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Predicting an individual's preference in concert halls from measurement-based auralizations

Matthew T. NEAL[1]; Michelle C. VIGEANT[1]

[1] Graduate Program in Acoustics, The Pennsylvania State University, University Park, PA USA

ABSTRACT

Past work in concert hall preference has indicated the existence of two different tastes: a preference for clarity and intimacy versus reverberance and envelopment. Previous studies have generated these groupings from a single set of preference ratings. The goal of the present study was to classify concert hall preference and investigate the repeatability of an individual's preference using realistic, measurement-based auralizations. Auralizations were generated for 14 halls in North America and Europe from a measurement database of room impulse responses (RIRs). RIRs were obtained using a 32-element spherical microphone array and a specialized sound source, a 20-element compact spherical loudspeaker array that was used to reconstruct the frequency-dependent radiation patterns of different orchestral instruments. Auralizations were rendered over a 30-loudspeaker virtual acoustics facility. Using these halls, each subject rated seven of the fourteen halls for preference along with five randomly selected subjective attributes from a larger set of ten attributes. A controlled randomization ensured even sampling across the study. Factor and correlation analyses were used to identify which attributes best predicted individual concert hall preference. In addition, the repeatability of preference was investigated to explore future work in efficient prediction of an individual's preference. [Work supported by NSF Award #1302741.]

Keywords: concert halls, spherical microphone array, individual preference

1. INTRODUCTION

The design goals of a concert hall are inherently subjective in nature, focused on ensuring a space will be acoustically pleasing to concertgoers. To further complicate this problem, this goal of success is quite difficult to pinpoint, as it has been shown to vary for different types of music and between different individuals. Classically, two discrete preference groups have been identified by multiple studies: one preferring a loud, reverberant sound and the other preferring a clear, intimate sound. These groups are often identified in a post-hoc sense, grouping subjects on their preference after statistical analysis of the data. Similar groups have been specified by Wilkens,[1] Barron,[2] and Lokki et al.[3-4] Many studies have taken a broader approach to subjective impression, conducting principal component and factor analyses to identify the number of dimensions required to explain the majority of variation in subjective perception. Such techniques have been employed using many different methods, including interviews,[5] live concert surveys,[2,6-7] simplified laboratory conditions,[8-9] measurement-based auralizations,[3-4,10-11] and simulation-based auralizations.[12]

The differences in approach often result from balancing the need for control, repeatability, and reproducibility while attempting to maintain realism to the actual experience of listening within a concert hall. For example, live listening studies ensure realism, at the expense of control in terms of the music, the listener, and many other non-acoustic factors. Auralization studies in laboratory setups can provide high degrees of control and repeatability, but the results of the study are inherently influenced by the realism, or lack of realism, in the measurement and auralization setups. The goal of the present study was to use realistic measurement-based auralizations based upon spherical array processing techniques to investigate concert hall perception and preference. This paper describes the identification of a subset of orthogonal factors of concert hall subjective impression and the subsequent investigation of how these factors correlate with each individual's preference.

[1] mtn5048@gmail.com (or mtn5048@psu.edu)

2. SUBJECTIVE STUDY EXPERIMENTAL DESIGN

2.1 Auralizations using the concert hall orchestral research database (CHORDatabase)

The concert hall orchestral research database, or CHORDatabase, was used as the basis of the auralizations for the present study.[13] This database includes spherical microphone array room impulse responses (MicRIRs) measured using a three-part omnidirectional sound source for objective sound field analysis. The database also contains MicRIRs measured in a single seat for twenty different stage source locations using a 20-element compact spherical loudspeaker array (CSLA). This array was designed to accurately represent the frequency-dependent radiation patterns of different instruments using spherical array beamforming techniques. These measurements allow for the generation of full-orchestral auralizations that are realistic and provide the control and direct comparability required for psychoacoustic testing. The database covers a wide variety of rooms, containing halls of different shapes and sizes, ranging in hall-averaged mid-frequency unoccupied reverberation times (T30) from 1.54 to 3.28 s. Full details regarding this database can be found in Ref. [14].

For this study, auralizations were generated in each of the halls at a central seat located 15 m from the stage. Auralizations were made using an anechoic recording database of 61 separate individual instrument tracks for Beethoven's 8th symphony.[15] To accommodate the 61-piece orchestra recordings, a 61-piece orchestral arrangement was created that was compatible with the 20 source locations measured with the CSLA in the CHORDatabase.[14] For each of the 61 source locations, the measurement location closest to the new position with the same instrument directivity was copied, and the direct sound in the new MicRIR was isolated. Then, the direct sound was rotated in the spherical harmonic domain, relative to the measurement / listener position, and adjusted in amplitude to match the new source position. This generated a set of 61 orchestral MicRIRs, which after convolution with each individual anechoic recording, were superimposed to generate a full-orchestral auralization in each hall. Relative levels between sections were balanced based upon a simulated free field auralization at a 15 m distance, as not to bias the balance towards any single hall. Final auralizations were presented over the Auralization and Reproduction of Acoustic Sound fields (AURAS) facility, a 30-channel higher-order Ambisonic auralization array located in an anechoic chamber on the campus of The Pennsylvania State University.[14]

2.2 Subjective ratings task and attribute selection

For subjective data collection, a multiple-stimulus comparative testing interface was selected. The interface, shown in Fig. 1, allows for simultaneous switching between eight different stimuli. Effectively, participants could 'transport' between halls while the musical passage was uninterrupted. This control gave subjects the ability to directly compare a wide variety of halls in a time-efficient test environment. Single-stimulus tests can produce similar results, but they have been shown to take more time to complete and provide lower repeatability within each subject's answers.[16] Additionally, if multiple subjective attributes are intended to be rated, it quickly becomes impractical to compare a large number of halls using a large number of subjective terms. This test type balanced the need for comparability, repeatability, and coverage in terms of hall and subjective attribute variety. The authors considered including more than eight stimuli, but informal piloting showed that including more than eight stimuli made the task exhausting, due to the exponentially increasing number of comparisons.

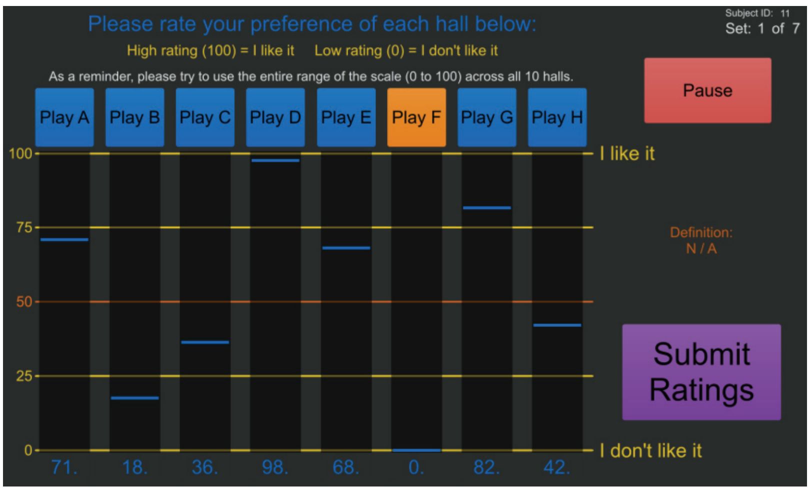

Figure 1 – The subjective testing interface used in the current study. The interface allowed for real-time switching between halls and provided anchors and definitions for the current attribute that was being rated.

A collection of all subjective factors found to be important from previous literature was generated, and after removing redundant terms, a comprehensive subset of ten attributes was selected – see Table 1. The attributes encompass almost all terms found to be important in previous overall concert hall perception literature, excluding only terms related to balance and ensemble. As the present study used a fixed orchestral arrangement, and as the study does not allow for musician adaptation to acoustic environment, the authors felt obtaining subjective data on these terms would not necessarily be well represented. The current study is also from a listener's point of view and not a performer on stage. Table 1 lists the ten attributes included in the study and the high and low scale anchor points. Scale anchors were largely taken from the room acoustical quality inventory (RAQI), a list of common terminology developed by a focus group of room acoustical experts.[12] Some adaptations were made when the authors felt the RAQI's English translation might cause unintended misinterpretation for native-speaking English subjects. More information regarding the definitions of each of these terms used in this study can be found in Ref. [14].

Table 1 –Attributes and anchors of the ten selected subjective terms and preference. Many of the anchors were selected from those suggested by the RAQI expert focus group.[12]

Attribute	High Anchor	Low Anchor
Brilliance (Brill.)	Very brilliant	Not brilliant
Envelopment* (Env.)	Completely surrounded*	Not at all surrounded*
Intimacy (Int.)	Intimate	Remote
Proximity* (Prox.)	Close	Far*
Reverberance (Rev.)	Reverberant	Dry
Source Width (SW)	Very wide*	Not wide (narrow)*
Spatial Clarity* (SC)	Clear	Blurred
Strength* (Str.)	Loud	Soft
Temporal Clarity (TC)	Clear	Blurred
Warmth (Wrm.)	Warm	Cool
Preference (Pref.)	I like it	I don't like it

*indicates a different in attribute or anchor terminology from the RAQI

2.3 Hall selection using k-means clustering

The CHORDatabase consists of 21 unique concert halls, but a maximum of eight halls was set to prevent excessive testing difficultly and subject exhaustion; this practical limit significantly reduces the variety and coverage of the current study. To retain the study's coverage, each subject received a set of stimuli consisting of seven randomly selected halls in the CHORDatabase and a single anchor stimulus. This low-end anchor was included across all subjects, providing a consistent baseline. Although anchor stimuli were consistent across subjects, the anchor was changed between subjective attributes, as low-end perceptions were not always compatible for opposing perceptions (e.g. reverberance and temporal clarity). This experimental design allowed for the inclusion of more than eight halls, extending the reach of the current study.

Although study coverage is increased, simple randomization introduces the possibility of biasing the preference ratings for a specific individual to the randomized subset that was received. For example, if one subject only rated the most reverberant halls, and their preference was for halls with high clarity, this preference would not be clearly indicated. To prevent bias, a clustering analysis was performed to establish and compare the perceptual similarity of the 21 halls. First, mid-frequency average early decay time (EDT), clarity index for music (C80), and strength (G) for each hall was calculated for the 15 m seat location. Then, each hall was assigned a point in a three-dimensional space, with each axis corresponding to each metric calculation. Each metric was mean-centered and normalized to the standard deviation across the 21 halls. Then, a k-means clustering analysis was run, computing clusters for all groupings from 2 – 20. As k-means clustering has a randomization which can influence the resulting clusters, each analysis for each value of k was run 1000 times, and the clustering solution with the lowest remaining squared error to cluster center was retained.

The solution for eight clusters is shown in Fig. 3, plotting each hall on this three-dimensional parameter space. The color and shape of the symbols indicates the cluster centers. First, it was important to determine if there are groups of halls which have nearly identical perceptual characteristics. If multiple halls contribute the same perceptual experience to the study, only a smaller subset would need to be included. For the clusters with more than two elements (groups 1, 2, and 3), each group was reduced to a representative sample of two halls within that group, and the other halls were removed from inclusion in the study. This resulted in 14 remaining halls, with the removed halls greyed-out (shown as a light color) in Fig. 2. Finally, within each cluster, seven pairs of halls were made, with some slight reorganization of groups 4, 7, and 8 due to the singleton clusters found in groups 7 and 8. This created seven pairs of perceptually similar halls. For the final randomization, each subject receiver one randomly selected hall from each pair, which ensured that all subjects saw a representative subset of halls across the entire database. All of the hall down selection and pairing was carefully validated with informal subjective listening to ensure that no perceptually unique halls were removed from the study and that hall pairs were indeed perceptually similar.

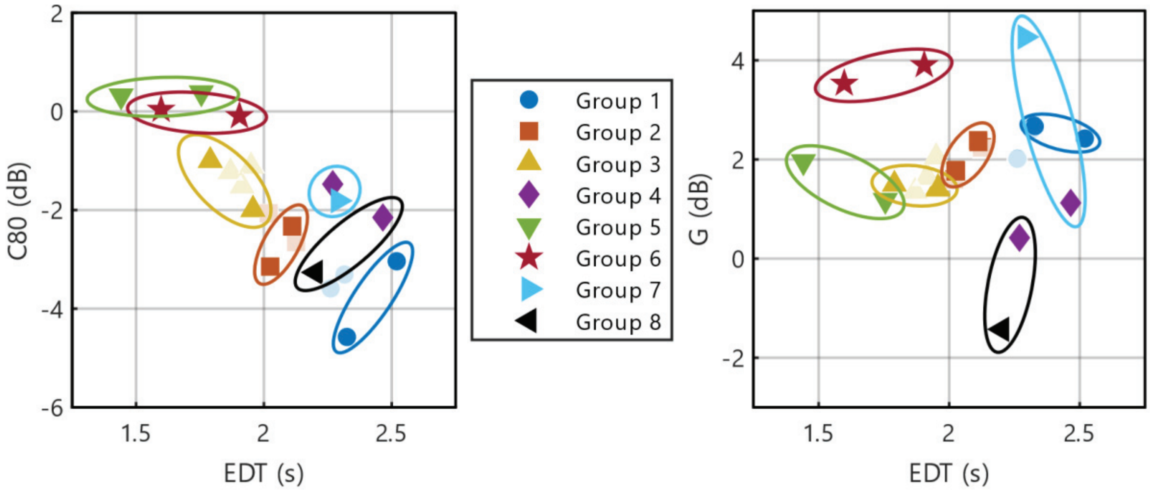

Figure 2 – All 21 halls in the CHORDatabase plotted in terms of metric values for EDT, C80, and G at the 15 m receiver location. Symbols and colors indicate the 8-cluster k-means clustering analysis. Greyed-out halls were not included in the subjective study, and circles indicate pairs for controlled randomization.

2.4 Incomplete-block experimental design and controlled randomization

For the final study, the previously described stimuli randomization technique was implemented into an incomplete-block experimental design. During the study, subjects first completed a formal training procedure, including a tutorial and practice questions. After training, subjects participated in eight rating sets, consisting of three sets regarding preference and five sets of randomly selected attributes from the overall set of ten. Preference ratings were done first, before subjects had been exposed to the individual perceptual terms, so that their preference was not biased to the specific attributes they were asked to assess. For all subjects, the first set of preference ratings was taken as an additional hidden practice set, and only the final two preference rating sets were used for statistical analysis. After the preference ratings were complete, subjects were given a short break followed by a second tutorial, instructing them to focus on specific clearly defined attributes, instead of preference. Then, subjects rated three of the subjective attributes, took a second short break, and rated the fourth and fifth subjective attributes. The test administrator had a discussion with each subject before the specific attribute ratings sets, asking them to explain back the terms in their own words. If a misinterpretation was found, the administrator corrected their understanding to the intended definition of the attribute. The overall test took approximately one hour and fifteen minutes to complete.

A visual diagram of the experimental design is provided below in Fig. 3. Subject 1 received a random selected from each of the seven hall pairs, and along with preference, five randomly selected attributes. Then, subject 2 would receive the same set of attributes, but with the compliment selection of halls, not rated by subject 1. Then, subjects 3 and 4 would receive the same random set of halls as subjects 1 and 2, respectively, but with the remaining five subjective terms. Thus, after every four subjects, each hall was rated once for each of the ten attributes, and rated four times (by two subjects, twice) in terms of preference. This experimental design increased the number of subjects needed to achieve higher sample sizes across the study, but it also doubled the coverage of the study in terms of both halls and attribute selection. Finally, the repetition of preference, in back-to-back sets, allows for assessment of the repeatability in preference ratings for each subject. Although the halls were consistent across all sets for a single subject, the order of the stimuli was randomized for every set.

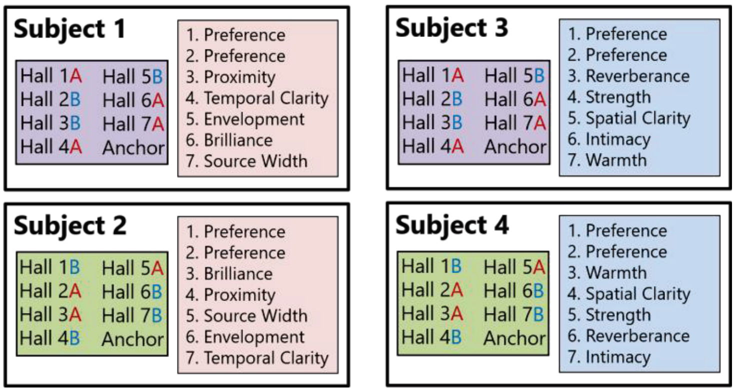

Figure 3 – A visual schematic of the randomization and incomplete-block experimental design for the subjective study. This randomization allowed for the inclusion of 14 halls, 10 subjective attributes, and preference repeatability assessment. A complete sample was obtained after every four subjects.

3. RESULTS

3.1 Descriptive statistics and correlations

Sixteen subjects participated in the experiment, all meeting minimum hearing thresholds of 15 dB-HL in the octave bands from 250 – 8000 Hz. Subjects were required to have at least five years of formal musical training and were required to be actively studying their instrument or involved in a musical ensemble. The subject pool included 11 males and 5 females with an average age of 24 years. The average musical experience across all subjects was 14 years.

For the data analysis, first, averages across subjects for each of the ten subjective attributes, along with preference, were made for each hall. To assess the degree of multicollinearity between attributes, correlations were calculated between the average subjective ratings for a sample size of $n = 14$ halls. Table 2 provides the Pearson correlation coefficients, where correlations coefficients with a magnitude such than $r \geq 0.5$ are highlighted in red and $r \leq -0.5$ are highlighted in blue. Many of the attributes are found to be highly correlated, indicating that a reduction in this perceptual space is likely possibly through principal component analysis and factor analysis.

Much of the clarity-related impressions, including temporal clarity, spatial clarity, intimacy, and proximity were found to show high correlation. Strength showed strong correlations with the spatial perceptions of envelopment ($r = 0.77$) and source width ($r = 0.87$). In general, all factors had at least two (brilliance) and up to six (reverberance) correlations exceeding a magnitude of 0.5. Another interesting analysis, found in the second column of Table 2, is the correlation of average preference with each of the ten subjective attributes. The highest correlation was found with proximity ($r = 0.81$), along with strong correlations with clarity factors and warmth as well. Little or weak correlation with average preference is found with brilliance, reverberance, and strength. Some of these results are quite surprising, but the low values of these correlations could also be due to different preferences between individuals. This finding will be further discussed in section 3.3.

Table 2 – Correlations between all ten subjective attributes and overall average preference. Strong positive correlations ($r \geq 0.5$) are shown in red, and strong negative correlations ($r \leq -0.5$) are shown in blue. Bold values are significantly different than zero ($p < 0.05$, $n = 14$).

	Pref.	Brill.	Env.	Int.	Prox.	Rev.	SW	SC	Str.	TC
Brill.	0.06	–	–	–	–	–	–	–	–	–
Env.	0.40	0.20	–	–	–	–	–	–	–	–
Int.	0.31	-0.16	-0.47	–	–	–	–	–	–	–
Prox.	**0.81**	0.16	0.41	0.31	–	–	–	–	–	–
Rev.	0.03	0.26	**0.67**	**-0.73**	0.00	–	–	–	–	–
SW	0.44	**0.65**	**0.68**	-0.25	0.47	**0.66**	–	–	–	–
SC	**0.60**	-0.14	0.06	**0.70**	**0.70**	-0.53	-0.06	–	–	–
Str.	0.29	0.51	**0.77**	-0.37	0.37	**0.72**	**0.87**	-0.03	–	–
TC	**0.68**	-0.16	-0.21	**0.66**	0.50	**-0.61**	-0.16	**0.74**	-0.32	–
Wrm.	**0.58**	-0.37	0.30	0.49	**0.63**	-0.25	0.05	**0.70**	0.07	0.50

3.2 Principal component and factor analyses

3.2.1 Number of perceptual dimensions using principal component analysis

Seeing high degrees of correlation between attributes, a principal component analysis (PCA) was run, determining a set of principal components (PCs) or eigenvectors associated with the ten-dimensional perceptual attribute space. Fig. 4 shows the variance explained by each individual PC using the blue bar graph, and the cumulative variance explained by the addition of each new dimension is shown with the red line. PCA naturally results in an elbow-like plot, where the first few PCs explain large amounts of variance, while the last few PCs explain marginal variance and are likely of questionable perceptual relevance. Selecting a number of dimensions to retain is a subjective choice, and in this case, the natural elbow appears to fall around 2 – 4 PCs, explaining 51.7%, 63.7% and 72.0% of the total variance, respectively. This paper will focus on the four-factor solution, but results for both the three- and four-factor solutions are provided in Ref. [14].

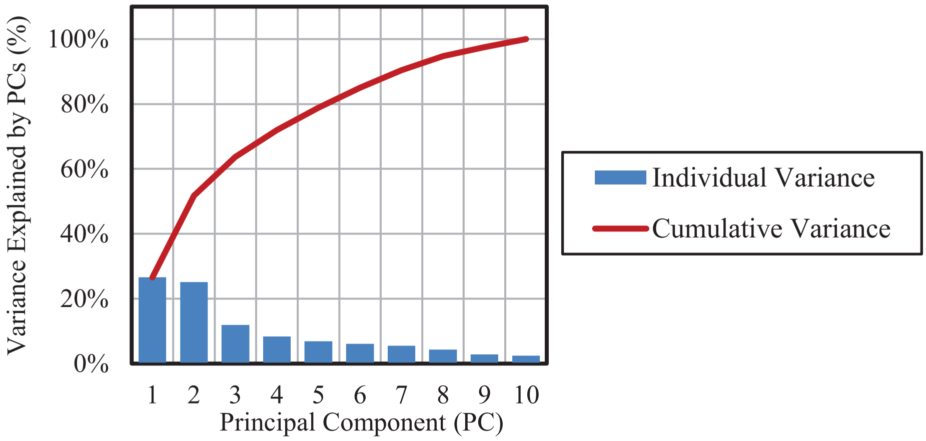

Figure 4 – Results of the PCA run on the raw perceptual data from the subjective study. The variance explained by each PC is shown in blue and the cumulative variance is indicated by the red line.

3.2.1 Orthogonal and interpretable factors using varimax rotation

As PCA often results in PCs that are difficult to interpret, a varimax rotation was used to define four new factors based on the first four PCs. This analysis resulted in a series of weighting factors that are used to calculate each factor score from the average perceptual ratings of the ten original attributes. To aid in interpretation, a correlation analysis was run between the four factors and the ten original attributes, along with average preference. The first factor, 4.1, is highly correlated with intimacy, spatial clarity, temporal clarity, and warmth. As well, it is negatively correlated with reverberance. This factor appears to be interpreted as a clarity factor, which is also correlated with average preference. The second and third factors show some similarity, both having high correlations with reverberance and strength. The second factor, 4.2 shows a stronger correlation with envelopment, while factor 4.3 appears to show an emphasis on proximity and source width. The second factor appears to be a strength / envelopment factor, while the third factor is a strength / source width factor, both showing spatial sound field interpretations. Finally, the last factor shows only one strong correlation with brilliance, providing a direct interpretation as a timbre / brilliance factor. It is important to note that although factors are found to be strongly correlated with individual attributes, average preference correlations are not as strong, all below a threshold of 0.6.

Table 3 – Correlations between the varimax-rotated factors and the original attributes. Strong positive correlations ($r \geq 0.5$) are shown in red, and strong negative correlations ($r \leq -0.5$) are shown in blue. Bold values are significantly different than zero ($p < 0.05$, $n = 14$).

Factor	Attribute										Avg.
(% Var.)	Brill.	Env.	Int.	Prox.	Rev.	SW	SC	Str.	TC	Wrm.	Pref.
4.1 (25%)	-0.15	0.00	**0.78**	**0.43**	**-0.54**	-0.05	**0.77**	-0.04	**0.59**	**0.69**	**0.58**
4.2 (19%)	0.13	**0.84**	-0.13	**0.31**	**0.49**	**0.37**	0.19	**0.82**	**-0.35**	**0.44**	0.38
4.3 (16%)	0.18	**0.33**	0.02	**0.66**	**0.56**	**0.89**	0.13	**0.59**	0.08	0.04	**0.59**
4.4 (12%)	**0.90**	0.00	-0.12	**-0.31**	0.15	**0.29**	-0.24	0.26	**0.29**	**-0.33**	-0.06

3.3 Correlations with individual preference

Although averaging ratings across subjects is valid for the ten well-defined attributes, preference is not inherently consistent between individuals. As such, the calculation of an average preference will only result in a general consensus and remove inter-individual differences. To highlight inter-individual differences, a correlation analysis was run between individual preference ratings and the factor scores for each hall. Individual preference ratings were taken as the average of the second and third preference sets for the seven halls rated by each subject. For all halls, factor scores were calculated based upon the average subjective scores for each of the ten attributes. In Table 4 below, each column represents a separate correlation analysis between the individual, subject-averaged preference ratings of seven halls and the average factor scores per hall. Although each subject rated a unique subset of halls, this analysis can be run for each subject, independent of hall subset, once each hall has been represented in the common perceptual factor space. A sample of preference correlations for 10 of the 16 subjects are provided in Table 4.

Table 4 – Correlation between individual preference and average factor scores from each hall. Strong positive correlations ($r \geq 0.5$) are shown in red, and strong negative correlations ($r \leq -0.5$) are shown in blue. Bold values are significantly different from zero ($p < 0.1$, $n = 7$).

Factor	Preference correlations (by individual subject ID)									
	6	3	5	2	10	11	9	13	1	14
4.1 – Clarity	-0.52	-0.12	0.05	**0.67**	**0.82**	**0.95**	0.15	-0.37	0.08	0.34
4.2 – Str. & Env.	**0.80**	0.65	**0.88**	**0.71**	0.11	-0.12	**-0.96**	0.29	-0.30	-0.14
4.3 – Str. & SW	**0.88**	**0.95**	**0.71**	0.36	0.12	0.14	**-0.68**	0.56	0.20	0.18
4.4 – Brilliance	0.57	0.34	0.03	-0.14	**-0.75**	-0.09	-0.12	0.66	0.24	-0.44
Repeatability	0.90	0.92	0.73	0.84	0.96	0.86	0.56	0.32	0.75	0.28

Traditionally, preference has been divided into two groups: one group preferring strength and reverberance, and the other preferring clarity and intimacy. At a high level, some subjects do fall into such categories. Subjects 6, 3, and 5 appear to show higher correlation with strength and spaciousness-related factors (4.2 – 4.3), while subjects 2, 10, and 11 show strong correlations with the clarity factor (4.1). Although subjects can be placed in two discrete groups, it removes the subtlety and individual variability in the data. For example, subject 6 has similar preference to 3 and 5, but 6 shows preference against clarity, in favor of strength and reverberance. Also, subject 3 appears to emphasize source width over envelopment, while subject 5 shows more of an emphasis on envelopment over source width. The two-group preference model would not accurately represent subject 2, who prefers clarity, but shows a strong correlation with the envelopment, not seen in the other subjects within the 'clarity' group.

Interestingly, subject 9 shows a highly unique preference against strength, source width, and envelopment. Although not a common preference, it is important to note that such individuals may exist, even if their preference goes against classical wisdom. Subject 13 shows less strong correlations with preference, but their results suggest a potential importance of the brilliance factor (4.4). A few subjects' results show limited correlation with any of the factors, which suggests either a preference that is difficult to define with the current factors, or a lack of a clearly defined preference, possibly from poor repeatability.

To assess repeatability, a correlation analysis was run between the repeated ratings across the two identical preference sets for each subject. Table 4 shows these correlations coefficients in the bottom row. In general, subjects show good repeatability, mostly exceeding a value of 0.7. This criterion was not met by 4 of the 16 subjects, which might call into question the validity of their preference interpretations. For example, subject 14 had poor repeatability, most likely causing the lack of correlation with preference. On the contrary, subject 1 showed good repeatability, but no clear correlations with the factor scores existed. This result could indicate a valid preference that is not easily interpreted with the standard factors. Subject 9, who had the unique preference toward less loudness and less envelopment, shows a marginal repeatability ($r = 0.56$). This observation may indicate that this preference might not be consistent, but if more subjects were tested with more repetitions, results could indicate whether or not this preference become stable. The consistency of the preference of subject 13 should also be questioned. The possible importance of the brilliance factor was suggested, but a very low repeatability correlation was found ($r = 0.32$).

4. CONCLUSIONS AND FUTURE WORK

A subjective study to investigate individual concert hall perception was conducted using full-orchestral auralizations measured with a spherical microphone array and compact spherical loudspeaker array (CSLA). Auralizations were rendered using higher-order Ambisonics over a 30-loudspeaker array. A subjective study was conducted to investigate the ratings of ten subjective attributes and preference across 14 different concert halls. Proximity and clarity-related factors were found to best correlate with overall average preference, as is also suggested in previous literature.[3] A set of four orthogonal factors were shown to explain 72% of the total variance in perception, which were interpreted as clarity, strength / envelopment, strength / source width, and brilliance. Comparing these factors with individual preference, most subjects showed good repeatability and large individual differences were observed, not captured fully in the traditional two-group preference model. Future work will involve collecting more subjective responses, connecting the perceptual data collected to high-resolution spherical beamforming analyses, and investigating an efficient method to predict an individual's preference in concert halls. With an efficient method, such a test could be repeated across many more musical passages and motifs to extend conclusions across musical genres.

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