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Interindividual differences in quality judgments and preferences of concert hall acoustics

Antti Kuusinen (antti.kuusinen@aalto.fi)
Tapio Lokki (tapio.lokki@aalto.fi)
Department of Media Technology
Aalto University
Espoo, Finland

ABSTRACT

The acoustic quality of concert halls can be studied in many different ways. While the focus is usually on revealing the average or common perceptual space, the interindividual differences in perception can also provide important insight and substance to the interpretation of acoustic phenomena. This paper discusses interindividual differences observed in two sensory evaluation experiments of concert hall acoustics. The dimensionality or complexity of sensory profiles provide one practical viewpoint to the sensory skill of the test subject. The analytical sensory data can be also connected to affective preference ratings by preference mapping. This technique allows for the evaluation of not only the determinants of the preference but also how individual preferences can be modeled. The ideal point models refers to "eclectic" listeners, whereas "the more, the better"-type of listeners are modeled with vector type models. The results depend not only on the individual, but also on the properties of the sample space, for instance, the range of acoustical conditions and the music used in the evaluations. These aspects are illustrated with examples from our previous studies conducted by individual vocabulary profiling. Finally, implications for future research are discussed.

1 INTRODUCTION

The objective of this paper is to analyse interindividual differences observed in two separate sensory evaluation studies of concert hall acoustics. The details and overall results of these studies have been published previously by Lokki *et al.*[1,2]. These studies have been performed with the same methodology, although the experiences gained in the first study resulted in some modifications for the second study. In brief, these studies have been performed by individual vocabulary profiling (IVP) where each individual developes an own set of descriptive attributes for a comparative evaluation of sound samples. The subjective evaluations were conducted in acoustically treated multichannel listening room. The stimuli were obtained by convolving anechoic symphony orchestra recordings with spatial room impulse responses measured in real concert halls with an array of six microphones. The source employed in the acoustical measurements was a loudspeaker orchestra which approximate the instruments and instrument positions of a real orchestra[3]. The details of the experimental procedure are outside the scope of this paper and an interested reader is referred to the publications mentioned in above and references therein. The main differences

Table 1: Main differences between the sensory evaluation studies IVP1 and IVP2.

Study	IVP1	IVP2
Halls	3	9
Pos./Hall	3	1 (12 m from stage)
Music excerpts	4	3
N. of subjects	20	17
Individual attributes	4 - 6	4
Total n. of attributes	102	60 (reliable)
Attribute groups	8	6
Repetition	NO	YES
Preferences	NO	YES

between the studies in terms of subjective listening tests are listed in Table 1 and discussed briefly in the following.

In the first study, abbreviated with IVP1, samples included three concert halls and three seating positions in each hall. Also, there were four excerpts of symphonic music; namely short segments of compositions by Beethoven, Bruckner, Mozart and Mahler. Thus, there were a total of 36 samples evaluated in the listening test. The test subjects were instructed to elicit and develop four to six descriptive attributes. Preference judgments were not collected in this study and the final evaluation was performed only once without repetition. A hierarchical cluster analysis (HCA) revealed 5-8 attribute groups interpreted as: reverberance related to size of space, enveloping reverberance, apparent source width, loudness/distance/openness, definition and balance. Multiple factor analysis (MFA) indicated that the first latent factor was associated with loudness, distance and openness and the second factor was associated with size of space and envelopment. The attributes in other attribute groups were scattered to more than one factor.

In the second study, abbreviated with IVP2, samples included nine concert halls where acoustic measurements were made at equal distance (12 m) from the stage. Three music excerpts were included this time: segments of compositions of Beethoven, Bruckner and Mozart. Hence, 27 samples were evaluated. Test subjects were instructed to elicit and develop four attributes. Preference jugments were collected at the end of the experiment. The final evaluation, except for preferences, was performed twice enabling the assessment of reliability of the attributes. A total of 60 attributes were reliably used in the evaluation. MFA was performed first on the descriptive data, and HCA of attributes was performed within the three dimensional factor solution. This order of analysis clarified and facilitated the interpretation of the latent structure, althought about 30 percent of the total variance was not included in the clustering of attributes. Six main attribute groups were identified: reverberance, loudness/envelopment, proximity, bassiness, clarity and definition. Preference judgments were associated the highest with proximity attribute group, while interindividual differences were manifested in the direction of reverberance - clarity. Accordingly, two groups of subjects with different preferences were identified: those who liked more reverberant and enveloping sound and those who valued more high level of clarity.

The primary interest of these studies have been in revealing and verifying the main perceptual aspects of concert hall acoustics and refining the correspondence between the physical measures and the subjective perceptions. In overall, the results and conclusions are well in line with other research conducted on the subjective perception of concert hall acoustics, see, e.g.,[4,5,6].

While overall results are always of the greatest interest, there is much additional information in the listening test data which is often overlooked, or at least, not formally reported. Thus, interindividual differences in perception are discussed in this paper. The complexities of individual perceptual spaces are analysed and compared by means of β-coefficient proposed by Schlich[7] as well as by classical principal component analysis (PCA). Effort is also made to reveal assessor groups who have defined and used attributes in similar ways.

In IVP2, preference data allows for investigating aspects which are associated with higher liking. Previously[2], test subjects were clustered into two clusters according to their preference data, but it is reasonable to assume that there are more interindividual differences and heterogeneity in respect to preferences. Thus, in this paper, a simple correlation analysis between the individual preferences and the subjective attribute groups is presented. The analysis in this paper is confined to the subjective perceptions and preference ratings. The more detailed analysis of relationships between subjective perceptions, preferences and the physical room acoustic measures are presented by Lokki *et al.*[2] and elaborated by Kuusinen et al.[8]. An interesting perspective to preference behaviour is obtained by regressing each individual's preference ratings onto the three dimensional factor solution resulted from the overall analysis. This technique is commonly known as external preference mapping[9], and has been used in the audio field for investigating perception of spatial sound reproduction systems[10]. The detailed presentation of preference mapping, including the influences of different music signals, is presented in Kuusinen et al.[8]. Here the results are discussed only in terms of differences between individuals on a general level.

2 THE DIMENSIONALITY OF SUBJECTIVE ACOUSTIC QUALITY

One way to analyse the dimensionality of individual data sets is principal component analysis (PCA), and the variances explained by each component. However, the classical problem of PCA is to decide how many principal components are retained in the analysis[11]. As an alternative measure, Schlich[7] proposes a β-coefficient as an estimator of the dimensionality of an individual sample space. The β -coefficient is calculated as follows:

$$\beta = \frac{(trace(W_i))^2}{trace(W_i^2)}, \qquad (1)$$

where the association matrix W_i is defined as: W_i = $X_i X_i'$ and $trace$ refers to the sum of the diagonal elements of a matrix. X_i is the centered data set of an assessor, with n rows (the number of samples) and p columns (the number of attributes).

There are two important properties of the β -coefficient that indicate why it can be used as a dimensionality estimator. First, the lowest dimensionality (a single dimension) is obtained when the attributes are fully correlated and second, the highest dimensionality is obtained when attributes are uncorrelated. In other words, β -coefficient varies from 1 to P_i = min(n - 1, p_i) where p_i is the number of attributes. It is probable that there is atleast some correlation between different attributes, so the highest dimensionality is not probably achieved. The β-coefficient can give an indication of the number of ideal attributes sufficient to describe the differences between samples, but it should not be regarded as being an exact truth about the dimensionnality of the sensory space. It must be stressed that the number of attributes used in the evaluation should be atleast twice the dimensionality implied by the β -coefficient[7].

The β -coefficients for each individual data set including all results of an assessor are presented in Tables 2a and 2b. Considering the dimensionalities of sensory profiles in both studies and between assessors, it can be clearly noted that the dimensionality is on average between two and three. In the first study, the range is from 1.4 to 3.4 and in the second study, from 1.4 to 3.2. Interestingly, the dimensionality estimates seems to be independent of the number of attributes developed. Also, taking account that the sample set in IVP1, consisted of three halls with three seating positions each, and in IVP2, of one position in nine halls, these results indicate that one individual's perception of concert hall acoustics can be in general with modelled with a three dimensional latent structure. Of course, interindividual differences are expected in the charateristics of the latent space, and in order to substantiate these differences, the usage of attributes are investigated more closely by grouping the assessors in term of descriptive attributes. For this purpose, the logical tables presented in Tables 2a and 2b are tabulated.

The logical tables are constructed by denoting 1 to those attribute groups where individual has *one or more* attributes. If there is more than one attribute, the total number of attributes is denoted in parentheses. These tables of 0s and 1s, are used for calculating a distance matrice containing, in this case, squared Euclidean distances, which are in turn used for clustering the assesssors into two groups with Ward's minimum variance method[12]. These tables reveal one peculiarity of subjective evaluations where stimuli are being evaluated with many attributes: it is possible that different attributes defined by the same individual correlate to the extent that they are clustered in the same attribute cluster when attribute clusters are determined globally. Tables 2a and 2b also indicate that while the individual profiles may be accounted for with three dimensions, the overall perceptual space is in fact more complex and consists of more dimensions, from 5 to 7 according to these data. Actually, the complexity estimates for the complete data matrices including all assessors, all attributes and all samples, are 3.1 and 5.0 for IVP1 and IVP2 respectively. Remembering that the subjective evaluations should include atleast twice the number of a theoretical ideal attributes indicated by β-coefficients, a good practice would then be to include approximately ten attributes if all assessors are required to use the same attributes, and around 4-6 attributes if assessor may select or define their attributes personally and/or when a concept aligment process among individuals can be realized.

Table 2 also presents RV-coefficients between the individual profiles and the consensus profile obtained with MFA. RV-coefficient is a generalized Pearson correlation coefficient between matrices and can be thought as a measure of similarity between data sets[7]. It is seen that the RVs are quite high in both studies, indicating a high level of consensus between the assessors. It can be noted that the RVs are a bit higher in IVP1 than IVP2, but it is difficult to draw any conclusive interpretation in this respect.

Considering the interindividual differences in attribute usage following observations can be made: In IVP1, the main distinction between groups of attributes relating to reverberance, the width of sound and openness; assessors who have employed reverberance related attributes, have not used attributes of width or openness, and vice versa. Moreover, all assessors, except AS4 and AS7, have defined 1 to 4 attributes related to loudness indicating that loudness variations were perceptually dominant in this sample set, and the easiest to judge. In IVP2, the division of groups is made in proximity and definition related terms, but it is also seen from the "Sum"-column that assessors in group 1 have been slightly better in defining attributes belonging to different attribute groups. The β-coefficients are also slightly higher for assessors in this group. Thus, it can be speculated that the assessor in group 1 have performed slightly better in terms of multidimensional discrimination.

In IVP2, assessors were also clustered into 2 groups according to their preference ratings, denoted in column PG. The two clustering approches result in unequal assessor groups which is an interesting aspect when the correlations between preferences and subjective attribute groups are analysed in the next section.

Table 2: Logical table and grouping of test subjects. The number of attributes belonging to a cluster is denoted in the parentheses. Abbreviations: AS = Assessor, NRA = Number of (Reliable) Attributes, DG = Descriptive Group, PG = Preference Group. (a) First IVP study, (b) Second IVP study

(a) IVP1: Attributes: Rev = Reverberance, Env = Envelopment, Wid = Width of Sound, LL = Loudness, Bal = Balance, Ope = Openness, Def = Definition

AS	NRA	Rev	Env	Wid	LL	Bal	Ope	Def	Sum	β	RV	DG
AS1	4	0	0	1	1	1	1	0	4	2.5	0.80	1
AS3	5	0	1	0	0	1	1	1(2)	4	1.4	0.68	1
AS4	6	0	0	1	1	0	1(4)	0	3	2.3	0.81	1
AS5	6	0	1	1(2)	1(3)	0	0	0	3	3.4	0.92	1
AS6	5	0	0	1(2)	1(2)	1	0	0	3	1.7	0.75	1
AS7	5	0	0	1	0	0	1(2)	1	3	1.9	0.78	1
AS8	6	1	0	1	1(2)	0	1(2)	0	4	2.4	0.89	1
AS10	4	0	0	0	1	1	1	1	4	1.9	0.76	1
AS11	6	0	1	1	1(2)	0	1(2)	0	4	2.3	0.85	1
AS12	5	0	0	1	1(2)	1	0	1	3	2.5	0.83	1
AS18	5	0	0	1	1(3)	0	1	0	3	2.1	0.88	1
AS20	6	1	0	1(2)	1	1	0	1	5	2.9	0.84	1
AS2	6	1	0	0	1	0	1	1(3)	4	2.1	0.80	2
AS9	4	1	0	0	1(2)	0	0	1	3	1.5	0.82	2
AS13	5	1(2)	0	0	1	1	1	0	4	2.3	0.77	2
AS14	5	1	1	0	1	0	0	1(2)	4	2.4	0.83	2
AS15	5	1	0	0	1(4)	0	0	0	2	2.3	0.90	2
AS16	4	1	0	0	1(2)	1	0	0	3	2.7	0.85	2
AS17	5	1	1	0	1(2)	0	0	1	4	2.8	0.82	2
AS19	6	0	1(2)	0	1(2)	0	0	1(2)	3	1.8	0.68	2
Sum	102	9(10)	6(7)	10(13)	18 (33)	8	10(13)	8(13)	69 (102)			

(b) IVP2: Attributes: Rev = Reverberance, LL/Env = Loudness/Envelopment, Bass = Bassiness, Prox = Proximity, Def = Definition, Cla = Clarity

AS	NRA	Rev	LLEnv	Bass	Prox	Def	Cla	Sum	β	RV	DG	PG
AS01	4	0	1	1	1	0	1	4	2.2	0.79	1	1
AS05	4	0	1 (2)	1	0	1	0	3	2.3	0.76	1	2
AS08	4	1	1	1	0	1	0	4	2.4	0.83	1	1
AS10	4	0	1(2)	0	1	1	0	3	2.3	0.81	1	1
AS11	4	0	1	1 (2)	1	0	0	3	2.2	0.78	1	1
AS13	3	0	1	1	0	1	0	3	2.4	0.74	1	2
AS15	4	1	0	1	1	1	0	4	2.5	0.63	1	2
AS18	2	0	0	1	0	1	0	2	3.2	0.52	1	2
AS21	4	0	0	1	1 (2)	0	1	3	2.4	0.71	1	2
AS02	4	0	1 (3)	0	0	0	0	1	2.1	0.85	2	2
AS07	3	1	0	1(2)	0	0	0	2	2.2	0.74	2	2
AS12	3	0	1 (2)	0	0	0	1	2	2.2	0.79	2	1
AS16	4	1	0	1 (2)	0	0	0	2	2.2	0.75	2	1
AS17	2	0	1 (2)	0	0	0	0	1	2.3	0.77	2	1
AS19	3	1 (2)	0	0	0	0	0	1	2.6	0.69	2	1
AS20	4	1	0	1 (2)	0	0	1	3	2.0	0.77	2	1
AS23	4	1	1 (3)	0	0	0	0	2	1.4	0.86	2	1
Sum	57	7 (8)	10 (18)	11 (15)	5 (6)	6	4	43 (57)				

3 DIFFERENCES IN PREFERENCE BEHAVIOUR

Preference ratings were only collected in IVP2, and hence, the analysis of the preference behaviours is confined to this study. In this paper, the interindividual differences are discussed in terms of correlations between the preferences and the attribute groups. Also, a few interesting results from the preference mapping analysis are presented.

3.1 Correlations between preferences and subjective attribute groups.

Spearman ρ rank correlation coefficients between preference ratings and averages of subjective attribute groups are calculated for each individual in Table 3. The descriptive group in which the assessor has been grouped is denoted in column DG. Spearman ρ is used because a non-parametric test are needed due to the small sample size. The differences between the preference groups are clear; the assessors in preference group 1 have significant positive correlations for Reverberance, Loudness/Envelopment and Bassiness while these are not observed for group 2, except for Bassiness to certain extent. Proximity, which was identified as the main driver of preference, is correlated with most of the individual preferences, as expected. Interesting feature is that even the assessors who were clustered into descriptive group 2, and did not use attributes related to proximity per se, show significant positive correlations between preference ratings and proximity attribute group.

Table 3: Correlations between preferences and subjective attribute groups.

AS	PG	DG	Reverberance	Loudness/Env	Proximity	Bassiness	Definition	Clarity
AS01	1	1	0.29	0.47 *	0.65 ***	0.64 ***	-0.14	-0.1
AS08	1	1	0.61 ***	0.54 **	0.3	0.26	0.29	-0.53 **
AS10	1	1	0.3	0.59 **	0.81 ***	0.63 ***	0.2	-0.16
AS11	1	1	0.57 **	0.73 ***	0.73 ***	0.73 ***	-0.1	-0.43 *
AS12	1	2	0.54 **	0.69 ***	0.52 **	0.67 ***	0.09	-0.32
AS16	1	2	0.38 *	0.62 ***	0.76 ***	0.76 ***	0.2	-0.18
AS17	1	2	0.63 ***	0.68 ***	0.55 **	0.45 *	0.13	-0.64 ***
AS19	1	2	0.3	0.3	0.11	0.26	-0.37	-0.42 *
AS20	1	2	0.17	0.38	0.71 ***	0.62 ***	-0.13	-0.04
AS23	1	2	0.48 *	0.74 ***	0.79 ***	0.81 ***	0.19	-0.34
AS02	2	2	0.09	0.24	0.56 **	0.33	0.43 *	0.16
AS05	2	1	-0.01	0.16	0.41 *	0.46 *	-0.26	0.17
AS07	2	2	-0.04	0.23	0.72 ***	0.59 **	-0.15	0.05
AS13	2	1	0.03	0.25	0.58 **	0.38 *	0.31	0.11
AS15	2	1	-0.05	0.18	0.54 **	0.33	0.19	0.18
AS18	2	1	-0.27	-0.16	0.19	-0.16	0.46 *	0.3
AS21	2	1	-0.02	0.25	0.63 ***	0.53 **	0.23	0.13

3.2 External preference mapping: Vector and ideal point models

In brief, external preference mapping[9] refers to a data analysis technique where the preference data is connected to an external data set, e.g., a common sensory profile and/or a set of physical measures. Here, the descriptive evaluation scores are first analysed by MFA, and the individual preference scores are regressed onto the resulting three dimensional latent structure. Considering the sample size in IVP2, it is possible to fit three regression models of different levels of complexity for each individual. Vector model is the most simple one, where the independent variables are the sample scores on the three main factors. Circular (or spherical) model adds the second order circular term to the model, and elliptical (or ellipsoidical) model adds second order terms separately for each factor. Vector model imply "the more, the better" -type of preference behaviour and circular and elliptical models define ideal points, that is, points which maximize or minimize the preference response, thus, implying an "eclectic" preference behaviour. However, for elliptical models, the ideal points may be also saddle-points. This can make the interpretation of the preference behaviour more difficult, when one direction maximizes the response and another direction minimizes the response.

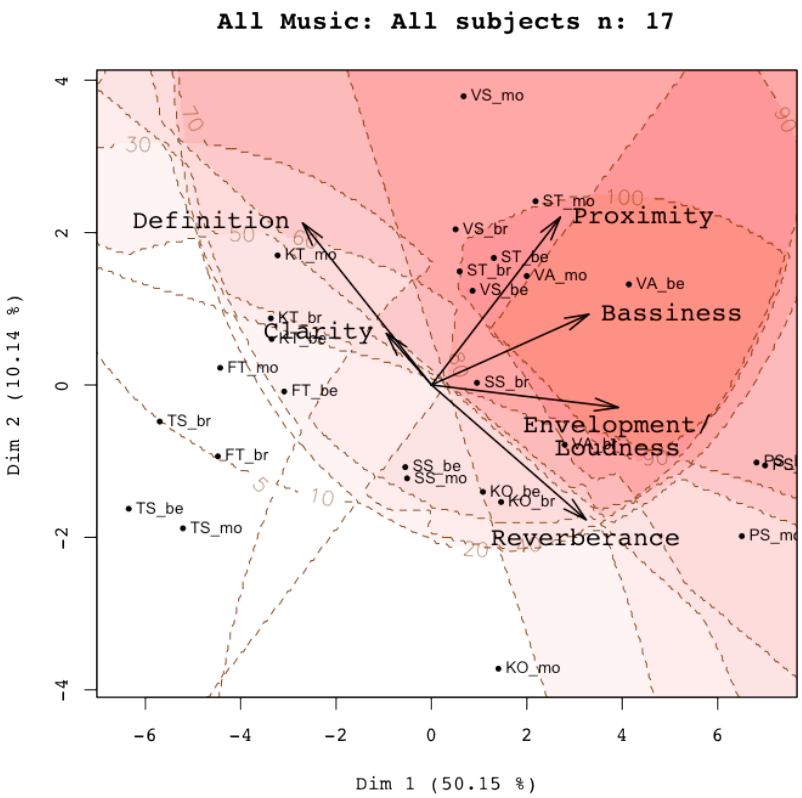
The regression models are first fitted and selected separately for each individual, The details of model selection procedure are described by Kuusinen *et al.*[8]. Then, the models are used to estimate the individual preference values and thresholds of mean preference which are mapped onto the latent sensory space. Finally, the individual maps are overlayed to obtain an overall view of the preference behaviour and to depict the areas where the areas of above mean preference values are matched between the individuals. Importantly, this technique preserves the information about the interindividual differences, while highlighting the regions of shared preferences. The overall result of this procedure is depicted in Figure 1, where the darker regions depict the areas of higher liking. Also, the interindividual differences in preference judgments are apparent in Figure 1 and can be described as follows.

There are 9 vector models and 8 ideal point models. Vector models and the observation that the ideal points are mostly located outside the sample space, indicate that the stimuli in this study do not seem to cover the optimal acoustical conditions. But, ideal point models also imply, that if the sample space would be constructed differently and would cover a wider range of perceptual differences, it could be possible to derive a theoretical ideal, i.e., hall with optimal acoustical conditions in respect to the preferences. Now, it is seen that the shared "hot" region is associated with higher levels of proximity, bassiness and envelopment which is in accoradance with the correlation results in Table 3. The "hottest" sample here is combination of Beethoven music excerpt and the simulated hall, VA. The interindividual differences are manifested in the diagonal denoted by Definition on one side and Reverberance on the other, which also separates the map into "positive" and "negative" regions.

4 CONCLUSIONS

The interindividual differences among assessors in two studies of sensory evaluation of concert hall acoustics were discussed. First, the grouping of assessors based on the descriptive attributes showed that the attribute sets often include heavily interrelated attributes. The differences between individuals in this respect imply that some are more skillful than others in multidimensional discrimination of sound samples. Second, the analysis of the dimensionalities of the individual data sets indicated that the personal perceptual spaces seem to be composed of as few as two to three latent perceptual dimensions. Additionally, the perceptual structures among assessors were observed to differ in their components, indicating that the overall space could be acconted for with around five to seven ideal attributes. This indicates that any subjective evaluation experiment aiming to cover the whole range of acoustic quality aspects, should either employ 4 - 6 individually elicited attributes and/or use concept aligment processes such as group discussions for attribute development, or include around 10 clearly defined attributes in the design, for example, in questionnaire studies. Taken together with the overall clustering of descriptive terms, these observations indicate that the quality of concert hall acoustics can be accounted for with five to seven perceptual aspects.

The interindividual differences in preferences, were observed in terms of correlations between different attribute groups as well as in terms of different regression models in preference mapping. While proximity is clearly associated with higher preference, some individual value more well defined sound with strong bass, and other value more reverberant and enveloping sound. A similar



Model	N	Avr. R^2
Vector	9	0.54
Circular	6	0.60
Elliptical	2	0.71
All models	17	0.58

Figure 1: Preference map in the two main latent factors illustrating the regions of highest liking, the correlations of attribute groups between the main dimension, as well as the differences between individuals. The number of models and the corresponding average R^2 values are shown on the right.

number of both vector and ideal point models were obtained when the preference ratings were regressed onto the three dimensions of MFA solution of the descriptive data. Although, the sample space was observed to not completely cover the whole range of perceptual aspects, so that, optimal or ideal conditions could be pinpointed within this space, important implication is that this sort of theoretical ideal could be possibly obtained with a different sample set. Finally, the observed interindividual differences in both studies highlight that in these type of experiments, some assessors tend to focus primarely on the differences in loudness and reverberance related aspects, while others are more inclined to include also definition, sound width, openness and proximity related attributes. Results also substantiate the idea that more aspects influence preference, than are being analytically perceived as prominent. Evidently also other sensory modalities, and particularly visual experience, play important roles in this respect and should be addressed in the future.

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