition, but very high ratings for both Reverberances. Figure 8(b) (Sello hall) shows that this hall has no surprises, the ratings go as expected when the distance to the orchestra grows. Finally, Fig. 8(c) reveals that on the balcony of the Tapiola hall (R6) the sound is not loud although reverberation gives a feeling of a large space. In addition, the position at rear in stalls (R8) is rated very low with all attributes.

Interesting comparison between the plots in Fig. 8 can be done with the dashed lines which show the perceptual profiles of R4 positions. The Konservatorio hall has the largest values, except for Definition, then the Sello hall, and the Tapiola hall was rated the least loud and enveloping. The dotted lines of the Konservatorio and Sello halls are from position R1 which was very close to the loudspeaker orchestra. Obviously, the direct sound in these positions was dominating, thus these seats gave similar sensory profiles.

C. Ordination with multiple factor analysis

In addition to clustering, ordination complements the multivariate analysis. Ordination orders multivariate objects so

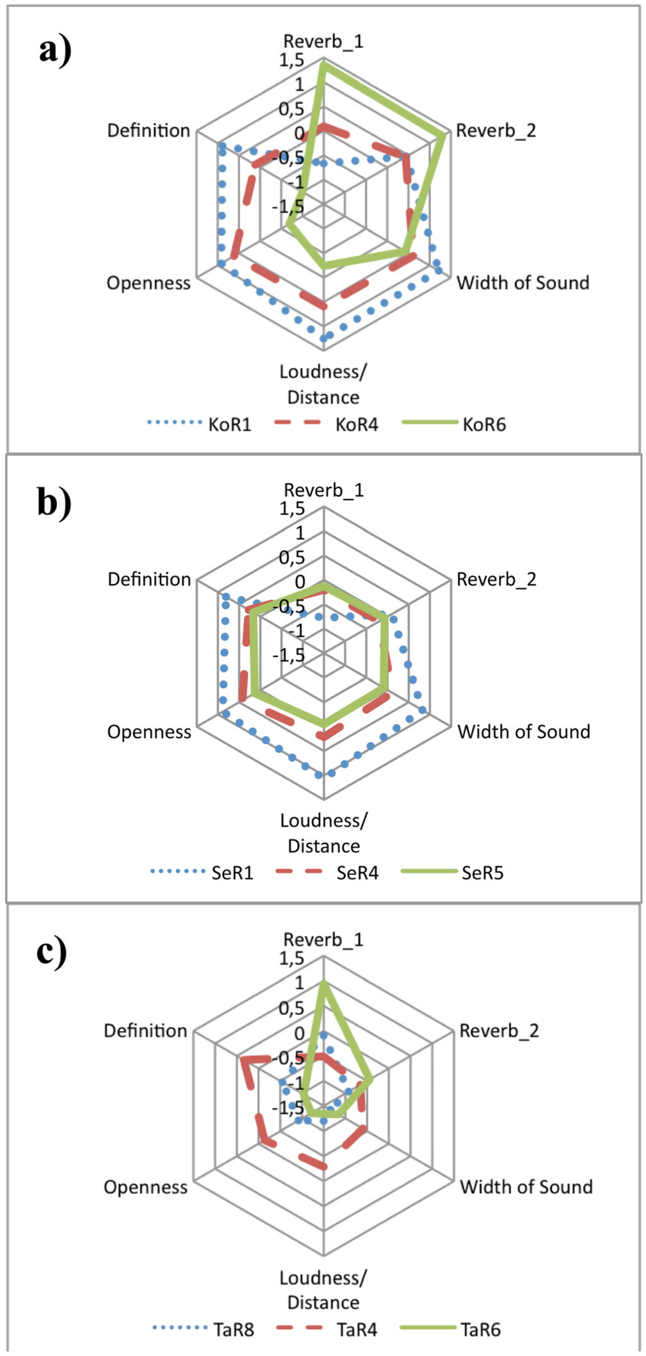

FIG. 8. (Color online) Spider plots of the data for all positions, (a) Konservatorio, (b) Sello, and (c) Tapiola. Note that positions R4 (marked with dashed line) are at equal distance from the loudspeaker orchestra in each hall.

that similar objects are near each other and dissimilar objects are farther from each other. In analysis of individually elicited sensory data Multiple Factor Analysis (MFA)[35,36] is often applied since it derives an integrated picture of the observations and of the relationships between the descriptive attributes. The basis of MFA is the Principal Component Analysis (PCA). First, the data is grouped into 20 groups by assessors (as shown in Fig. 5), and PCA is performed on the data set of each assessor. It is reasonable to group the data by assessors because they were advised to find the independent descriptors of the spatial aspects of sounds. Each set is then normalized by dividing all its elements by the square root of the first

TABLE III. Multiple factor analysis, variances explained by the first eight components.

	Eigenvalue	Percentage of variance	Cumul. percentage of variance
comp 1	16.89	51.37	51.37
comp 2	4.71	14.33	65.70
comp 3	1.17	3.56	69.26
comp 4	0.96	2.91	72.17
comp 5	0.85	2.59	74.76
comp 6	0.74	2.24	77.00
comp 7	0.59	1.78	78.78
comp 8	0.57	1.73	80.51

eigenvalue of its PCA, and thus the maximum axial inertia of each group of variables is set to 1. Then, all 20 sets are merged into a single matrix and a global PCA is performed on it. Finally, the individual data sets are projected onto the global analysis.

MFA analysis was performed with the FactoMineR package[37,38] on the centered and scaled data, organized as depicted in Fig. 5. The variances explained by the first eight components can be seen in Table III. The first two dimensions explain 65.7% of the data, and the contribution of higher dimensions is rather small. Thus, it is reasonable to analyze the results on the first two dimensions.

First, the behavior of assessors is presented in Fig. 7(a). The figure expresses how each assessor is related to the main principal components. The proximity of the assessors, except AS03 and AS30, and the value close to one on the first axis proves that the assessors had good consensus regarding the main axis. On the second axis, assessors performed more differently: some low values close to 0 suggest that these assessors did not apply attributes contributing to the second dimension.

The loadings of all 102 attributes to two main principal axes can be visualized with a variable factor map, as presented in Figs. 7(b) and 7(c). In this representation, a vector points in the direction where the variance of the data points is largest and the length of the vector shows the goodness of the projection. A color indicates the group, based on hierarchical clustering and LDA. The attribute groups Loudness, Distance and Ungrouped that contribute to the main principal axis, are plotted in Fig. 7(b). The consensus between assessors is very good since all vectors are in a dense package. Figure 7(c) shows attributes of the other six groups. Reverberance_1 and Reverberance_2 both comprise the second dimension. However, as shown by hierarchical clustering and LDA, the reverberance is divided into two subgroups, one possibly related to the size of the space and another one related to enveloping reverberation. This is interesting because the detailed definitions of attributes already indicate such a division, but the data clearly show it. Width of Sound attributes form a well-defined and dense group suggesting good consensus among assessors. The Width of Sound attributes are also located between enveloping reverberance (Reverberance_2) and Loudness/Distance. Openness is mainly in the principal direction, although a few individual attributes overlap with Definition attributes. Interestingly, Definition attributes are pointing in almost the opposite direction as Reverberance_1, which is related to the size of the space. This is an expected result, since individual attributes in the Definition group are related to the ability to hear individual instruments and to localize them. Finally, Balance attributes are quite distributed in several directions and the lengths of the vectors suggest that higher dimensions would explain the variances of these attributes better.

Finally, MFA makes it possible to see how individual samples are mapped to the space defined by principal component dimensions. Here all 36 samples (3 halls $\times$ 3 positions $\times$ 4 signals) are plotted on a biplot in Fig. 9. First of all, it seems that the three halls have a characteristic sound since they are more or less separated, as illustrated with colors. On top of the samples, the average vectors of the individual attributes in each attribute group are plotted. These directions can be considered as perceptual dimensions and their orientations show the directions of the largest variances

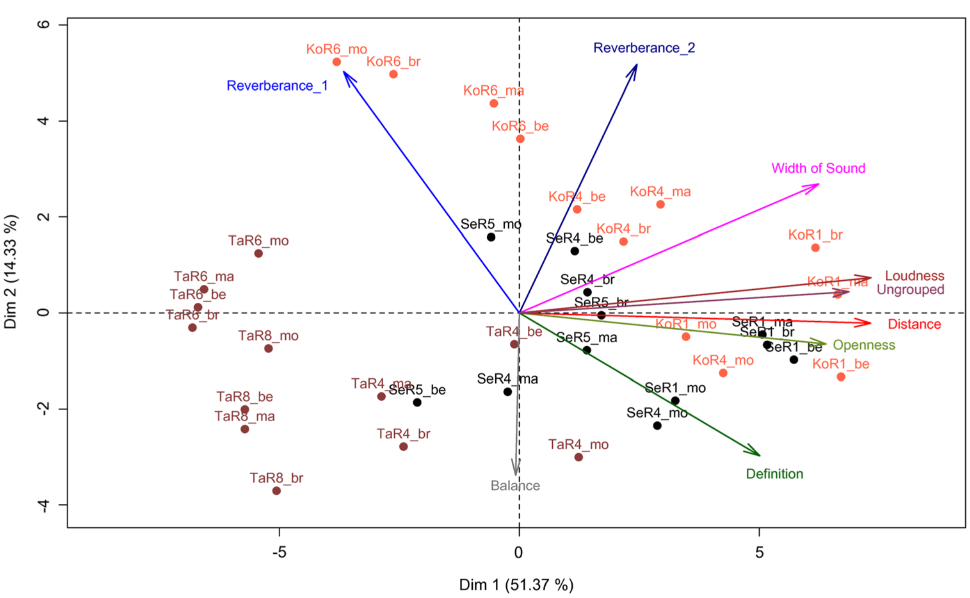

FIG. 9. (Color online) MFA results for the recording positions. The abbreviations are Se = Sello, Ko = Konservatorio, and Ta = Tapiola for halls, and mo = Mozart, be = Beethoven, br = Bruckner, and ma = Mahler for signals. For example KoR1 months means position R1 in Konservatorio hall with stimulus signal Mozart.

in the data. When the samples are projected to these perceptual dimensions, it can be seen how individual samples are ordinated by the assessors. The main dimension is the Loudness/Ungrouped/Distance/Openness direction where close listening positions (R1s) and distant listening positions (R6s and R8, cf. Fig. 4) are mapped to both ends. The Ungrouped attributes are nearly overlapping with Loudness attributes, suggesting that assessors have possibly ordered the samples based on loudness, even though they have used some other attributes. The Reverberance_2 dimension best separates the halls, regardless of the listening position or music. Conversely, Reverberance_1 orders the positions so that the highest rates are given to the farthest positions, confirming the interpretation of the Reverberance_1 as describing the size of the space. The Definition direction is also well justified, since the clearest sound is at the nearest or middle positions, which contrasts with the very diffuse and reverberant fields of farther positions, e.g., KoR6 on the balcony in the Konservatorio hall. Finally, the Width of Sound direction indicates that the Konservatorio and Sello halls produce wider perceived sound than Tapiola hall. In addition, a perceived wide sound is generally considered a function of low frequency energy, and in particular, lateral energy:[39] therefore, the Width of Sound vector between enveloping Reverberance_2 and Loudness is well justified.

D. Confidence ellipses

As Fig. 9 suggests, there is a clear difference between halls. In addition, listening positions also seem to be spatially separated, but this should be validated with statistical methods. A good method for visualizing the significance of differences is with the use of 95% confidence ellipses, which are empirical descriptions of the variability of the sensory evaluations.[40] Such analysis calculates the distributions of the centers of gravity with resampling and then deduces a confidence region for each of them. Figure 10 shows the confidence ellipses for independent variables.

Figure 10(a) shows that the panel of 20 assessors provided sensory profiles that are different for each concert hall. There is also a significant difference between halls because the confidence ellipses do not overlap. Listening positions are quite well separated, as only some R1, R4, and R5 ellipses overlap. The size of the confidence ellipses indicates that the extreme positions (TaR6, TaR8, KoR6, and SeR1) have less variability than the others. Finally, the ellipses of the stimulus signals are superimposed, which means there are no significant differences, although the orientation of the Mozart ellipse suggests that Mozart has been perceived slightly differently.

E. Hierarchical multiple factor analysis with objective data

The Hierarchical MFA (HMFA)[41] is an extension to MFA that allows the analysis of hierarchical data, including objective room acoustic parameters. When the data are organized as shown in Fig. 11, HMFA applies the MFA first for the data of each musical piece, and then another MFA on the novel factors to rotate the factor spaces. Finally, the

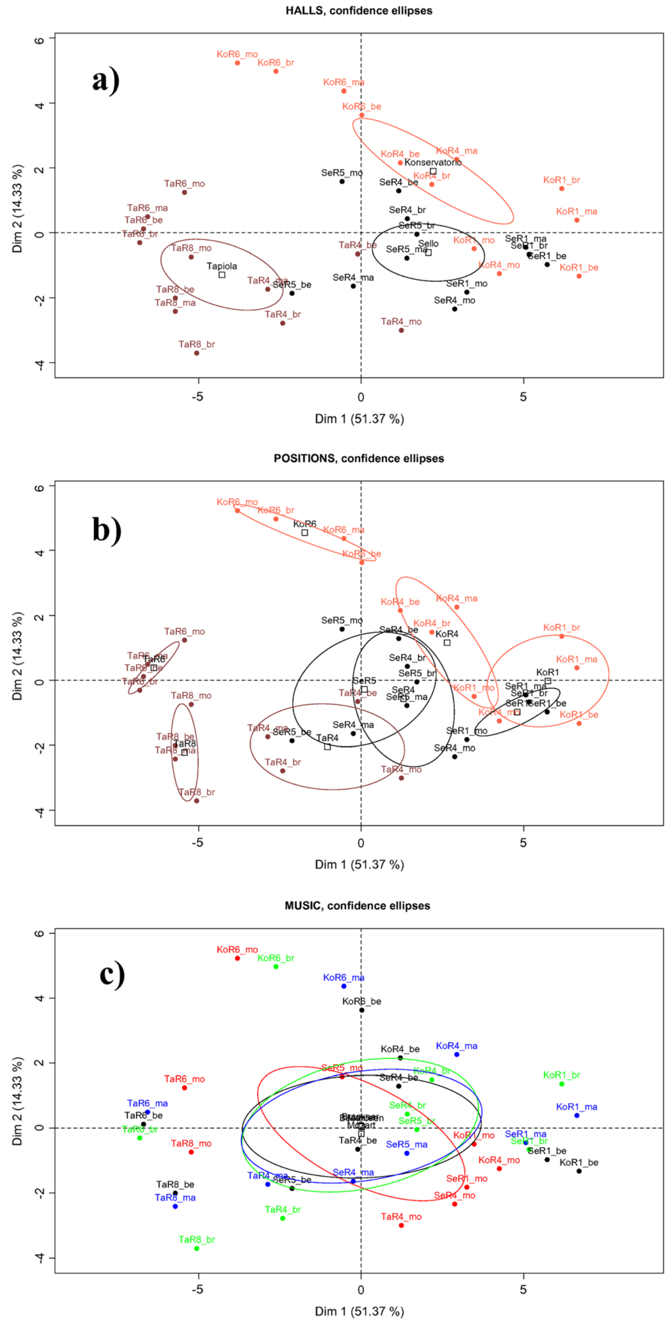

FIG. 10. (Color online) Scatter plots of the data with 95% confidence ellipses.

result is linked with equal weight to the PCA of the objective data to enable the comparison of all data in the common factorial space.

The objective data, i.e., room acoustic parameters were analyzed from the impulse responses measured from 24 loudspeaker channels to all receiver positions. Table IV shows the means of 24 values for each receiver position, computed according to the guidelines of the ISO3382-1 standard.[42] Table IV is adapted from the standard and it suggests the objective parameters and their relevant octave bands to describe subjective listener aspects. Note that the measurements were not strictly according to the standard because the sound sources were not omnidirectional.

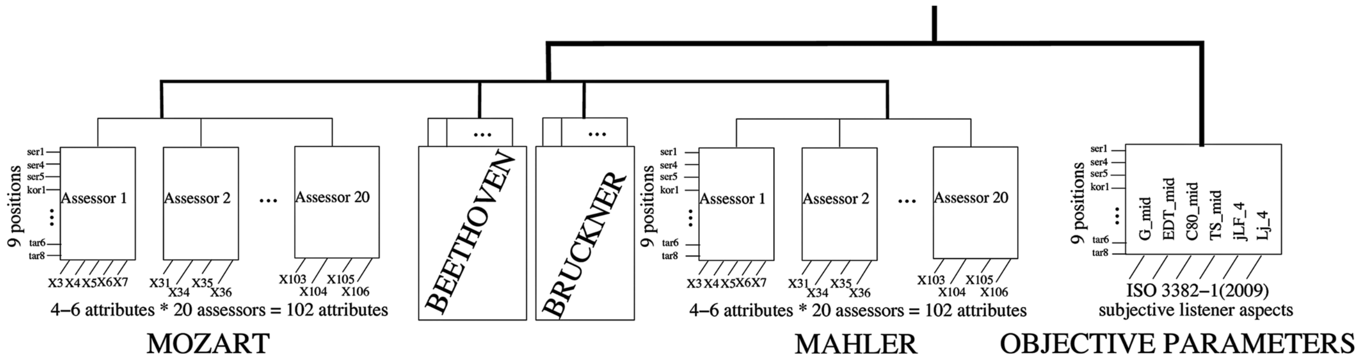

FIG. 11. The organization of the data for the HMFA analysis.

However, the small active loudspeakers are not far from omnidirectional in the octave bands used.

Figure 12 shows the HMFA results. The data are quite well presented in two dimensions because dimensions 1 and 2 explain 74.5% of the total variance of the data. The plots illustrate the mapping of listening positions on the common factorial space. In addition, the objective data are included as individual vectors and the subjective perceptual dimensions are shown with average vectors of attribute groups for each musical piece.

The first comparison in Fig. 12(a) is done in the main principal direction, by plotting the vectors of Loudness and Distance, and subjective level of sound as defined in Table IV. With all pieces of music, the average vectors point almost to the same direction as the objective loudness vector, meaning that *G* orders the samples in the same order as assessors when they rated samples according to Loudness and Distance related attributes. In other words, *G* predicts the perceived loudness and distance in these three concert halls very well. Figure 12(b) shows that perceived Width of Sound is well predicted with the objective listener envelopment (LEV), but not with the objective Apparent Source Width. This suggests that the assessors might have been listening to the overall width of the sound field, not particularly the width of the orchestra.

The ISO3382-1 suggests that perceived reverberance can be measured with mid frequency early decay time (EDT). Figure 12(c) illustrates the perceptual dimensions of Reverberance_1 and Reverberance_2 for each piece. The objective reverberance vector is in the middle of all vectors, thus EDT predicts to some extent the reverberance. However, only one objective measure cannot explain the difference of two reverberance attribute groups, in particular when the musical piece seems to also introduce variation to the data. Finally, Fig. 12(d) shows that the objective clarity measures TS and C80 point exactly to the opposite directions and the averages of Definition attributes are not parallel with this line. Therefore, neither TS nor C80 could predict well the judged definition or clarity for the used samples.

VI. DISCUSSION AND FUTURE WORK

The clustering and (H)MFA analyses show that the applied IVP method is suitable for concert hall acoustics evaluation. IVP enables identifying salient perceptual attributes, without prior knowledge. (H)MFA was performed based on the individual attributes of each assessor, but a consistent and reasonable grouping of the attributes and ordering of the samples were obtained. In other words, the individually elicited attributes worked surprisingly well and provided a good consensus between assessors who were trained during the experiment but cannot be considered as expert assessors.[14]

The vocabulary elicitation provided a long list of attributes that are very useful for future studies on the perception of concert hall acoustics. Due to the chosen music samples, many attributes are related to loudness or distance since they were obviously the easiest criteria with which to rate

TABLE IV. Acoustic quantities grouped according to listener aspects according to ISO 3382-1 (2009) standard (Ref. 42). Note that G and L_j are only relative values because the sources were not omnidirectional as defined in the standard.

Subjective listener aspect	Acoustic quantity	Average of octave bands	Sello			Konservatorio			Tapiola		
			R1	R4	R5	R1	R4	R6	R4	R6	R8
Subjective level of sound	G in dB	500 to 1000	9.3	9.5	8.5	9.8	8.9	9.4	7.3	5.5	4.8
Perceived reverberance	EDT in s	500 to 1000	1.7	1.5	1.6	2.2	2.1	2.2	2.0	2.0	1.8
Perceived clarity of sound	C80 in dB	500 to 1000	− 0.4	0.4	0.5	− 0.4	− 2.3	− 3.4	− 1.1	− 1.8	− 0.9
Perceived clarity of sound	TS in ms	500 to 1000	119	108	112	135	159	168	141	146	137
Apparent Source Width	j_{LF} in %	125 to 1000	35	34	31	35	33	30	26	25	31
Listener Envelopment	L_j in dB	125 to 1000[a]	2.0	0.6	− 0.3	1.5	1.0	2.3	− 2.0	− 4.0	− 4.1

[a]Energy averaged.

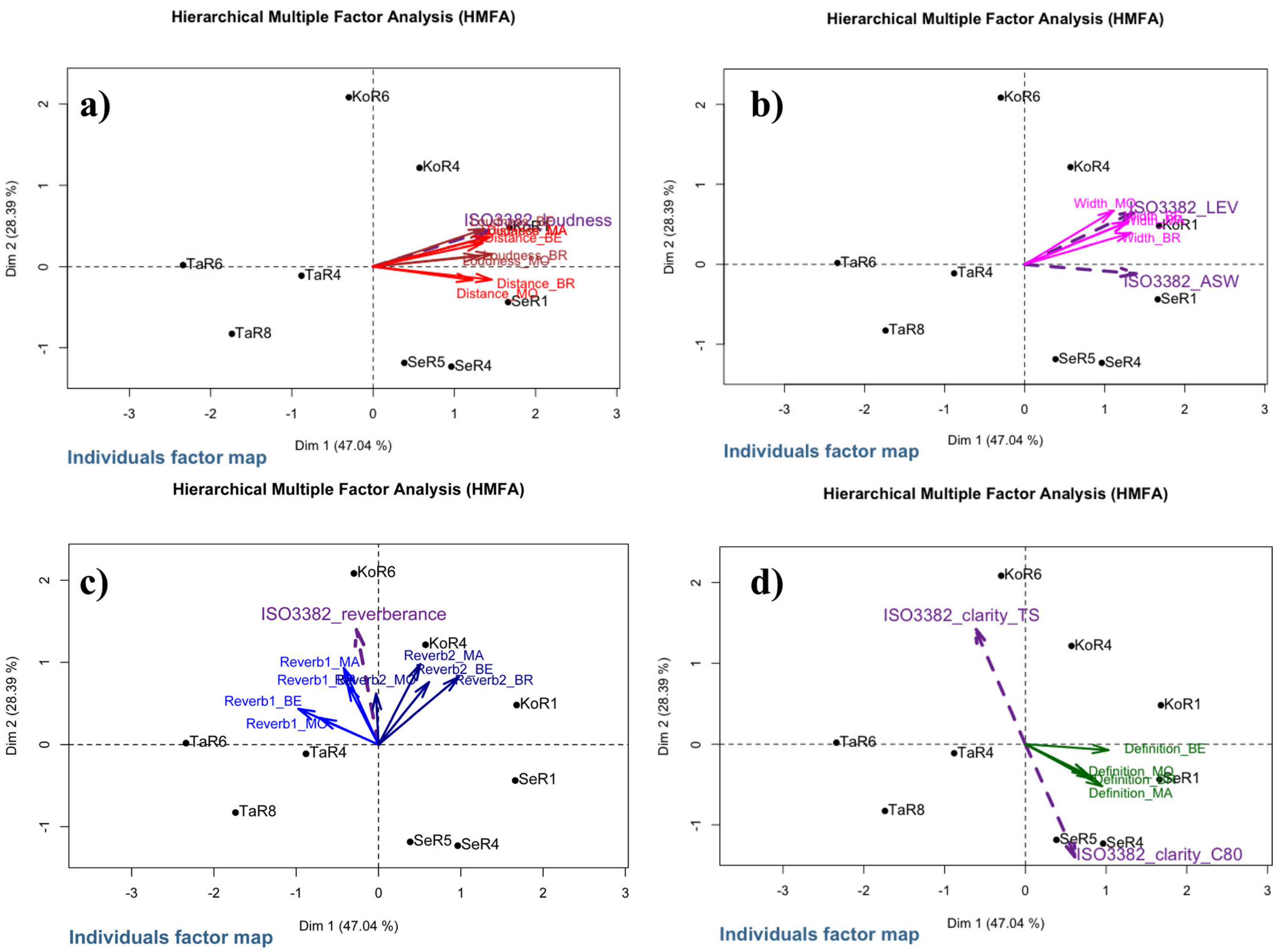

FIG. 12. (Color online) HMFA results of recording positions (MO = Mozart, BE = Beethoven, BR = Bruckner, MA = Mahler). (a) Loudness. (b) Apparent Source Width. (c) Reverberance. (d) Clarity.

samples. Almost all assessors introduced at least one attribute related to reverberation and one attribute on definition or clarity. Many attributes also described width, broadness or source width, probably due to instructions given to concentrate on the spatial aspects of the samples. Interestingly, the list has some attributes describing the timbre or frequency content of the sound, but these attributes are spread out in several clusters. Finally, attributes on the overall quality of the samples or coding artifacts do not exist at all.

The clustering was done based on hierarchical clustering, but some attributes could be moved to another group. For example, both LDA and MFA analyses suggest that attribute X5 (emphasis on bass) could be in the Width of Sound group instead of Reverberance_2. In fact, all other attributes related to bass perception are in the group of Width of Sound. In spite of such borderline cases, the clustering of attributes is quite clear.

The result of this study suggests that at least five perceptual dimensions were identified. They are reverberance related to the size of the space, enveloping reverberance, width of sound, loudness/distance, and definition. The findings are well inline with previous studies. Loudness, for example, has been found to be an important factor in many studies.[2,3,5,7,8] In addition, reverberance is also a major factor in related studies.[2–5,7,9] Other found perceptual dimensions include many attributes familiar to acoustics researchers.

This study demonstrated the potential of the sensory evaluation method for assessing concert hall acoustics. However, obvious future work includes development of the methodology to achieve more detailed results. First, the loudspeaker orchestra requires some development for a better-sounding, fully controllable orchestra. In addition, some absorption and diffusive elements on the stage would simulate better the real orchestra, consisting of dozens of players. The recording and the sound rendering processes produce good quality spatial sound, but they are not perfect yet. The concert halls chosen could represent better and well-known halls, and the recording positions should not be as extreme as in this study. This strategy would reduce the dominance of loudness and distance attributes and hopefully would reveal more details of perceptions.

VII. CONCLUSIONS

Sensory evaluation of concert hall acoustics, implemented with individual vocabulary profiling, has been studied. It was shown that such methodology works well for assessing subjective differences between concert halls and between seats in one hall. The study measured effective perceptual characteristics in a statistically robust manner and helped identify salient perceptual attributes. The method allowed the simultaneous comparison of sound samples, which were recorded in three concert halls by using a virtual orchestra consisting of 34 loudspeakers.

The results include the clusters of individual attributes, sensory profiles of studied concert halls and the ordination of sound samples. The main cluster was formed with attributes describing loudness and distance because such attributes discriminate best between the sound samples. Attributes related to reverberation were divided into two subgroups. One of them was related to enveloping reverberance and the other to the size of the space. The samples were also ordered based on definition or clarity where the order is reversed compared to the reverberation describing the size of the space. The three recorded concert halls were clearly distinct from one another and musical signals seem to provide each a slightly different sensory profile. Even though the results are good, it should be noted that they depend heavily on the used stimulus set. More similar studies are needed in the future to have better overall understanding of concert halls.

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