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Relationships between preference ratings, sensory profiles, and acoustical measurements in concert halls

Antti Kuusinen,^{a)} Jukka Pätynen, Sakari Tervo, and Tapio Lokki
Aalto University School of Science, Department of Media Technology, P.O. Box 15500, FI-00076 Aalto,
Finland

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Preferences of concert hall acoustics are explored with preference mapping. The investigation is performed on previously gathered data from individual vocabulary profiling of nine concert halls and three pieces of symphonic music, namely, excerpts of compositions by Beethoven, Bruckner, and Mozart. Individual preferences are regressed onto a latent three-dimensional sensory space obtained by multiple factor analysis of descriptive sensory data. Overlaying individually estimated preference surfaces onto one another produces preference maps which illustrates both the overall preference of the stimuli as well as differences between individual listeners. A comparison of the maps between music motifs illustrates how each music signal affects the weighting of different acoustical qualities in preference judgments. Differences in preferences between individuals are pronounced in the excerpts of Beethoven and Bruckner, while the responses are more homogeneous for Mozart music motif. Overall, proximity is identified as the main aspect associated with preference, but also loudness, envelopment, and bass are important. A correlation analysis of objective parameters and subjective perceptions substantiates the importance of lateral sound energy for good concert hall acoustics. Particularly, the lateral early energy fraction at high frequencies is found to be associated with the perception of proximity, and hence, also with preference.

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I. INTRODUCTION

An early study on reverberation time (RT) by Kuhl (as summarized by Kuttruff¹) demonstrated that the preferred RT in concert halls depends on the performed music and that opinions about “optimal” acoustic conditions may differ considerably between individual listeners. Although several important acoustical factors have been revealed since, and the current knowledge extends far beyond the classical RT, the dependence of subjective perception on the musical signal as well as on the individual listener has been less studied. More needs to be known also about these aspects, when the correspondence between physical measures and subjective perceptions in concert halls, including preferences, is being refined.

Here, subjective perception and preferences in concert hall acoustics are explored with preference mapping of nine concert halls and three excerpts of symphonic music. The current investigation is based on a sensory evaluation experiment on concert hall acoustics previously reported by Lokki *et al.*² The same data are used as before, but now the focus and novelty is in the detailed analysis of the individual preference responses and the differences between the three music motifs. The main contributions of this work are as follows: First, an external preference mapping technique³ is used to study the relationships between the subjective perceptual qualities and preference responses by regressing the preferences of each listener onto a common latent sensory

space. This analysis elaborates the results presented previously by Lokki *et al.*² with a comparison between the three music excerpts. The analysis also takes into account the differences in preferences between individual listeners. Preference mapping is adopted from the field of sensory science, but appears to be feasible also in studying the listening experience in room acoustics. Considering the multidimensionality of the perceptual phenomena in concert halls, and the different “tastes” of listeners, these types of methods are beneficial in obtaining insight on the different sources of variance that may be present when subjective listening experience is studied. Second, a correlation analysis between acoustical measurements, preferences, and perceptual qualities is presented and provides a complementary view to the data. The results add to the growing evidence of the importance of directional properties of sound field for several perceptual factors, as well as for preference. Especially, higher levels of early and late lateral sound energy at above 2 kHz frequency bands are associated with greater preference.

II. BACKGROUND

A. Previous studies on the perception and preferences of concert hall acoustics

Previous research^{4–9} on concert hall acoustics indicate that there are up to eight main perceptual elements making up the overall perception of acoustical quality in concert halls. The number of elements or the dimensionality of the perceptual space slightly differ between different studies, but taken together the findings indicate that the main perceptual characteristics can be described in terms of reverberance,

^{a)}Author to whom correspondence should be addressed. Electronic mail: antti.kuusinen@aalto.fi

loudness, spaciousness (width and envelopment), definition or clarity, and intimacy or proximity. Also attributes such as warmth, brilliance, and balance have come up in several investigations. Among these attributes, spaciousness¹⁰ or spatial impression¹¹ has been found to be strongly associated with preference, so that listeners tend to prefer sound fields which enhance the experience of auditory spaciousness. Moreover, auditory spaciousness has been found to be composed of at least two separate aspects: Auditory source width (ASW) and listener envelopment (LEV).¹²

Studies have also indicated that listeners may greatly differ in their preferences but can be grouped into few groups according to their preference responses. Barron⁵ identified two groups: One that liked more reverberance and another that preferred more intimacy. Wilkens and Plenge (after Kuttruff¹) also found two groups: The ones who preferred “loud” sound and those who preferred “clear” sound. Similar results were obtained also by Soulodre and Bradley¹³ who found that mainly clarity and treble but also loudness to some extent were significantly correlated with preferences.

Much work has been done to develop objective room acoustical parameters which would correspond to subjective perceptions. This work has led to the ISO 3382-1:2009¹⁴ standard, which currently defines five audience related aspects: Level of sound, reverberance, clarity, ASW, and LEV. Considering preferences, Beranek¹⁵ has concluded that the subjective rank-orderings of concert halls are most importantly correlated with binaural quality index (BQI), early decay time at mid frequencies (EDT_{mid}), strength factor at mid frequencies (G_{mid}), and in 125 Hz octave band (G_{125}), surface diffusivity index, and initial-time-delay gap, in that order. BQI was strongly correlated with the early lateral energy fraction (LF) averaged over 125, 250, 500, and 1000 Hz frequency bands. The comparative evaluation of European concert halls by Schroeder *et al.*¹⁶ revealed that RT, when significantly divergent from the optimal 2.2 s, was highly correlated with consensus preference. In addition, interaural cross correlation coefficient (IACC) and definition parameter D showed negative correlations. It was suggested that IACC and RT may be orthogonal factors, because in physical measures these were found to be uncorrelated, even when the preference data did not show such evidence.

Ando's work^{17–19} and the theory of subjective preference of concert hall acoustics is perhaps the most elaborate account of acoustic preferences up to date. He has concluded that listening level (LL), the delay of early reflections, RT, and the magnitude of the IACC are four orthogonal objective factors of preference of sound fields in concert halls. Moreover, by preference tests where these parameters are manipulated individually, an optimal level for each parameter can be derived. These values can then be compared with the measured values of a real hall in order to reveal the audience areas which best match the preferences of the individual. It is notable that the sound signal itself, via its autocorrelation function, affects the derivation of the optimal acoustic conditions. Hence, not only the individuality of the listeners but also the interaction between the music and acoustics is attempted to be taken into account. Ando's

studies are a significant contribution in many respects, but it is not well established that with musical signals the four factors are also perceptually orthogonal when independency is observed in physical measures.

The previous work on subjective perception and preferences have led many researchers to conclude that there are a number of perceptual features which are perceived by most listeners, but there are also great differences between individuals in terms of the most important features. Kahle⁷ has further pointed out that the different weightings on different perceptual features are manifested in preference responses. The current work elaborates these observations by mapping individual preference responses to a latent sensory space obtained by sensory profiling. The differences between individuals can be observed in the visual representations of the preference maps, where individual preference surfaces as well as areas of shared preferences can be identified. The analysis method, i.e., external preference mapping,³ is briefly presented below. A summary of the data and previously reported results as presented in Lokki *et al.*² and which the current work is based on, is presented in Sec. IIC.

B. External preference mapping

The basic idea of external preference mapping is to investigate which aspects are essential for consumers' preference or acceptability for products or stimuli.³ The preference data is connected to and analyzed in terms of another data set, which can be the result of sensory evaluation and/or some physical measures of the stimuli. By revealing the relationships between data sets, the properties of the best-liked products or stimuli can be analyzed. Moreover, this analysis technique and the resulting visualizations preserve the inter-individual differences between assessors so that information on the level of consensus and/or different groups of people is also available. Preference mapping has been extensively used in the sensory evaluation of food products, including beers,²⁰ cheese,²¹ and semi-solids,²² just to name a few, but it has also been applied for evaluation of spatial sound reproduction systems.²³

In practice, the response variables, i.e., the preference data of each subject, are regressed onto the principal components or factors of the latent perceptual space. The term “external” is used because the predictor space is effectually external to the preference data. The term “internal” preference mapping would be used if the preference data were used to obtain the latent space where the results are being interpreted in. The interpretation of an internal preference space can be elaborated by correlating variables with the dimensions of the internal preference space. Such approach was used, e.g., by Schroeder *et al.*¹⁶ who analyzed which objective measures were significantly correlated with the dimensions of the preference space.

In external preference mapping, each assessor's preference responses are modeled separately in the latent sensory space. The aim is to seek for the most appropriate model for each individual in terms of the latent factors and use this model for visualization and interpretation of the results. The complexity of each individual regression model may vary

but basically two model types can be identified: A vector model (linear regression) and an ideal point model (quadratic regression).³ Vector model implies “the more, the better”-type of preference, whereas an ideal point model refers to “some amount is ideal”-type of preference. In contrast to the vector model, the advantage of an ideal point model is that when a positive ideal point is observed inside the sample space, it offers a possibility to define a theoretical “ideal” sample with conditions that combine those of the surrounding samples. Generally in practice, ideal point models used in preference mapping are either circular or elliptical models because higher order quadratic models are more difficult to interpret. In a circular model, the ideal point can be either positive or negative, that is, a point that maximizes or minimizes the preference response. For elliptical models an ideal point can be also at once both positive and negative, that is, a saddle point. The interpretation in the case of saddle points can be cumbersome when around the saddle point preference increases in one direction and decreases in another. A saddle point occurs when there are regression coefficients of the different quadratic terms with opposite signs.

C. Summary of the experiment and previously reported results

In brief, the sensory evaluation experiment consisted of anechoic symphony orchestra recordings of three excerpts of symphonic music²⁴ convolved with spatial impulse responses obtained from eight real halls and one simulated hall. The music excerpts were:

- (1) L. van Beethoven (1770–1791), Symphony No. 7, movement I, bars 14–16, 7 s;
- (2) A. Bruckner (1824–1896), Symphony No. 8, movement II, bars 41–46, 7 s;

- (3) W. A. Mozart (1756–1791), An aria of Donna Elvira from the opera Don Giovanni, Act II, Scene III, bars 1–5, 7 s.

The concert halls included two fan shaped halls: Finlandia hall (FT, 1695 seats) and Kulttuuritalo (KT, 1388 seats), rounded rectangular Sibelius hall (ST, 1229 seats) and five small shoebox halls: Vanajasali (VS, 703 seats), Tapiolasali (TS, 690 seats), Promenadisali (PS, 688 seats), Konservatorio (KO, 517 seats) and Sellosali (SS, 397 seats). The ninth hall was a hybrid hall combining the direct sound from ST, the late reverberation (faded in between 50 and 100 ms) from KO and simulated early reflections (see, Lokki *et al.*² for more details and floor plans of these halls). The values of the ISO 3382-1:2009 (Ref. 14) parameters are presented in Table I. For each receiver position/hall, the parameters were first calculated separately for each source position following the guidelines in the standard and then averaged to obtain the values tabulated in Table I.

Loudspeaker orchestra²⁵ and an array of six microphones were employed for capturing the room impulse responses at 12 m from the stage in each hall. Stimuli were played back in a semi-anechoic listening room with a three-dimensional (3D) sound reproduction system. Subjective evaluations were performed with individual vocabulary profiling (IVP), where each test subject develops his or her own set of descriptive attributes for the comparison and evaluation of the stimuli. A total of 60 attributes were reliably used in the evaluations. Also preference ratings were collected. Details of the experiment, data analysis, and results can be found in Lokki *et al.*,² but the main results are briefly described in the following.

First, multiple factor analysis²⁶ (MFA) was performed on the descriptive data, i.e., on the ratings of the stimuli of all 60 attributes. MFA revealed that there were three latent

TABLE I. Acoustic quantities grouped according to listener aspects in ISO 3382-1:2009 standard (Ref. 14). Note that *G* and *LJ* are only relative values because the sources were not omnidirectional as defined in the standard.

			Concert halls									
Subjective aspect	Acoustic quantity		Ave. of oct. bands	FT	VS	KT	KO	ST	PS	SS	TS	VA
Subjective level of sound	G_{low}	[dB]	125 and 250	4.17	6.36	5.71	5.38	6.75	9.71	5.40	2.98	3.84
	G_{mid}	[dB]	500 and 1 k	2.36	4.68	2.81	5.03	4.41	6.25	4.60	2.55	2.87
	G_{high}	[dB]	2 k and 4 k	1.41	1.77	0.74	3.18	2.54	3.62	2.68	2.24	1.73
Perceived reverberance	EDT_{low}	[s]	125 and 250	1.76	1.84	2.25	2.41	2.17	2.59	2.04	2.04	2.55
	EDT_{mid}	[s]	500 and 1 k	1.95	1.81	1.94	2.02	1.94	2.60	1.49	2.09	2.44
	EDT_{high}	[s]	2 k and 4 k	1.78	1.53	1.59	1.78	1.47	2.00	1.36	1.41	2.02
Apparent source width	LF_{low}	[%]	125 and 250	17	23	15	19	22	29	19	20	37
	LF_{mid}	[%]	500 and 1 k	14	18	12	20	22	24	19	17	25
	LF_{high}	[%]	2 k and 4 k	13	18	10	17	23	23	20	15	23
Listener envelopment	LJ_{low}	[dB]	125 and 250 ^a	−6.07	−3.09	−3.63	−3.75	−2.52	1.04	−4.29	−6.67	−4.42
	LJ_{mid}	[dB]	500 and 1 k ^a	−9.09	−6.88	−8.65	−5.11	−7.52	−3.70	−7.03	−8.26	−6.67
	LJ_{high}	[dB]	2 k and 4 k ^a	−11.53	−11.15	−12.69	−8.84	−10.86	−7.90	−9.96	−11.37	−9.46
Perceived clarity of sound	C80_{low}	[dB]	125 and 250	−1.46	−1.09	−2.95	−3.49	−2.18	−4.57	−3.16	−2.77	−8.62
	C80_{mid}	[dB]	500 and 1 k	−0.70	0.18	−0.62	−2.81	0.90	−3.55	1.17	−1.41	−4.84
	C80_{high}	[dB]	2 k and 4 k	2.24	2.31	2.61	1.05	3.47	0.24	2.20	3.53	−0.77

^aEnergy averaged.

FIG. 1. (Color online) Agglomerative hierarchical clustering with the attributes contribution to the three first factors of MFA solution. Previously published in Lokki *et al.* (Ref. 3).

factors, each explaining a significant amount of the total variance in the data. The variances explained by these factors are 50.15%, 10.14%, and 7.05%, respectively. Second, a clustering analysis (using agglomerative hierarchical clustering with Euclidean distances and Ward's minimum variance method) of the 60 attributes was performed in this latent 3D space using the transformed sample scores of each attribute on the three factors. Three main clusters and six attribute groups were revealed: The largest attribute cluster included attributes describing reverberance and envelopment/loudness (26 attributes), the second largest cluster consisted of bass and proximity related attributes (21), and the third cluster was identified as being related to clarity and definition (10). Three additional attributes did not belong to any of these groups. These additional attributes are not included in the current study. The dendrogram of the attribute clusters is presented in Fig. 1. Third, cluster analysis was also performed on the preference ratings. This clustering revealed two groups of assessors: Assessors who tend to like louder, enveloping, and reverberant sound, and assessors who like

more proximate and clear sound. Finally, proximity was identified as the main driver of preference and it was argued that none of the standardized room acoustical parameters were associated with either proximity or overall preference.

In order to maintain coherence between the current work and the previously reported results, the six attribute groups, reverberance, envelopment/loudness, bassiness, proximity, clarity, and definition, are employed also throughout the current investigation. Equally, the two groups of assessor, i.e., the preference groups are the same.

III. METHODS

A. Mapping of preferences

Figure 2 illustrates the data analysis process of the external preference mapping technique employed in this study. Preference mapping is performed by regressing each listener's preference scores Y_i onto three main dimensions or factors X_1 , X_2 , and X_3 of common latent sensory space obtained by MFA (Ref. 26) of the descriptive data. Taking into

FIG. 2. (Color online) Illustration of the data analysis procedure in the preference mapping technique.

TABLE II. Selection of regression models. Adjusted R^2 values are the model averages.

Music	All		Beethoven		Bruckner		Mozart	
	N	Adj. R^2	N	Adj. R^2	N	Adj. R^2	N	Adj. R^2
Vector	9	0.54	5	0.84	6	0.81	12	0.84
Circular	6	0.60	3	0.83	4	0.87	3	0.92
Elliptical	2	0.71	3	0.99	2	0.98	0	—
All models	17	0.58	11	0.88	12	0.86	15	0.85
No fit	0	—	6	—	5	—	2	—

account the degrees-of-freedom (df) in our data set, three regression models of different levels of complexity, namely, vector [Eq. (1)], circular [Eq. (2)], and elliptical models [Eq. (3)] can be considered,

$$Y_i = \alpha_i + \beta_{i1}X_1 + \beta_{i2}X_2 + \beta_{i3}X_3 + e_i, \quad (1)$$

$$Y_i = \alpha_i + \beta_{i1}X_1 + \beta_{i2}X_2 + \beta_{i3}X_3 + \beta_{i4}(X_1^2 + X_2^2 + X_3^2) + e_i, \quad (2)$$

$$Y_i = \alpha_i + \beta_{i1}X_1 + \beta_{i2}X_2 + \beta_{i3}X_3 + \beta_{i4}X_1^2 + \beta_{i5}X_2^2 + \beta_{i6}X_3^2 + e_i, \quad (3)$$

where $i = 1, 2, \dots, 17$ denotes assessors. The individual regression models are built for all music together as well as for each music piece separately. The model with the most suitable fit is selected according to the following heuristic decision rule. To begin with, an F-test is performed for each model in order to check which of the models are significantly fitted ($p < 0.1$). For each fitted model, the normality of the model residuals was checked with visual regression diagnostics as well as with the Shapiro-Wilk test. Any violations of normality were not detected. If only one model is found significant, it is chosen without further considerations. If none of these models are found significant, it is concluded that the preference data could not be fitted with these three dimensions and a preference map for the corresponding preference data (i.e., an assessor) cannot be produced. If there is more than one significant model, a more elaborate model is tested against a reduced model with a second F-test. If this F-test implies that a reduced model could be appropriate ($p > 0.2$), the adjusted R^2 and the significance of the independent variables between the models are compared. The more elaborate model is chosen over a simpler one when the corresponding adjusted R^2 is higher and there is at least one significant ($p < 0.1$) independent variable which is excluded from the reduced model. Thus, simpler and more specific models are favored over the more elaborate models, because in the cases where different music excerpts are analyzed separately, the small number of df produces the problem of over-fitting. The dependent variables, i.e., the preference scores have only nine observations per music piece and three, four, or six independent variables in the models, as specified in Eqs. (1)–(3). Finally, to further reduce the ambiguity in model selection, Akaike Information Criterion (AIC)²⁷ is calculated for each model in order to verify that the selected model

indeed is the most appropriate one. AIC measures the relative goodness of fit of a statistical model so that the lower the value, the better the fit. The selection procedure was performed per individual for all data together as well as per music motif. Table II presents the number of selected models with respective average adjusted R^2 values.

Individually selected regression models are used to estimate preference values, i.e., individual preference maps inside the 3D factor space and the respective thresholds of individual mean preference. Overlaying these individual preference maps and their threshold contours produces the preference maps illustrated in Figs. 3 and 4. The individually estimated threshold contours (drawn with dashed lines) add up to percentages of listeners (indicated by the numbers) who have preference estimates above their individual averages. A darker color illustrates that more assessors share their estimated preferences on that area and a lighter color designates the areas of lower preference, i.e., the areas where only few individuals' predicted preference ratings are above their average. Thus, preference maps illustrate the directions and regions of common/shared preferences between assessors in the sensory space. Finally, the arrows represent the average directions of the attributes in each attribute cluster in three-dimensions, where lengths have been scaled for illustration purposes to fit the preference map. The arrows can be treated as an indication of correlation with the axes.

B. Correlation analysis

The mapping of preferences is complemented by analyzing the correlations between preferences, subjective attributes, and standardized objective measures tabulated in Tables III–VII. The Spearman ρ rank correlation coefficient is used because the number of observations per objective measure is quite small (nine) and there are some outliers as discussed before. Besides calculating the correlations with the average values of the music motifs, the correlations are also calculated separately per each music excerpt to enable comparisons further in this respect. Preference mapping and correlation analysis are both performed thoroughly in R statistical programming language with the help of the FactoMineR²⁸ package.

IV. RESULTS

A. Regression models

When all music pieces are analyzed together, there are nine vector models and eight ideal point models. The variances explained by the models are from 0.54 to 0.71 (see Table II). In the cases of Beethoven and Bruckner, there are almost an equal number of vector (five) and ideal point (six) models and for six assessors none of these models produced a significant fit. Interestingly, considering the Mozart excerpt, there are as many as 12 vector models and only 3 ideal point models. For all separate music motifs, the variances explained by these models are high, from 0.81 to 0.99. For circular, but particularly for elliptical models, it is clear that high adj. R^2 values result from the lack of df; that is, over-fitting the data. However, over-fitting is not considered as a major issue

FIG. 3. (Color online) Preference maps including all music pieces: (a) All assessors, dimensions 1 and 2; (b) all assessors, dimensions 1 and 3; (c) preference group 1, dimensions 1 and 2; (d) preference group 2, dimensions 1 and 2.

because the more elaborate model is selected over a simpler one only when it is clearly reasonable in terms of the heuristic decision rule described previously. Besides, although the models are built separately for each individual, the results are illustrated by overlaying individual preference maps. This means that the interpretation is essentially performed at a more general level.

B. Interpretation of the preference maps

The preference maps illustrated in Figs. 3(a)–3(d) and Figs. 4(a)–4(i) can be compared as follows. First, Fig. 3(a), where all test subjects are analyzed together and all music signals are included, shows that the map is in overall divided by its diagonal, following the directions of reverberance and definition. The positive side is in the right upper corner in the directions of proximity, bassiness, and envelopment/loudness. Samples situated in the positive areas correspond to halls VA, ST, VS, and PS. The area of common preference is indicated directly by bassiness, but proximity and envelopment/loudness are also seen to be nearly as important. The case of Mozart, Fig. 4(g), is very similar and the preference map is well structured and clear, implying a high level of agreement between the test subjects. In contrast, the maps are more dispersed in the excerpts of Beethoven and Bruckner. The map of Beethoven [Fig. 4(a)] is quite cluttered but still a division in the main dimension can be noted, with the regions of common liking on the right side of the

map. For Bruckner [Fig. 4(d)], the proximity attribute cluster and VS and ST samples designate the area of common preference. Importantly, the maps of Beethoven and Bruckner reflect a certain heterogeneity in terms of assessors' opinions, which makes drawing clear-cut and definitive conclusions of the results more difficult. However, we may note that the least preferred samples correspond to halls TS, FT, and KO, while SS and KT are neither liked nor disliked.

It is also interesting to compare the maps where the test subjects have been clustered into two groups. Regarding Group 1 [Figs. 3(c), 4(b), 4(e), and 4(h)] the maps are split by the second dimension in Bruckner and Mozart music motives, while the Beethoven music motif shows three different preference surfaces: One vector, and two ideal point models with one positive ideal point, and one saddle point. Excluding Beethoven motif, a combination of high levels of proximity, definition, and bassiness is associated with a higher preference and a high amount of reverberance is disliked. For Group 2 [Figs. 3(d), 4(c), 4(f), and 4(i)], it can be observed that in general the main dimension divides the maps into regions of common liking on the right side, with bassiness and envelopment/loudness being the main drivers of preference with proximity and reverberance also showing some significance.

To summarize, Group 2 likes the acoustics of PS hall and the main aspects influencing their preference seem to be reverberance, bassiness, and envelopment/loudness. In contrast, VS and ST are preferred by Group 1 and the main components of preference are proximity and bassiness as well as

FIG. 4. (Color online) Preference maps for three music excerpts and for two assessor groups. (a) Beethoven: All assessors, (b) Beethoven: Group 1, (c) Beethoven: Group 2, (d) Bruckner: All assessors, (e) Bruckner: Group 1, (f) Bruckner: Group 2, (g) Mozart: All assessors, (h) Mozart: Group 1, (i) Mozart: Group 2.

TABLE III. Spearman ρ correlations between subjective attribute groups and preferences. **, and *** denote significance levels of 0.05, 0.01, and 0.001 respectively. Abbreviations: All: All music, Be: Beethoven, Br: Bruckner, Mo: Mozart, Rev.: Reverberance, LL/Env.: Loudness/Envelopment, Prox.: Proximity, Bass.: Bassiness, Def.: Definition, Cla.: Clarity.

Attr. group	All subjects				Pref. Group 1				Pref. Group 2			
	All	Be.	Br.	Mo.	All	Be.	Br.	Mo.	All	Be.	Br.	Mo.
Rev.	0.50	0.78*	0.78*	0.22	0.00	0.42	-0.13	-0.47	0.80*	0.92**	0.68	0.33
LL/Env.	0.67	0.90**	0.47	0.53	0.10	0.47	0.07	-0.02	0.93***	0.98***	0.88**	0.68
Prox.	1.00***	0.90**	0.82*	0.95***	0.73**	0.53	0.48	0.85**	0.83**	0.92**	0.78*	0.85**
Bass.	0.82**	0.87**	0.80*	0.78*	0.42	0.58	0.38	0.48	0.93***	0.75*	0.97***	0.78*
Def.	0.12	0.15	-0.33	0.52	0.08	0.10	-0.35	0.63	-0.02	0.15	-0.38	0.47
Cla.	-0.23	-0.73*	-0.33	0.17	0.20	-0.32	-0.02	0.78*	-0.60	-0.88**	-0.78*	0.08

TABLE IV. Spearman ρ correlations between objective parameters and preferences. *, **, and *** denote significance levels of 0.05, 0.01, and 0.001 respectively. Abbreviations: All: All music, Be: Beethoven, Br: Bruckner, Mo: Mozart, G1: Pref. group 1, G2: Pref. group 2.

Parameter	All subjects				Pref. Group 1				Pref. Group 2			
	All	Be.	Br.	Mo.	All	Be.	Br.	Mo.	All	Be.	Br.	Mo.
G_{low}	0.62	0.45	0.57	0.55	0.37	0.55	0.40	0.28	0.58	0.42	0.57	0.55
G_{mid}	0.55	0.57	0.45	0.40	0.12	0.45	0.23	-0.17	0.70*	0.73*	0.73*	0.55
G_{high}	0.25	0.37	0.07	0.17	-0.23	0.23	-0.15	-0.50	0.43	0.55	0.40	0.28
EDT_{low}	0.28	0.65	0.63	0.10	-0.25	0.13	-0.20	-0.32	0.68	0.72*	0.63	0.25
EDT_{mid}	-0.13	0.22	-0.35	-0.12	-0.70*	-0.5	-0.82*	-0.38	0.33	0.47	0.30	-0.02
EDT_{high}	0.08	0.37	-0.03	0.13	-0.25	-0.27	-0.37	0.05	0.48	0.60	0.50	0.20
LF_{low}	0.65	0.72*	0.53	0.63	0.12	0.30	-0.03	0.27	0.78*	0.72*	0.80*	0.68
LF_{mid}	0.67	0.88**	0.48	0.62	0.10	0.45	0.00	0.05	0.87**	0.90**	0.82*	0.70*
LF_{high}	0.83*	0.88**	0.70*	0.82*	0.40	0.70*	0.27	0.33	0.82*	0.73*	0.75*	0.82*
LJ_{low}	0.68	0.53	0.60	0.57	0.33	0.52	0.37	0.25	0.70*	0.55	0.68	0.63
LJ_{mid}	0.50	0.68	0.37	0.37	-0.05	0.30	0.00	-0.22	0.78*	0.87**	0.82*	0.53
LJ_{high}	0.45	0.72*	0.27	0.37	-0.12	0.32	-0.10	-0.30	0.75*	0.88**	0.73*	0.50
$C80_{low}$	-0.03	-0.55	0.07	0.10	0.37	-0.05	0.30	0.48	-0.47	-0.58	-0.43	0.00
$C80_{mid}$	0.18	-0.18	0.33	0.20	0.63	0.53	0.70*	0.37	-0.30	-0.47	-0.32	0.07
$C80_{high}$	-0.23	-0.63	-0.17	-0.23	0.07	-0.18	0.07	0.13	-0.60	-0.77*	-0.63	-0.28
Pref. All	1.00	1.00	1.00	1.00	0.82***	0.72*	0.75*	0.80*	0.88***	0.85**	0.72*	0.95***
G1	0.82***	0.72*	0.73*	0.80*	1.00	1.00	1.00	1.00	0.50**	0.38	0.25	0.62
G2	0.88***	0.85**	0.72*	0.95***	0.50**	0.38	0.25	0.62	1.00	1.00	1.00	1.00

definition to some extent. Thus, proximity and bassiness are shared as positive factors between groups that can also be seen in the overall maps. Inter-individual differences in preferences are pronounced in the excerpts of Beethoven and Bruckner, while preferences are more homogeneous in the case of Mozart. While these interpretations of preference mapping are made solely in the subjective space, the correlation analysis of subjective data and the objective parameters provides another viewpoint for these results.

C. Correlations for preferences

A complementary view to the preference maps is given in Table III where the correlations between preferences and

different attribute groups are calculated. In addition, the correlations between preferences and objective parameters are presented in Table IV. Correlations have been calculated by taking the averages over all subjects as well as over two preference groups separately, denoted with G1 and G2. The correlations between the averages of all subjects indicate that the most important aspects have been proximity and bassiness. Definition is not associated with preference and the importance of clarity seems to depend on the music excerpt as well as on the preference group to some extent. The main differences between the two preference groups are observed with reverberance and loudness/envelopment attributes; G2 shows significant correlations in both respects, while such correlations are not observed for G1. The high

TABLE V. Spearman ρ correlations between objective parameters and reverberance and loudness/envelopment attribute groups. *, **, and *** denote significance levels of 0.05, 0.01, and 0.001 respectively. Abbreviations: All: All music, Be: Beethoven, Br: Bruckner, Mo: Mozart.

Parameter	Reverberance				Loudness/Env			
	All	Be.	Br.	Mo.	All	Be.	Br.	Mo.
G_{low}	0.37	0.42	0.18	0.20	0.42	0.48	0.43	0.43
G_{mid}	0.80*	0.83**	0.57	0.75*	0.73*	0.68	0.75*	0.78*
G_{high}	0.70*	0.68	0.52	0.90**	0.55	0.52	0.58	0.58
EDT_{low}	0.72*	0.80*	0.65	0.65	0.72*	0.68	0.83**	0.83**
EDT_{mid}	0.37	0.33	0.47	0.43	0.47	0.43	0.42	0.47
EDT_{high}	0.47	0.43	0.63	0.17	0.60	0.55	0.52	0.48
LF_{low}	0.52	0.50	0.45	0.50	0.72*	0.75*	0.63	0.75*
LF_{mid}	0.83**	0.82*	0.77*	0.80*	0.90**	0.92**	0.90**	0.90**
LF_{high}	0.63	0.62	0.53	0.62	0.73*	0.82*	0.73*	0.73*
LJ_{low}	0.47	0.53	0.25	0.28	0.55	0.60	0.57	0.60
LJ_{mid}	0.88**	0.90**	0.73*	0.85**	0.87**	0.80*	0.87**	0.92**
LJ_{high}	0.95***	0.93***	0.85**	0.97***	0.88**	0.83**	0.90**	0.88**
$C80_{low}$	-0.68	-0.73*	-0.72*	-0.70*	-0.58	-0.52	-0.72*	-0.67
$C80_{mid}$	-0.38	-0.37	-0.50	-0.35	-0.47	-0.38	-0.42	-0.47
$C80_{high}$	-0.83**	-0.80*	-0.93***	-0.63	-0.77*	-0.68	-0.77*	-0.67

TABLE VI. Spearman ρ correlations between objective parameters and proximity and bassiness attribute groups. *, **, and *** denote significance levels of 0.05, 0.01, and 0.001, respectively. Abbreviations: All: All music, Be: Beethoven, Br: Bruckner, Mo: Mozart.

Parameter	Proximity				Bassiness			
	All	Be.	Br.	Mo.	All	Be.	Br.	Mo.
G_{low}	0.62	0.40	0.78*	0.50	0.62	0.63	0.67	0.83**
G_{mid}	0.55	0.62	0.72*	0.30	0.62	0.57	0.75*	0.60
G_{high}	0.25	0.32	0.55	-0.02	0.27	0.17	0.40	0.27
EDT_{low}	0.28	0.53	0.38	-0.05	0.57	0.6	0.48	0.50
EDT_{mid}	-0.13	0.32	-0.08	-0.33	0.17	0.20	0.12	0.07
EDT_{high}	0.08	0.55	-0.08	0.02	0.40	0.47	0.33	0.27
LF_{low}	0.65	0.83**	0.60	0.52	0.73*	0.70*	0.75*	0.60
LF_{mid}	0.67	0.85**	0.67	0.43	0.72*	0.65	0.72*	0.58
LF_{high}	0.83**	0.78*	0.83**	0.68	0.73*	0.65	0.73*	0.68
LJ_{low}	0.68	0.52	0.82*	0.48	0.68	0.72*	0.73*	0.88**
LJ_{mid}	0.50	0.77*	0.58	0.23	0.67	0.62	0.75*	0.52
LJ_{high}	0.45	0.72*	0.57	0.18	0.58	0.05	0.65	0.43
$C80_{low}$	-0.03	-0.40	-0.12	0.20	-0.38	-0.37	-0.28	-0.17
$C80_{mid}$	0.18	-0.35	0.23	0.35	-0.17	-0.22	-0.12	0.02
$C80_{high}$	-0.23	-0.68	-0.17	-0.17	-0.55	-0.5	-0.53	-0.27

level of proximity is important for both groups, particularly in the excerpt of Mozart, while bassiness, loudness/envelopment, and reverberance seem to be factors of liking especially for assessors in $G2$. Previously,² it was concluded that while assessors in $G2$ like a more reverberant, loud, and enveloping sound, $G1$ was associated more with a defined and clear sound. This distinction is observed to hold mainly for $G2$, but not for $G1$, as the only significant correlation with the preferences of $G1$ and clarity is found with Mozart. However, although the correlations for definition are not significant, the correlations are still consistently higher for the Mozart music excerpt than for the other two motifs.

Considering correlations between preferences and objective parameters tabulated in Table IV, the main significant correlation for all music pieces and the averaged data over all assessors is with early lateral sound energy at high frequencies, LF_{high} . In the case of Beethoven, also

correlations with LF_{mid} , LF_{high} , and measure of late lateral sound energy at high frequencies, LJ_{high} are significant. Preferences of $G2$ are prominently associated with both early and late wideband lateral sound energy. Also, the preference for loud sound is reflected by a significant correlation with G_{mid} . The correlations with EDT measures are also quite high although significant only for EDT_{low} in the excerpt of Beethoven. For $G1$, any consistent correlations between music pieces are not found.

D. Correlations between subjective attributes and objective parameters

First, in order to obtain an overall view of the relative subjective importance of the objective parameters in this sample set, the measured values are scaled by their respective just-noticeable-differences (JNDs)²⁹ and centered on

TABLE VII. Spearman ρ correlations between objective parameters and definition and clarity attribute groups. *, **, and *** denote significance levels of 0.05, 0.01, and 0.001 respectively. Abbreviations: All: All music, Be: Beethoven, Br: Bruckner, Mo: Mozart.

Para- meter	Definition				Clarity			
	All	Be.	Br.	Mo.	All	Be.	Br.	Mo.
G_{low}	-0.58	-0.43	-0.80 *	-0.32	-0.12	-0.23	-0.37	0.08
G_{mid}	-0.37	-0.03	-0.72 *	-0.22	-0.65	-0.70 *	-0.80 *	-0.50
G_{high}	-0.10	0.12	-0.43	-0.27	-0.63	-0.52	-0.70 *	-0.82 *
EDT_{low}	-0.03	0.27	-0.13	-0.3	-0.53	-0.62	-0.72 *	-0.45
EDT_{mid}	0.23	0.03	0.33	-0.15	-0.47	-0.38	-0.37	-0.53
EDT_{high}	-0.02	-0.08	0.13	-0.17	-0.55	-0.6	-0.47	-0.15
LF_{low}	0.27	0.00	0.02	0.48	-0.45	-0.55	-0.52	-0.27
LF_{mid}	0.35	0.35	0.02	0.27	-0.70 *	-0.75 *	-0.83 **	-0.52
LF_{high}	0.37	0.27	-0.03	0.45	-0.43	-0.52	-0.63	-0.27
LJ_{low}	-0.48	-0.30	-0.73 *	-0.27	-0.18	-0.32	-0.47	0.05
LJ_{mid}	-0.08	0.13	-0.38	-0.03	-0.80 *	-0.85 **	-0.88 **	-0.63
LJ_{high}	0.07	0.27	-0.25	-0.07	-0.88 **	-0.87 **	-0.95 ***	-0.78 *
$C80_{low}$	-0.08	-0.38	-0.05	0.23	0.63	0.67	0.68	0.63
$C80_{mid}$	-0.17	-0.08	-0.32	0.13	0.52	0.48	0.38	0.45
$C80_{high}$	0.07	-0.13	0.13	0.12	0.90 **	0.95 ***	0.83 **	0.55

FIG. 5. The ranges of JNDs of objective measures.

zero mean. Figure 5 illustrates the objective measures after the scaling. The outliers are also important, because they denote the “true” range of the samples presented in the subjective evaluations. It is worth mentioning that PS and the simulated hall, VA, are outliers in several instances. While the parameter values in the case of VA are ambiguous and may not be representative of the subjective perceptions, PS, with high levels of low frequency G , middle EDT, as well as envelopment, is in many terms extreme in this sample set. This is seen also in the perceptual maps, where PS samples are situated in the areas of high reverberance. Note also that the JNDs used for scaling in this case are those determined in laboratory conditions and these might be different in real rooms.

Considering the objective parameters overall, EDTs (low, mid, and high) manifest the greatest range, followed by $C80_{mid}$ and G_{low} . LFs, particularly at middle and high frequencies and G_{high} exhibit the lowest variances in this sample set. It is reasonable to assume that the ranges of these objective parameters are reflected in subjective evaluations. Indeed, the number of attributes in each attribute cluster, presented in Fig. 1 and Table VIII, are quite well in line with JND ranges of objective parameters; the largest cluster being reverberance and loudness/envelopment with 26 attributes (8 and 18), bassiness and proximity having 16 and 5 attributes, respectively, and definition and clarity together 10 attributes. These results indicate that in this sample set, the largest variations are in the factors related to reverberance, loudness, and envelopment. Also, these aspects might be most prominent and the easiest to evaluate in the listening test.

TABLE VIII. Number of attributes per attribute cluster and preference group.

Attribute groups	Number of attributes		
	All (17 as.)	Group 1 (7 as.)	Group 2 (10 as.)
Reverberance (8) / Envelopment-Loudness (18)	26	8	18
Bassiness (15) / Proximity (6)	21	10	11
Definition (4) / Clarity (6)	10	5	5

The correlations for reverberance and loudness/envelopment attribute groups are presented in Table V. Overall, the reverberance attribute group is most highly correlated with late lateral sound energy at high and mid frequencies (LJ_{mid} and LJ_{high}) as well as early lateral sound energy at mid frequencies (LF_{mid}). Depending on the music excerpt, significant correlations are also found with strength parameter G , particularly at mid and high frequencies (G_{mid} , G_{high}), early decay time at low frequencies (EDT_{low}) as well as negative correlation with clarity parameter ($C80_{high}$). Differences between music signals are small; reverberance with Mozart seems to be associated more with strength at high frequencies (G_{high}) than in other pieces and EDT_{low} is found significant only in Beethoven excerpt.

Attributes related to loudness and envelopment are clustered in the same main cluster with reverberance, and hence, similarities in the correlations with objective parameters in this respect can be expected. Indeed, the association between the subjective perception of loudness/envelopment and early and late lateral sound energy is again clear. The wideband early lateral energy, manifested in correlations with LF, seems to be more pronounced than for reverberance.

The correlations between objective parameters and proximity and bassiness attribute groups are presented in Table VI. Considering proximity, lateral energy is again important, particularly correlations are significant with early lateral energy at high frequencies (LF_{high}). In the Beethoven excerpt, a pronounced association is with wideband early lateral energy (LF), and with late lateral energy measures LJ_{mid} and LJ_{high} . In contrast, in the excerpt of Bruckner, lower frequencies seem to be more important for perception of proximity than in other pieces, observed through significant correlations with G_{low} and LJ_{low} .

For the bassiness attribute group, correlations with objective measures at lower frequency bands can be expected. However, this is only partly observed. High correlations are found with G_{low} for all music pieces, but significance is only attained in the Mozart excerpt. Correlation with LJ_{low} is significant for all music pieces, but not when all pieces are analyzed together, and LF_{low} is significantly correlated in excerpts of Beethoven and Bruckner. The association with bassiness and sound energy from sides is apparent especially when all music motifs are included in the analysis.

The correlations for the small attribute groups of definition and clarity are presented in Table VII. For definition, only significant correlations are found with Bruckner's excerpt: G_{low} , G_{mid} , and LJ_{low} exhibit significant negative correlations. For clarity related attributes, significant negative correlations are observed with the LJ_{high} parameter, as well as with LJ_{mid} and LF_{mid} except for Mozart. Clarity parameter C80 at high frequencies is also significantly correlated with subjective clarity, except in the case of Mozart.

V. CONCLUDING REMARKS

External preference mapping was performed on the data from an IVP of concert hall acoustics. The sensory and preference data were linked by regressing each individual's preference responses onto the main dimensions of the overall latent sensory space obtained from the profiling. Overall, about half of the selected regression models were vector models and half ideal point models. A comparison between music signals revealed that for the Mozart music motif, most of the models were of a vector type whereas there were almost equal numbers of vector and ideal point models in the two other pieces of music. Also, preference maps indicated that the preferences were more homogeneous in the case of the Mozart music excerpt. Preference maps also showed that proximity may be viewed as the main driver of preference shared by most people. Many also like loud sound with enough bass while definition and reverberance seem to be dividing, but, nevertheless, important factors. The inter-individual differences did not allow for straightforward interpretations about how the importance of acoustic qualities change between these three music pieces.

As a method, external preference mapping appears a quite feasible approach in analyzing the multidimensional relationships between the data sets and enabling an assessment of individual preference models, the level of agreement, and the determinants of shared preferences. However, it also involves some amount of manual labor in selecting the most appropriate regression model for each assessor. Because regression analysis and the model selection procedure depend greatly on the context, it is difficult to determine the "best" approach in this respect. If these methods were used in a more confirmatory setting with the focus on testing exact statistical hypotheses, clearly more conservative decision rules would be appropriate.

The stimuli in this experiment represented the acoustics of eight real halls and a simulated one. The main objective of the listening experiment was to investigate the perceptual differences between the nine halls at the same, albeit somewhat close distance from the stage. Thus, it is worth considering that the original focus of the study was not on the effects of the different music excerpts. The assessors were asked to define attributes which could be used with all three music excerpts, and this way the experiment might have precluded the most prominent effects related to the music motifs. The effects of different motifs could be better studied, for example, by allowing assessors, or groups of assessors, to define separate attribute sets for each music motif,

and investigate if and how those attribute sets differ. Alternatively, more prominent effects of the music signal could be revealed if a wider span of musical styles, for instance, excerpts of more contemporary compositions, were available for the subjective evaluations. Also, a closer look into the acoustic properties, such as spectral content, tempo, roughness, and dynamics could provide more insight on how the properties of the music influence the perception and prominence of various room acoustical features. Future studies addressing these aspects would also benefit from strict experimental control of the variables related to the musical features.

The correlation analysis revealed that the early arriving lateral energy in higher frequency bands seems to be of particular importance for both proximity and preference. This result is in line with the results reported by Lokki *et al.*,³⁰ who concluded that the engaging acoustic experience is produced by early reflections from the side which preserve the information and the temporal structure of the higher harmonics. Moreover, Blauert and Lindemann¹⁰ also concluded that "all spectral components of early lateral reflection contribute to auditory spaciousness as well as to preference." Their results also indicated that the lateral reflections which were composed of components below 3 kHz were associated with expanded perception of depth, whereas the broadening of an auditory event was linked to the presence of components above 3 kHz. Considering that there are continuous changes in spectral composition of sound in musical signals, the perceptual expansion of both depth and width will occur in conjunction when the means for broadband lateral reflections are provided. Adding to these results, the current study linked the experience of auditory proximity—identified as the main factor of preference—to the properties of early reflections from the side, and particularly to the presence of lateralized sound energy above 1.4 kHz (at 2 and 4 kHz octave bands). This emphasis on higher frequency bands has not been present for example in the calculations of BQI.¹⁵

Regarding other objective measures, EDT_{low} , G_{mid} , and G_{high} were positively correlated and $C80_{\text{high}}$ negatively correlated with reverberance. Similar correlations were also observed with the loudness/envelopment attributes. The strength parameter G at low frequency bands was not associated with bass as strongly as expected, whereas association with wideband early lateral energy and bassiness was found to be significant. In the Bruckner music motif, G_{low} and G_{mid} parameters, were both associated positively with proximity and negatively with definition. $C80_{\text{high}}$ was correlated with subjective clarity as could have been expected. Overall, the results of correlation analysis highlight the importance of lateral sound energy and its association to various perceptual aspects in concert halls.

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