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Auditorium Acoustics Assessment with Sensory Evaluation Methods

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ABSTRACT

This paper reports a concert hall acoustics evaluation study which was performed with individual vocabulary profiling method. The key point in this method is that each assessor applied his individual attributes with which he rated the samples. The samples were recordings in three positions in three concert halls and parallel comparison between the samples was obtained by applying a virtual symphony orchestra, consisting of 34 loudspeakers, to excite the hall. The subjective results of 20 assessors showed that the main perceptual dimensions in this case were loudness and reverberance. In addition, clear group of attributes were formed for apparent source width, definition and distance. The applied methodology allows also the comparison of subjective results and objective room acoustic parameters. It is shown that ISO3382-1 parameters cannot explain all the variance in the subjective data.

INTRODUCTION

Since the pioneering work of Sabine [1], 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 “excellent” acoustics. Table 1 collects the main studies which have concentrated on understanding the perceptual characteristics of concert halls. As indicated by Kahle and Jullien [2], the different subjective responses can depend on the acoustics, the musical piece, the subject and the position in a hall. These facts make the subjective assessment of concert hall acoustics very challenging and the applied methodology varies between studies.

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, non-identical stimuli and the mood of subjects [2]. Kürer at 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 exciting halls with anechoic recordings, played back by two loudspeakers on the stage. In IRCAM, room acoustics simulation has been 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. One shortcoming in all of these studies has been that only one or two sources on the stage do not represent well a real symphony orchestra.

Despite of the numerous earlier studies, the human perception of concert hall acoustics is not fully understood yet. Our aim is to bring novel methodology to the field to enable better understanding of the descriptors that contribute to the perception of acoustics. We have tried to overcome several drawbacks of earlier subjective concert hall evaluation studies. Our target was to design a listening test in which different halls and seats could be compared while all other factors remain constant. For that the excitation of the halls was done with perfectly controllable orchestra, a virtual orchestra consisting of 34 loudspeakers. The loudspeakers played the anechoic symphony music that was again recorded in carefully selected listening positions with multi-microphone technique. Then, for the actual listening test in the laboratory conditions, the recorded musical excerpts were reproduced with an advanced 16-channel spatial sound reproduction system. Thus, a simultaneous comparison of samples was possible. In addition, a sensory evaluation method, namely the individual vocabulary profiling (IVP) [14], was applied in the listening test to gain a deeper understanding of the perceptual criteria applied to the rating of recorded samples and to solve the possible ambiguities of predefined attribute interpretation.

This paper is organized as follows. The procedure to create the stimuli for the listening test and the methodology of the applied listening test is reviewed next. Then the main results of the subjective listening test is shown. As a novelty, the sensory profiles of studied concert halls are presented. In addition, the standard objective data is linked to the subjective listening test results with advanced statistical analysis and the correspondence of the objective and subjective data is discussed.

Table 1: The subjective auditorium acoustics assessment experiments, data collected from various references, mainly [5–7].

Who	Year	Excitation	Recording/ Reproduction	Attributes	Analysis	Main Findings
Sabine	1900	-	-	-	-	1. loudness, 2. interference and resonance, 3. reverberation and echos
Beranek	1960s-	live orchestra	in-situ listening	interviews	mapping with objective data	1. reverberance, 2. loudness, 3. spaciousness, 4. clarity, 5. intimacy, 6. warmth, 7. hearing of stage
Hawkes & Douglas	1970s	live orchestra	in-situ listening	16 semantic differential scales	factor analysis	1. reverberance, 2. balance and blend, 3. intimacy, 4. definition, 5. brilliance
Barron	1988	live orchestra	in-situ listening	questionnaire	correlations	G, EDT, LEF, Two preference groups: reverberance and intimacy
Kahle	1995	live orchestra	in-situ listening	questionnaire of 29 questions	PCA, correlations	8 descriptive factors
Berlin group	1970s	live orchestra	dummy-head/ headphones	questionnaire	19 direct attribute scales	1. loudness (G), 2. clarity (Ts), 3. timbre (EDT ratio). Two preference groups: loud sound and clear sound
Göttingen group	1970s	anechoic music/ 2 loudspeakers on real stage	dummy-head/ 2 loudspeakers	preference, paired comparison (equalized loudness)	factor analysis	negative correlation between distinctness and preferred consensus factor; RT, D50, IACC
Lavandier	1989	anechoic chambre music/ simulation	simulation/ 9 loudspeakers	non-verbal dissimilarity method	INDSCAL	11-14 descriptive factors
Soloudre & Bradley	1995	anechoic music/ one omni loudspeaker	dummy-head/ 2 loudspeakers	paired comparison, preference	correlation	1. clarity, 2. treble
Lokki et al.	2010	anechoic music/ 34 loudspeakers on real stage	B-format/ 16 loudspeakers	individual vocabulary development	AHC, LDA, (H)MFA, RDA	1. loudness and distance, 2. reverberance (2 groups), 3. definition, 4. apparent source width

CONCERT HALL ACOUSTICS ASSESSMENT

In this section, the used listening test method and the recording of the stimuli are briefly overviewed. The detailed description of the process is documented in other articles [15, 16].

The Applied Sensory Evaluation Method

The subjective evaluation was performed with individual vocabulary profiling [14] in which each assessor develops his own set of attributes for the evaluation of stimuli. The implemented concert hall acoustics evaluation method consisted of four separate listening sessions for each assessor. Each session lasted a maximum of two hours 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.

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 [15]. 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 [17], and they all had musical background because they were mainly students of acoustics, psychology, and musicology.

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. 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 to create 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.

Figure 1: Used graphical user interface (original Finnish texts translated to English).

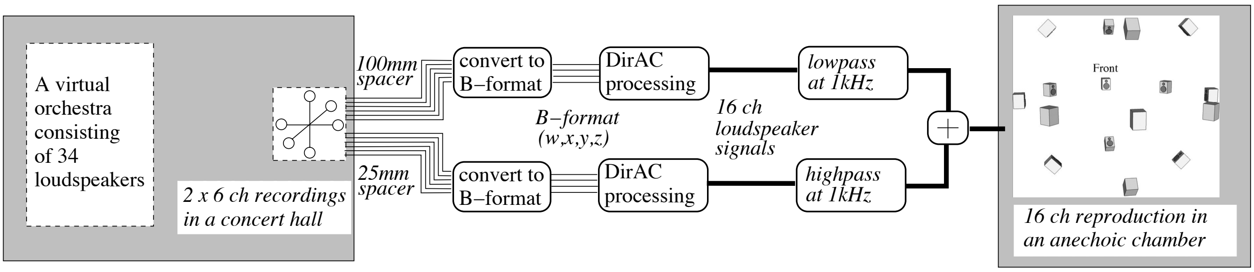

Figure 2: Signal processing chain to obtain comparable stimuli for the subjective evaluation. The loudspeaker orchestra is recorded with 6 microphones twice, with 25 mm spacer and 100 mm spacer. Both six microphone signals are converted to B-format signals that are processed with DirAC for rendering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

A very important feature in individual vocabulary profiling is that the assessor should be able to evaluate stimuli comparatively. This is hard to achieve because multiple sound samples cannot be listened to simultaneously. However, by playing samples in parallel and enabling seamless 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.

Recording of 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. [18], see also [16]. The main enhancement was the extra loudspeakers for string instruments lying on their backs on the floor, thus emitting high frequencies also to the upper hemisphere. This arrangement was chosen to roughly compensate for the difference between a string instrument and a loudspeaker radiation patterns [19].

The loudspeaker orchestra emitted anechoic music from 34 loudspeakers to excite each hall identically. The recording of anechoic symphony music has been reported earlier by Pätynen et al. [20]. Moreover, the details of the signal processing needed to create a natural sounding loudspeaker orchestra have been reported by Lokki and Pätynen [21]. Four musical excerpts were used from different composer, see details from [18].

In each receiver position, each musical piece was recorded 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 [22] when six omnidirectional signals are converted to a first order B-format signal (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) [23] to create 3D spatial sound reproduction. DirAC performs a time-frequency analysis of the B-format signal and computes the sound intensity and diffuse 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. It has been proven [24] that DirAC produces better perceptual quality in loudspeaker listening than other available techniques, such as Ambisonics [25], using the same microphone input.

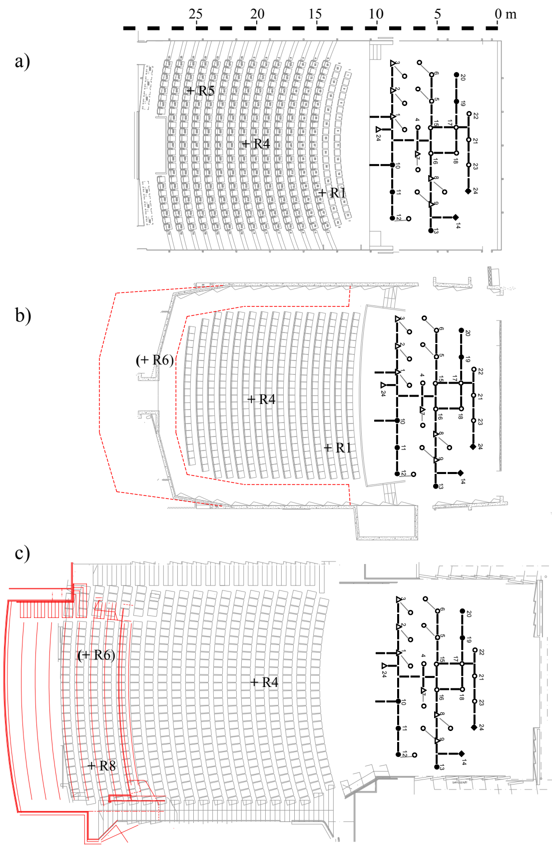

Figure 3: Halls and recording positions, a) Sello, b) Konservatorio, c) Tapiola. The layout of the loudspeaker orchestra was exactly the same on each stage.

The measured concert halls (plans in Fig. 3) were not a selection of world famous concert halls, but they were easily 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, but 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. Tapiola hall 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. 3; 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. 3.

RESULTS

Twenty assessors completed the individual vocabulary profiling and each of them elicited four, five, or six attributes. In total, 102 attributes were collected, and each assessor completed 16, 20, or 24 sets of evaluations. One set consists of nine samples that were rated with an attribute. The presentation order of music and attribute were both randomized. Because one attribute was applied for all musical pieces, it is possible to see how attributes are grouped within the entire data set. Therefore, a data matrix 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.

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, agglomerative hierarchical clustering (AHC) based on Euclidean distances, and in conjunction with Ward's minimum variance method [26], was applied to the entire data set. The colored dendrogram in Fig. 4 shows that data are grouped into seven clusters. The main cluster is still manually divided into three subgroups based on the definitions of the individual attributes. All elicited attributes are collected in Table 2, 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. [15], and the attributes in Table 2 are translated by the authors of this article.

Each of the formed groups consist of 7 to 16 individual attributes (see Table 2). First, the minor branch of the dendrogram has two groups, named Reverberance_1 and Reverberance_2. Based on the individual attributes, it could be stated that Reverberance_1 is related to the size of the space. In contrast, Reverberance_2 seems to be related to enveloping reverberation since four non-reverberation attributes are broadness, envelopment, width, and bass. Another possibility is that assessors rating reverberation in group Reverberance_1 have listened to "stop-chord reverberation" and Reverberance_2 is related more to running reverberation. Nevertheless, the separation between these two groups is clear.

The next group of attributes is Apparent Source Width, which 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 frequency balance or bass, are also indicated by three assessors. The main cluster contains attributes related to Loudness, Distance, and Ungrouped. Although assessors seem to have rated samples similarly according to Loudness and Distance attributes, they are considered as 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, but it is here taken as an own group.

The last branch in Fig. 4 contains groups of Balance, Openness, and Definition. Based on attribute descriptions Balance is even related to the timbre (balance between low and high frequencies) or to the localization/direction (left - right balance). Definition could be described as the clarity or separability of instruments or melodies. In addition, localization- and timbre-related attributes are mentioned, mainly about the high frequency content of the signals (clarity). Finally, the last cluster is Openness that can be described by the ability of music to breath freely, or how airy is the music. In addition, a few assessors describe the separability of instruments. Some distance- and timbre-related attributes are also in this group.

Sensory Profiles of the Studied Concert Halls

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 since they give information how these halls sound. The grouping is our interpretation of these individual attributes 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. 5. In these profiles an average of individual attributes within a group is calculated. In addition, Balance attributes are not presented and one average value of the main cluster (including Loudness, Distance, and Ungrouped) is used.

Figure 5 lets us characterize the studied halls as follows. The Sello hall has the greatest definition and it is less reverberant that the others. In addition, it produces wide perception of sound as does also the Konservatorio hall. However, the Konservatorio hall is the most reverberant and enveloping since it has the highest values of Reverb_1, Reverb_2, and Source_Width. The Tapiola hall gives reasonable reverberation (Reverb_1), but envelopment is poor (Reverb_2 and Source_Width). Interestingly, the definition is also the smallest. However, the choice of the recording positions might has an effect to the results since in the Tapiola hall the positions are on average at longer distance.

Detailed Analysis with Multiple Factor Analysis

In addition to clustering, ordination complements the multivariate analysis. Ordination orders multivariate objects so 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) [27, 28] 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. 6), and PCA is performed on the data set of each assessor. Each set is then normalized by dividing all its elements by the square root of the first 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 [29, 30] on the centered and scaled data, organized as shown in Fig. 6. The first two dimensions explain 65.7 % of the data, and the contribution of higher dimensions is rather small. Therefore, the results are showed only on the first two dimensions. The loadings of all 102 attributes to two main principal axes can be visualized individually with a variable factor map [16]. Here such a map is not presented, instead a biplot in Fig. 7 is showing only the average vectors of each attribute group and the individual attributes are marked with small labels. In addition, the biplot is showing how individual samples are mapped to

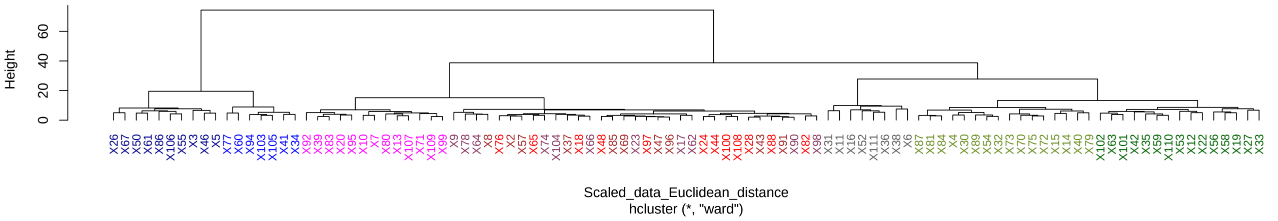

Figure 4: Grouping of attributes is based on agglomerative hierarchical clustering with Ward's method based on Euclidean distances.

Table 2: 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
Apparent Source Width (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), sharpness (X104), liveness (X64), muddy (X98), stand out (X9), intimacy (X90), eq (X62), 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

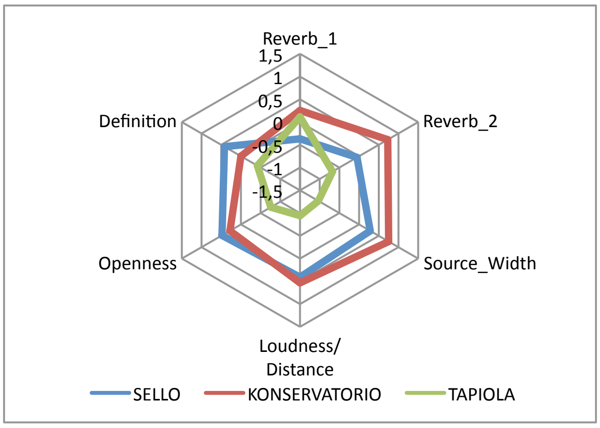

Figure 5: Spider plots of the data for halls

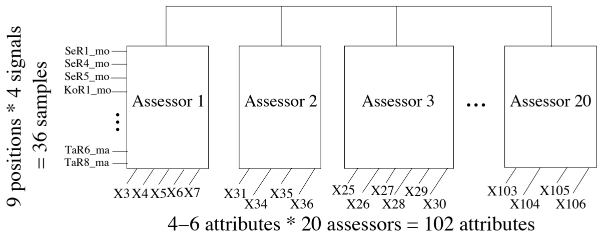

Figure 6: The rows of data matrix consist of 4 musical pieces × 9 receiver positions (3 positions in 3 halls). 102 columns contain 4 – 6 attributes by 20 assessors.

the space defined by principal component dimensions. Figure 7 contains a lot of information and the main observations are summarized next.

First of all, it seems that the three halls have a characteristic sound since they are more or less separated, as illustrated with colors. The average vectors of each attribute group can be considered as perceptual dimensions and their orientations show the directions of the largest variances 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. 3) are mapped to both ends. The Ungrouped attributes are overlapping with Loudness attributes, suggesting that assessors have possibly ordered the samples based on loudness. The Reverberance_2 dimension separates the halls best, 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 Apparent Source Width direction indicates that the Konservatorio and Sello halls produce wider perceived sources than Tapiola hall. In addition, a perceived wide sound source is generally considered a function of low frequency energy, and in particular, lateral energy [31]: therefore, the Apparent Source Width vector between enveloping Reverberance_2 and Loudness is well justified.

Sensory Profiles of All Seats

Figure 8 shows the listening test data for each recording position with spider plots. First plot on the left shows the sensory profiles of positions in the Konservatorio hall. The front position R1 is rated the highest with all perceptual dimensions except Reverb_1 and Reverb_2. In contrast, the position on the balcony (R6) is in the totally reverberant field giving low ratings for definition, but very high ratings for both reverberances. The middle plot (Sello hall) shows nicely that this hall has no surprises, the ratings go as expected when the distance to the orchestra grows. On the right plot, it can be seen 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 red lines which show the perceptual profiles of "equal" 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 blue curves of the Konservatorio and Sello halls are from a position (R1) which is very close to the loudspeaker orchestra. Obviously, the direct sound in these positions is dominating, thus these seats gave similar sensory profiles, i.e., the hall does not affect to the sound at all.

ANALYSIS WITH OBJECTIVE ROOM ACOUSTIC PARAMETERS

The ISO3382-1 standard defines the objective parameters for measuring concert halls [32]. Table 3 is adapted from the standard and it suggests the objective parameters and their relevant octave bands to describe subjective listener aspects. Here the obtained subjective data are compared with the single number objective data averaged on the octave bands as indicated in Table 3.

Room acoustic parameters were analyzed from the impulse responses measured in all 9 receiver positions. They were calculated as the mean of 24 values, one from each loudspeaker channel following the guidelines of the ISO3382-1 standard [32]. The measurements were not strictly according to the standard because the sound sources were not omnidirectional. However, the used small active loudspeakers are not far from omnidirectional at the low and mid frequency octave bands.

For comparison of subjective and objective ordination, the data were organized as shown in Fig. 9 for the Hierarchical Multiple Factor Analysis (HMFA) [33]. The analysis does first the MFA for the data of each piece and then one common HMFA for all pieces. Then, it links this result with equal weight to the PCA of the objective data. Such analysis is very convenient because both objective and subjective data are mapped to the same space, defined by common principal components. This enables direct comparison of individual attribute vectors and the locations of the samples.

Figure 10 shows the HMFA results with the locations of each piece and the objective data. Each listening position is represented through the five points corresponding to objective data and four musical pieces. In addition, the mean point of subjective data and the general mean point (black dot) is visualized. Figure 10a shows that music used in sample rating has a slight effect. If ratings would have been the same with all pieces then the colored dots would have been in the same positions. In addition, the objective data granted more importance to the second dimension than the subjective data. Results also show that the data are quite well presented in two dimensions because dimensions 1 and 2 explain 74.5% of the total variance of the data. Figure 10b shows that no real information can be extracted from higher principal dimensions.

Figure 11 shows similar result than Fig. 7, but now the objective data is included as individual vectors. The subjective perceptual dimensions are computed as an average of all musical pieces. Because the music has some effect to the ordination, the comparison of the objective and subjective directions is done so that average vector for each piece is computed, see Fig. 12.

The first comparison is done in the main principal direction, by plotting the vectors of Loudness, Distance, and subjective level of sound as defined in Table 3. It can be seen in Fig. 12a that with all pieces the average vectors point almost to the same direction than G vector, meaning that G orders the samples exactly in the same order than assessors when they rated samples according to Loudness and Distance related attributes. In other words, G predicts very well the perceived loudness and distance in these three concert halls.

The ISO3382-1 suggests that perceived reverberance can be measured with EDT. Figure 12b illustrates the perceptual dimensions of Reverberance_1 and Reverberance_2 for each piece. It can be seen that the EDT vector is in the middle of all vectors and there is noticeable music dependency. It could be concluded that EDT predicts to some extend the reverberance, but naturally only one measure cannot predict the difference between running and "stop-chord" reverberances.

Interesting result can be seen in Fig. 12c, which shows that perceived Apparent Source Width (ASW) is much better predicted with the objective LEV than with the objective ASW. This suggests that assessors might have been listening to the overall width of the sound field, not particularly the width of the orchestra. Interestingly, the ASW and LEV directions orders the positions so that largest values are first for Konservatorio positions (KoR1, KoR6, KoR4), then for Sello positions (SeR1, SeR4, SeR5) and finally for Tapiola positions (TaR4, TaR8, TaR6), i.e., ASW and the objective LEV separate the halls best. Finally, Fig. 12d shows that the objective TS and C80 point exactly to the opposite directions and almost orthogonal to this line are the directions of Definition and Openness. Thus, neither TS nor C80 could predict the judged definition or clarity for these samples.

DISCUSSION AND CONCLUSIONS

Almost all studies on concert hall acoustics have found loudness to be one of the most important characteristics of a hall, as can be seen in Table 1. Here the main principal direction is also loudness, meaning that assessors rated the samples consistently with loudness. Loudness and distance (or related words) were produced by the assessors most frequently during attribute elicitation, suggesting that there were the differences that were most obvious to them. Reverberance has also been one major perceptual direction in many studies. Interestingly, in this study two clearly separated groups of reverberance were found. Other found perceptual dimensions are definition, openness, and apparent source width. The last one could also be related to the overall width of the perceived sound because only some

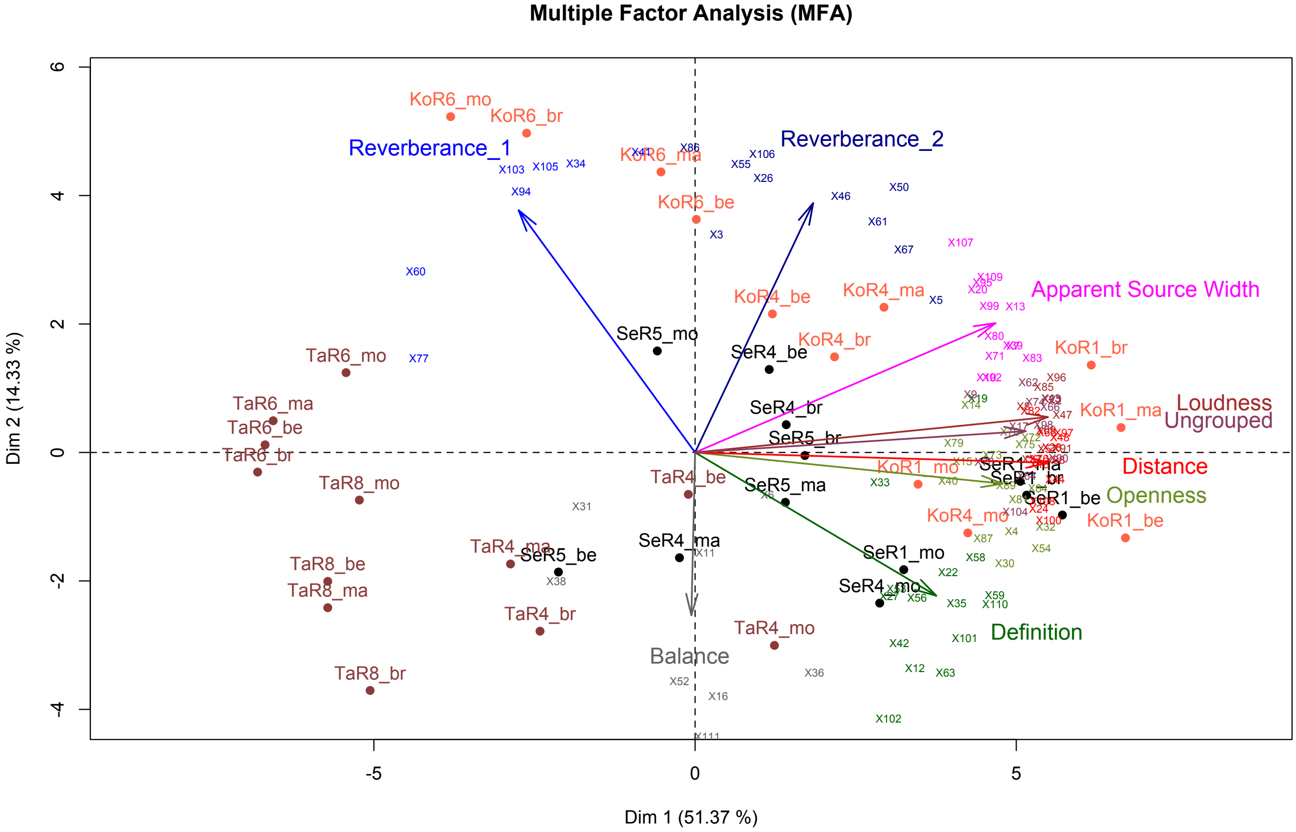

Figure 7: MFA results for the recording positions, colored by concert halls. The abbreviations are Se = Sello, Ko = Konservatorio, and Ta = Tapiola for halls, and mo = Mozart, be = Beethoven, br = Bruckner, and ma = Mahler for musical pieces. For example KoR1_mo means position R1 in Konservatorio hall with stimulus signal Mozart.

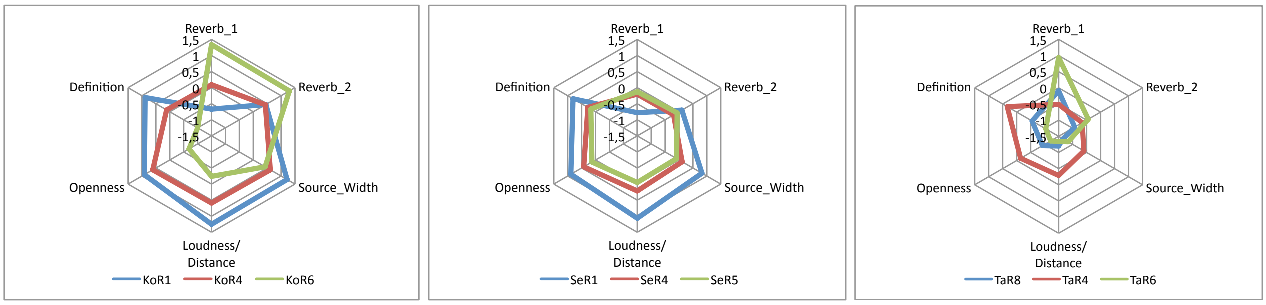

Figure 8: Spider plots of the data for all positions. Note that positions R4 (marked with red) are at equal distance from the loudspeaker orchestra in each hall.

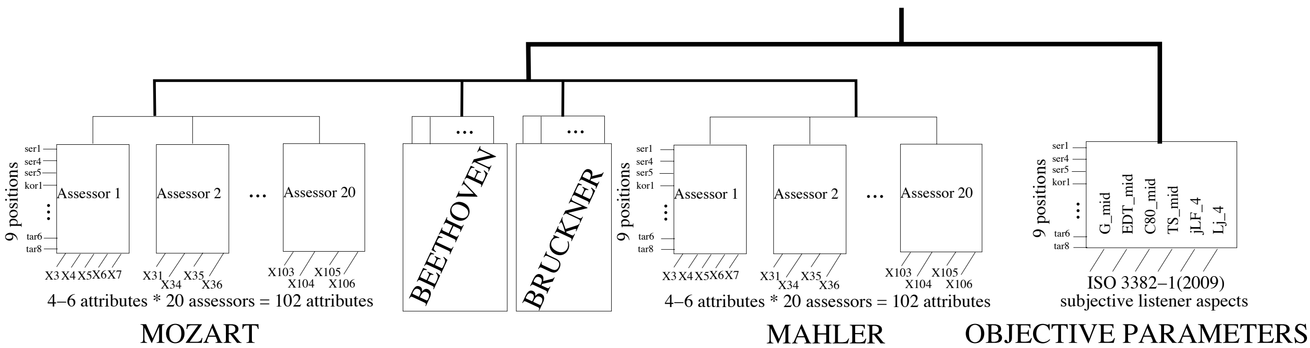

Figure 9: The organization of the data for the HMFA analysis.

Table 3: Acoustic quantities grouped according to listener aspects according to ISO 3382-1 (2009) standard [32]. 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** R1	R4	R5	**Konservatorio** R1	R4	R6	**Tapiola** R4	R6	R8
Subjective level of sound	G in dB	500 to 1000	14.1	14.2	13.2	13.6	12.8	13.4	11.9	10.1	9.4
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*	9.5	9.0	8.0	9.4	9.1	9.8	7.0	5.9	4.7

*energy averaged

attributes were defined explicitly as width of the sound source.

The HMFA revealed interesting facts about the correspondence of subjective and objective data. Objective G matched well with subjective loudness, as did also LEV to subjective ASW (or perception of width). However, C80 values did not correspond with the subjective definition ratings and subjective reverberance had quite large variance among assessors, thus it cannot be predicted with a single EDT measure. The HMFA results also showed that the listened music has an effect to the perceived acoustics and because objective measures are computed from impulse responses they cannot explain the variation between used musical pieces. In fact, with the Redundancy Analysis it can be shown that the presented objective room acoustic parameters explain only 61.2% of the variance of the whole data [34]. Therefore, in the future some room acoustic parameters which can be computed directly from the recorded music, not from the impulse responses, should be developed.

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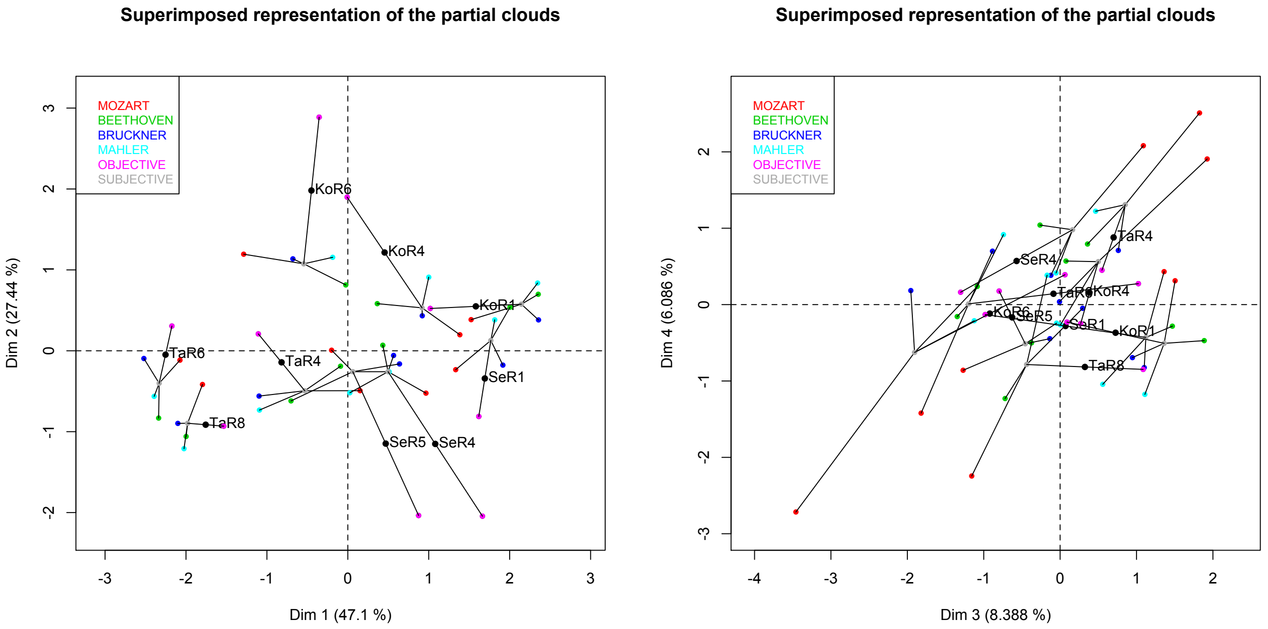


(a) Dimensions 1 and 2, 74.5% of the total variance. (b) Dimensions 3 and 4, 14.5% of the total variance.

Figure 10: Superimposed representation of music and objective parameters.

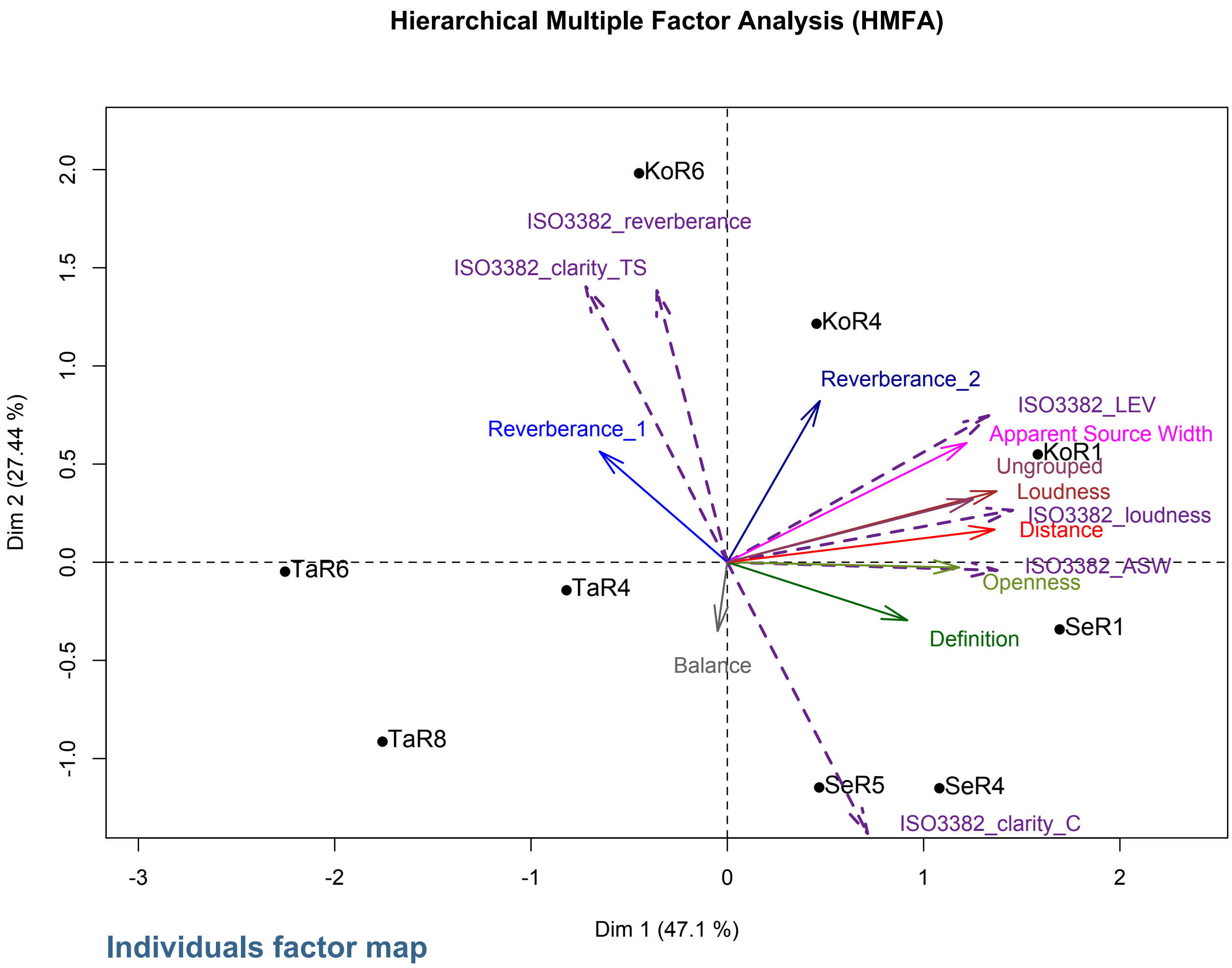
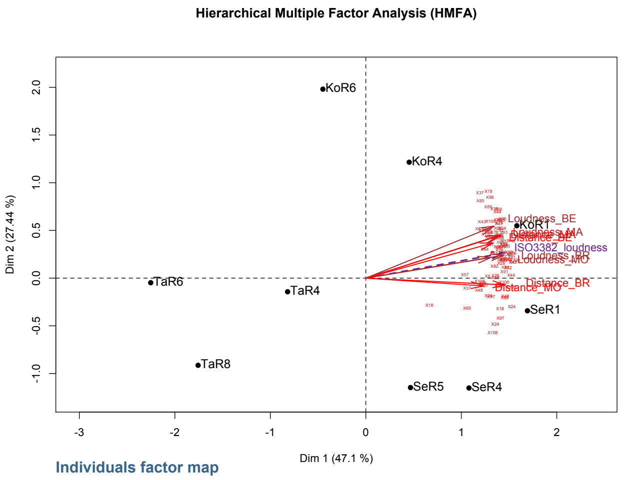
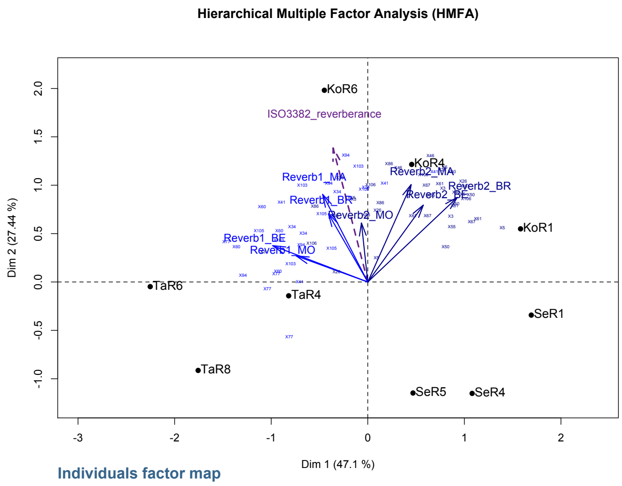


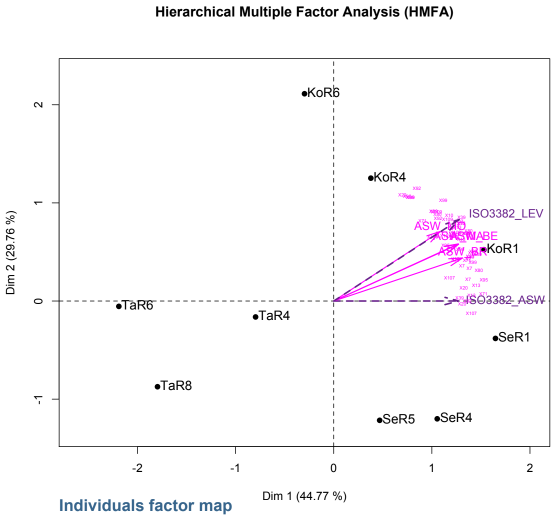
Figure 11: The result of the HMFA analysis which shows the ordination of samples in the main principal component space with both the subjective and objective data. The subjective vectors are averages of individual attribute vectors as in Fig. 7.



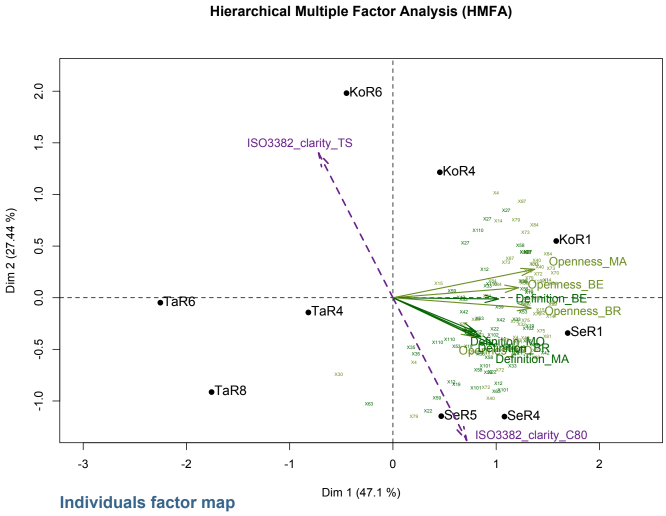
(a) Loudness, Distance and ISO3382_loudness.



(b) Reverberance_1, Reverberance_2 and ISO3382_reverberance.



(c) ASW and ISO3382_ASW.



(d) Definition, Openness and ISO3382_Clarity.

Figure 12: Comparison of ISO3382-1 parameters and subjective results (MO = Mozart, BE = Beethoven, BR = Bruckner, MA = Mahler).

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