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JASA ARTICLE

Chamber music hall acoustics: Measurements and perceptual differences

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ABSTRACT:
This study investigates the room acoustics of seven chamber music halls of various modern and historical architecture by means of objective room acoustic measures and a subjective listening experiment. The acoustic measurements were performed with heavy cloth covering the audience areas to simulate occupancy in the halls. A loudspeaker quartet was used for auralizations, which were reproduced in a surrounding loudspeaker array. The perceptual differences between the halls were evaluated in terms of envelopment, warmth, clarity, proximity, and preference by using a paired comparison paradigm. The subjective evaluations were conducted in two different laboratories and latent class analysis was used to study the agreement between laboratories and the emergence of different listener groups in the ratings of each attribute. Concerning preference, the emergence of two groups found in the study of large symphony halls was confirmed, where one group prefers rich, enveloping sound and one group prefers high clarity. The perceptual ratings were not clearly associated with a specific hall shape, but rather depended on the distribution of early and late sound energy. Thus, the distinction between rectangular and non-rectangular floor plans previously found for large symphony halls was not observed with these smaller halls.
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I. INTRODUCTION

Chamber music halls (or recital halls in the U.S.) are performance spaces intended for chamber music performed by small ensembles. These halls play an important part in the music scene. Yet, their acoustic characteristics have received less attention than those of larger halls intended for symphonic music.

The article is organized as follows: Sec. II gives an overview on previous research relevant to chamber music hall acoustics, and provides ranges of objective parameters that were recommended for such halls. Section III presents the architecture and the acoustic properties of the measured halls with standard acoustic parameters and spatial energy plots. Section IV describes the listening experiment and analysis methods. Results are presented in Sec. V. Discussion of the results (relating them to the specific hall architecture) as well as opportunities for future work, are provided in Sec. VI, and the main findings are summarized in Sec. VII.

II. BACKGROUND

The acoustics of chamber music halls has been studied to a much lesser extent than that of symphonic halls. Previous research mainly presented acoustic measurements and design parameters of modern or historic chamber music halls. One of the most comprehensive surveys was conducted by Hidaka *et al.*,[1] who measured nine modern Japanese halls and nine historic European halls, according to the ISO 3382 standard, monaurally and binaurally without an audience. Values for the occupied state were estimated from the measured values using a transformation formula.[2] The mid-frequency reverberation times (RTs) were between approximately 1.1 and 2 s. Based on the interviews with musicians, they suggest that for halls with 500–600 seats, values between 1.5 and 1.7 s are optimal. They also give other specific design guidelines, for instance, regarding the necessity of large- and fine-scale diffusion.

Beranek gave similar recommendations for the RT in chamber music halls, which was 1.6–1.8 s for halls under 700 seats.[3] He also suggested target strength G values of 9–13 dB.

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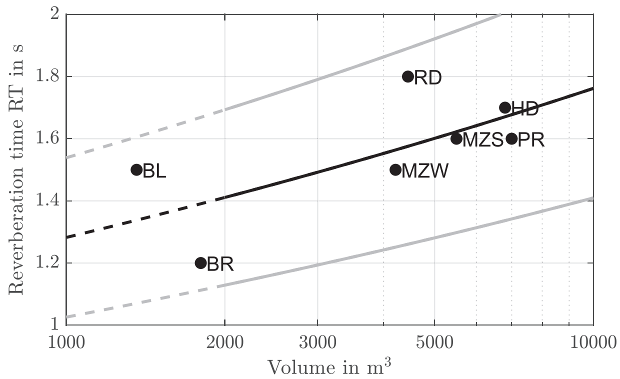

FIG. 1. Recommended mid-frequency reverberation times for music performance as a function of hall volume from Ref. 5, extrapolated to smaller volumes between 1000 and 2000 m^3. The 20% tolerance limits are shown in gray.

Barron[4] described nine chamber music halls by means of monaural acoustic measurement data and discussed the shapes and other design parameters of the halls. He states that small auditoria are "easier and much less demanding to design" than larger halls, e.g., due to the greater amount of reflections per time in smaller rooms. According to him, the main goal is to create a feeling of intimacy. Also, clarity is considered to be an important characteristic for chamber music. Since providing the audience with sufficiently strong early reflections is easier in smaller than in larger halls, and therefore, less of a concern, reverberation time (RT) is suggested as a main design parameter, which can be selected relatively freely according to the intentions of the designer. In line with Hidaka's recommendations, RT targets of 1.4–1.7 s are given. Furthermore, Cremer's target curves[5] are introduced as the best current recommendation, even for small halls. They provide a guideline for RT, depending on the room volume (see Fig. 1). Barron argues that these curves may be appropriate for chamber music halls, as chamber music halls with more room volume are more likely designed with larger chamber orchestras in mind, which would benefit from higher RTs. Along with these discussions, Barron only provides informal subjective listening impressions.

Meyer discusses the development of chamber music and the halls in which it is performed,[6,7] and observes five chamber music hall types from the various architectural eras, ranging from large rooms in palaces to domestic rooms to modern halls. He suggests that due to the very different listening conditions among these hall types, there may not be a strong connection between chamber music as a genre and the halls in which it is performed. He concludes that chamber music "is not generally associated with a typical kind of room."

The only perceptual work known to the authors regarding room acoustics of chamber music was a demonstration, rather than an experiment, conducted by Meyer.[8] Eighty listeners drove to three different rooms (a lecture hall, a piano demonstration hall, and a museum foyer), where they listened to string quartets performed by the same ensemble. Listening impressions were discussed, but there was no formal evaluation. Given that the activity was a demonstration, rather than a scientific experiment, only general conclusions were made, such that excess reverberation (one room had a RT of 2 s at mid frequencies and 3 s at low frequencies) did not lead to sufficient clarity for fast passages.

To summarize, there is a limited number of studies on chamber music halls and no studies where the perceptual differences for the audience would have been evaluated by means of a structured listening experiment. However, the literature provides target values for RT and strength that can be compared to the values measured in the halls selected for our study.

III. HALLS AND ACOUSTIC MEASUREMENTS

Table I shows full names and locations of the seven chamber music halls included in this study, along with physical and acoustical parameters (octave band values are in Fig. 2). Ground plans and sections can be seen in Fig. 3 together with spatial energy plots. The plans are in scale with respect to each other and aligned with respect to the receiver position in the audience area.

The hall selection spans different sizes, types, and shapes of halls. Five halls have a rectangular ground plan; one is a pentagon and one is fan shaped. Among the rectangular halls, Irenensaal Baierbrunn (BR) is oriented crosswise with semi-circular seating [Fig. 3(a)]. It was designed as a copy of Beethovensaal Bonn. It has built-in absorbent acoustic banners that were partially deployed during the measurement. Konzerthaus Blaibach (BL) also has a rectangular ground plan but it is tilted in its longitudinal cross section, i.e., audience floor and ceiling are inclined by about

TABLE I. List of chamber music halls included in the study. Acoustic parameters were computed from measurements with occupancy simulation and are shown as averages between the 500 and 1000 Hz octave bands for G, EDT, T_{20}, C_{80}, and between the 125 and 1000 Hz octave bands for J_{LF} and L_J, following ISO 3382-1 for frequency averages, according to listener aspects.

	Hall	Shape	Podium height (m)	Inclined	V (m^3)	N (seats)	V/N (m^3/seat)	G (dB)	EDT (s)	T_{20} (s)	C_{80} (dB)	J_{LF}	L_J (dB)
BL	Konzerthaus Blaibach	Rectangular	0	Y	1360	200	6.8	13.1	1.7	1.5	–0.7	0.17	5.3
BR	Irenensaal Baierbrunn	Crosswise Rectangular	0	Y	1800	180	10.0	10.7	1.3	1.2	2.6	0.10	0.8
HD	Haydnsaal Eisenstadt	Rectangular	1.0	N	6800	670	10.1	9.1	1.9	1.7	0.6	0.20	1.0
MZS	Mozartsaal Stuttgart	Pentagon	0.8	Y	5500	750	7.3	11.9	1.5	1.6	4.0	0.19	1.1
MZW	Mozartsaal Vienna	Rectangular	0.8	N	4215	705	6.0	11.1	1.4	1.5	0.7	0.25	2.7
PR	Prinzregententheater	Fan-shaped	0.4	Y	7000	1080	6.5	9.8	1.8	1.6	1.9	0.10	–0.1
RD	Franz–Liszt–S. Raiding	Rectangular	1.1	N	4450	590	7.5	11.5	1.7	1.8	0.1	0.24	4.2

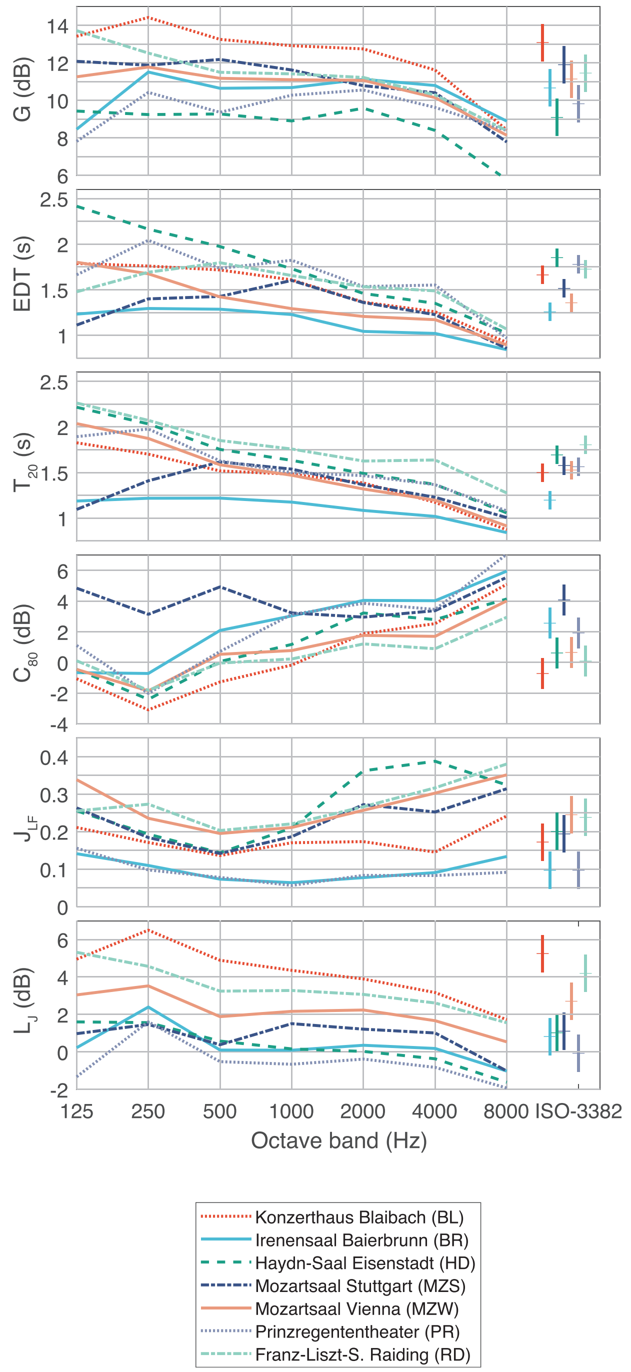

FIG. 2. (Color online) Objective room acoustical parameters (averages of four source positions) of the measured halls at 7 m distance, with occupancy simulation. "ISO-3382" signifies the single number quantity defined in the ISO-3382-1:2009 standard and the length of the vertical bar is the just noticeable difference.

22° [Fig. 3(b)]. Both BR and BL are small halls with around 200 seats. Mozartsaal in Konzerthaus Vienna (MZW) and Franz–Liszt–Saal in Raiding (RD) have a flat floor and balconies on three sides [Figs. 3(c) and 3(d)]. Haydnsaal Eisenstadt (HD) has an elongated rectangular shape with a mostly flat floor and one short balcony on each end. At the time of measurement, it had its usual sound- absorbent curtains along the rear stage wall [Fig. 3(e)].

Mozartsaal Stuttgart (MZS) has a pentagonal ground plan with an inclining audience in most areas and a flat ceiling [Fig. 3(f)]. The audience distribution reminds one of a vineyard-style design, but without seating surrounding the stage on all sides. MZW, HD, RD, and MZS have between 600 and 700 seats.

Prinzregententheater is fan shaped, i.e., trapezoid with an inclining audience area. It doubles as a small opera house [Fig. 3(g)] and has 1080 seats. For chamber music productions, such as voice recitals, its safety curtain and orchestra pit are closed.

A. Acoustic measurements

Acoustic measurements were made using a dodecahedral loudspeaker with individually controllable drivers (a modified Müller-BBM m|dod 250 A, Planegg, Germany) and a six channel open microphone array of 50 mm diameter (G.R.A.S, type 50-VI, Holte, Denmark), so that the measurements resulted in a set of 12×6 impulse responses per source/receiver combination. The measurement setup was chosen to enable auralization for the subjective comparison of the halls. The auralization method is presented in Sec. IV F.

The dodecahedral loudspeaker was sequentially placed at four positions typical for a quartet ensemble on stage. Equal relative positions between the source locations were ensured by use of a transparent foil laid out on the ground. The distance to the stage leading edge, if one existed, was on average 1.6 m for the two closest source positions (see Fig. 4). The stage was always empty except for the measurement loudspeakers. The height of the center of the dodecahedron was 1 m.

The receiver was located at approximately 7 m distance from the front line of the quartet and on average 1.6 m to the left of the centerline of the hall. The receiver positions are marked in Fig. 3. The microphone was positioned at ear height in each hall, at around 1.2 m, depending on the seat construction.

In contrast to the previous studies by Lokki *et al.*,[9,10] where halls were measured and studied empty, the sound absorption caused by an audience was simulated by covering as much of the audience area as possible with a heavy cloth. This method has been described in more detail by Hidaka *et al.*[2] The amount of available fabric, however, did not cover the audience areas completely in all halls: The fabric covered all seats only in the smallest halls, BR and BL, it covered around 85% of seats in RD, HD, MZW, and MZS, and in the hall with most seats, PR, only half were covered. Acoustic measurements, objective parameter values, and the auralizations used in the listening experiment correspond to this "occupied" condition.

B. Objective room acoustical parameters

Room acoustical parameters as defined in the ISO:3382–1 standard[11] are shown as single values in Table I and in octave bands in Fig. 2. For parameter computations, according to the standard, impulse responses from an

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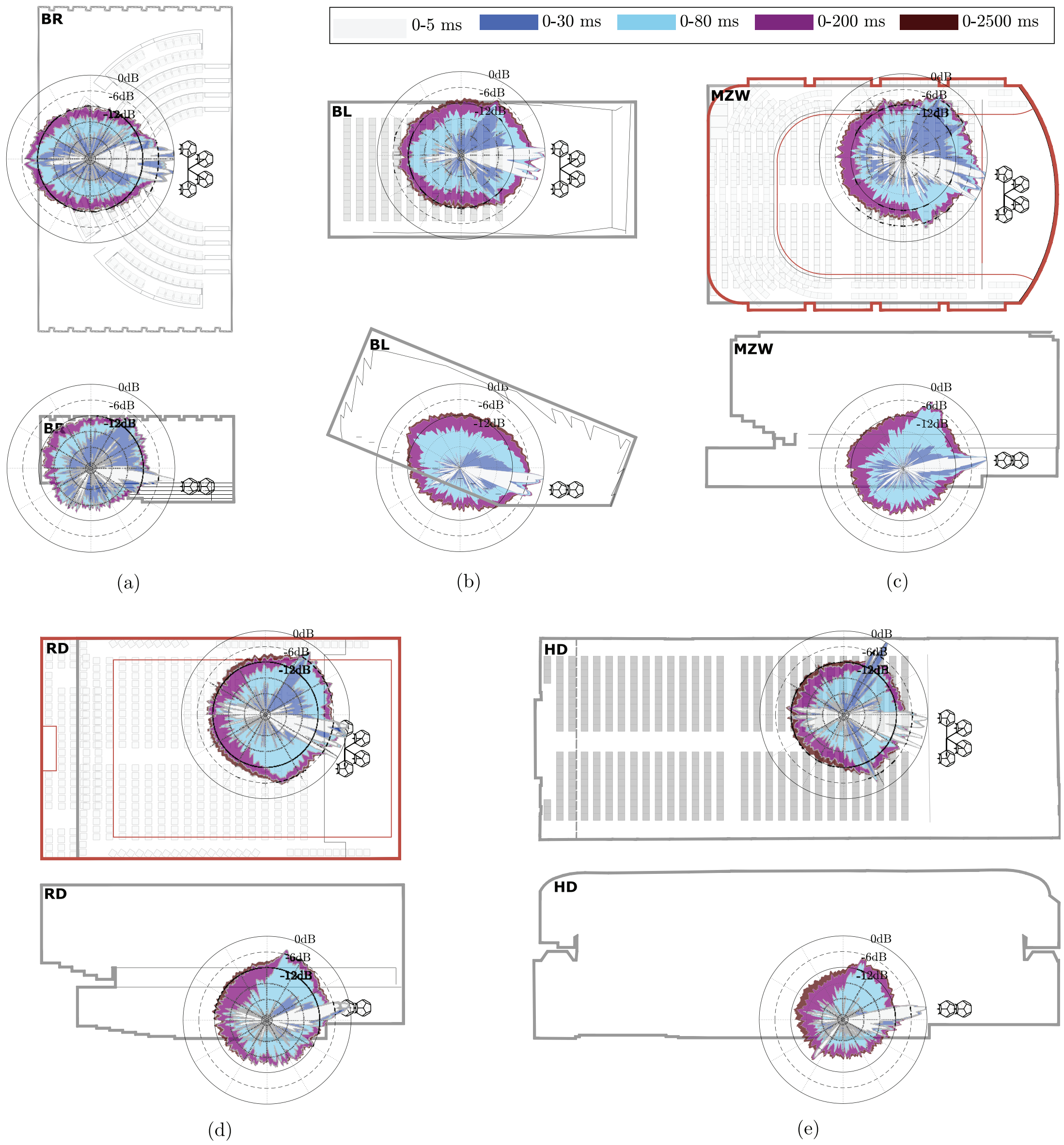

FIG. 3. (Color online) (a)–(e) Spatial energy distribution for rectangular halls BR, BL, MZW, RD, and HD, each with ground view above and side view below. The plots show the cumulative arrival of sound energy in increasing time windows. (f) and (g) Spatial energy distribution for non-rectangular halls, MZS and PR, each with ground view above and side view below. The plots show the cumulative arrival of sound energy in increasing time windows.

omnidirectional source to an omnidirectional receiver are required. For this, the response of the topmost, omnidirectional microphone of the receiver array was used. The responses of the 12 individual loudspeaker drivers were summed together, thereby creating an omnidirectional excitation. The calculated values were averages of the four source positions to the receiver position at seven meters.

Strength values G are around 11 dB at mid frequencies, with differences of ±2 dB between the halls. The large hall, HD, with the highly absorbent stage has the lowest G and the small, highly reflective hall, BL, the largest. Mid-frequency T_{20} is on average 1.6 s, ranging from 1.2 to 1.8 s. Early decay time (EDT) values are similar to T_{20} values in the present halls. Most halls have a tendency for higher RT at low frequencies, except MZS, where the RT decreases towards low frequencies below 1 kHz. Clarity C_{80} ranges from –0.7 dB in BL to 4 dB for MZS. The spatial parameters, early lateral energy fraction (J_{LF}) and late lateral sound level (L_J), also vary strongly among halls, indicating differences in spatial distribution of the reflected energy. These can be seen in more detail in Fig. 3, where the larger shoebox-shaped halls, HD and RD, show a round late energy distribution, whereas the fan-shaped PR has a much narrower shape, for example. Single values of early lateral energy fraction J_{LF} reach from 0.10 in PR and BR to 0.25 in MZW. There appears to be a relationship to late lateral sound level L_J, which is also the lowest in PR and BR. The highest amount of late lateral sound level, 5.3 dB, is found in BL, which is also the hall with highest strength.

Comparing the measured values to the recommended values from the literature, we see that all seven halls lie within 20% of the RT target curves for music halls

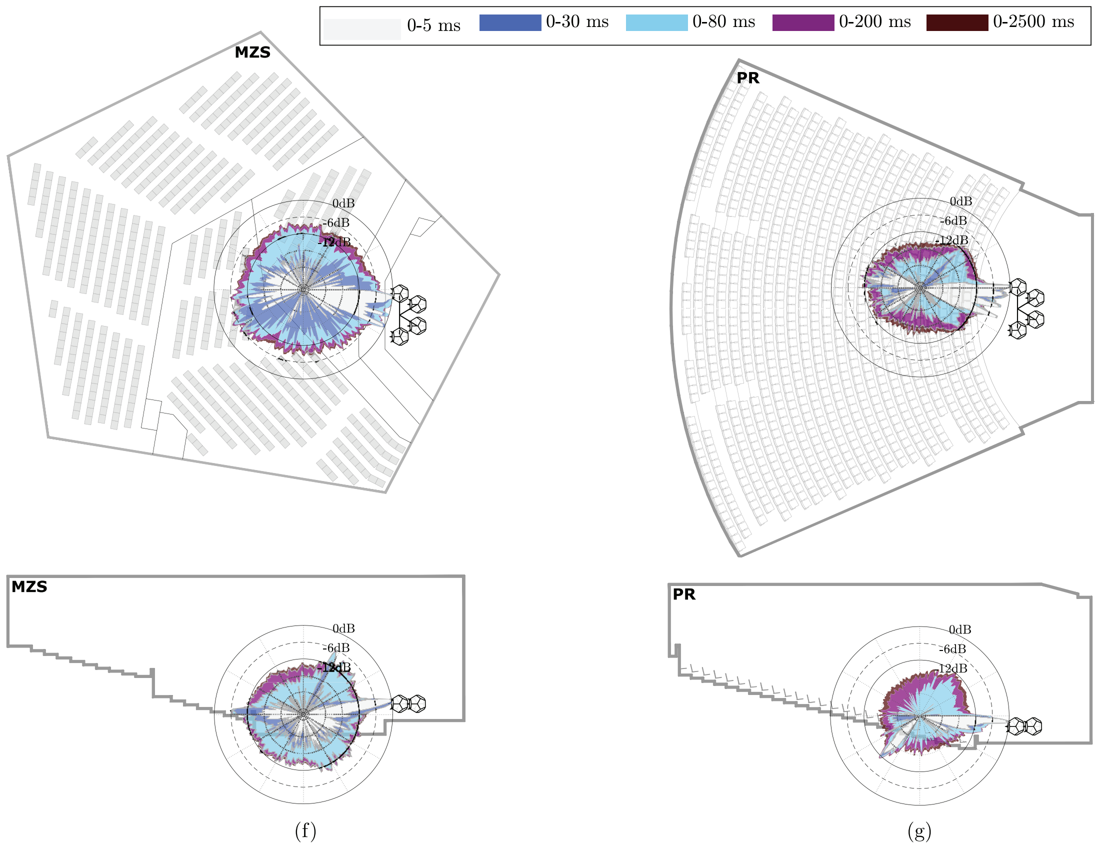

FIG. 3. (*Continued*)

according to Ref. 5 (see Fig. 1). BL and BR are relatively small in size and close to the upper and lower limit of these bounds, respectively. RD is close to the upper limit while all other halls are close to the suggested mean values. With an RT of 1.8 s, RD is also just above Hidaka's recommendation of 1.5–1.7 s, for halls between 500 and 600 seats, and on the upper end of Beranek's recommendation (between 1.5 and 1.8 s for halls of under 700 seats). The measured strength values are approximately within his target of 9–13 dB, where the small but reverberant BL is on the upper end, with 13.1 dB. Overall, this shows that the selected halls span the full, wide range of sizes and parameters considered relevant for chamber music halls, and while some values are on the limits of what is recommended, no hall would be deemed completely unsuitable for chamber music.

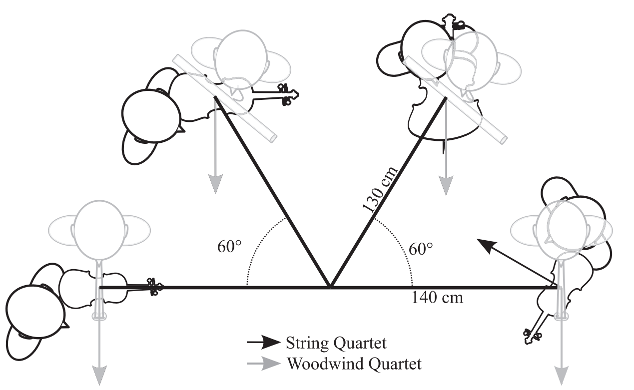

FIG. 4. Loudspeaker quartet ground plan and orientation of string (Vl1, Vla, Vc, Vl2) and woodwind instruments (Ob, Bsn, Bsn, Ob).

C. Spatial cumulative energy plots

As a next step, all six channels of the microphone array impulse response were used for analysis with the spatial decomposition method (SDM).[10,12,13] SDM is based on short-term direction of arrival estimation using the time difference of arrival between the six capsules of the microphone array. The directional data obtained from the SDM analysis stage allows for further investigating the spatial energy distribution, as shown in Fig. 3. For the analysis visualized therein, all four sources were combined together as can be seen by the four direct sound peaks are visible in the plots. Some distinct differences in the directional distributions can be observed between early reflection distribution (blue) as well as total energy (brown). The longitudinal rectangular halls in Fig. 3 have strong early side reflections which are much weaker in the crosswise oriented hall, BR. Ceiling reflections are also prominent, except for hall BL, where the ceiling is angled. The total energy differs slightly on closer inspection, in level as well as in shape and orientation. The non-rectangular halls, MZS and PR, differ more strongly between each other and when comparing to a rectangular hall, such as HD. While HD shows a very strong side reflection and an overall almost round shape of energy

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distribution, PR exhibits less early energy and an overall ellipsoid shape. MZS receives very strong early energy from frontal directions and surrounding rear walls.

While the objective parameter values and the spatial cumulative energy plots already illustrate many acoustic differences between these halls, a subjective evaluation was carried out to characterize the perceptual differences and to analyse the correlation between the subjective and objective data.

IV. SUBJECTIVE EVALUATION

Subjective evaluation was carried out at two different sites: at the Aalto University Acoustics Laboratory (Aalto) in Finland and at Müller-BBM (MBBM) in Germany. The following describes the listening experiment in detail.

A. Auralization

For auralization, SDM analysis was conducted on all of the 12 drivers individually. Then, SDM synthesis was used to create a response for each driver and each loudspeaker channel in the reproduction array. This yielded a set of $12 \times L$ responses for each of the four sources, where L is the number of reproduction loudspeakers. Finally, each of the 12-channel anechoic recording channels (see Sec. IV C) was convolved with the corresponding set of reproduction channel responses and the signals were added together. See Fig. 5 for an overview of the system.

B. Reproduction setups

The subjective evaluations were carried out in an anechoic multichannel listening chamber at Aalto Acoustics Lab and in the listening room at MBBM. The anechoic room at Aalto fulfills strict ISO 3745 requirements[30] down to 50 Hz, before installment of loudspeakers and mounting rig. The room at MBBM is not certified to the aforementioned standard, but all walls, as well as ceiling and floor, are treated with sound-absorbing material and the room has a very short RT, $T_{20} \leq 0.07$ s, from 63 Hz to 8 kHz.

The reproduction system at Aalto comprised 47 Genelec 8331AP studio loudspeakers (Iisalmi, Finland) at a distance of 2.04 m from the listening position (see Fig. 5). Calibrated frequency responses from individual loudspeakers in the room were within ±1.5 dB between third-octaves 250 and 2000 Hz.

The room at MBBM had 22 loudspeakers [16 Genelec 8130 A, 5 Neumann KH120A (Berlin, Germany), and 1 K + H M50 (Wedemark, Germany)] surrounding the listener on three levels. Here, the physical distances to all loudspeakers were not the same. These differences were compensated for by delaying respective loudspeaker signals to the largest distance of 2.47 m. Measured, A-weighted sound pressure levels from individual loudspeakers were within ±0.3 dB for pink noise.

In both rooms, there were more loudspeakers in the frontal hemisphere than at the back, as the spatial resolution of human hearing is the most accurate in front. For these tests, small adjustments were made to both loudspeaker setups, so that the direct sound of the four instruments in the quartet was rendered using exactly one loudspeaker each, placed very close to the correct angle that the instrument would have had on stage, at azimuth angles of 7°, 1°, –8°, and –16°. Due to small positioning errors of the microphone array and differences in the inclination of the seating area, the incidence angles of the direct sounds were not necessarily equal between halls. Therefore, before rendering, the directional data of each hall was rotated to match the direct sound to the four frontal reproduction loudspeaker directions.

The sound pressure level L_{Aeq} of the reproduction in the listening rooms was set using a B&K type 2250 (Nærum, Denmark) sound level meter. The levels for one of the signals used (staccato-strings, see Sec. IV C) was 68 dB on average (softest hall 66 dB, loudest 70 dB). The stimuli using the other signal (legato-woodwinds) were played back at an average level of 70 dB, with the softest hall measured at 68 dB and the loudest around 73 dB, similar to the differences in strength that were measured. Level differences between laboratories were at most 1 dB for 12 out of 14

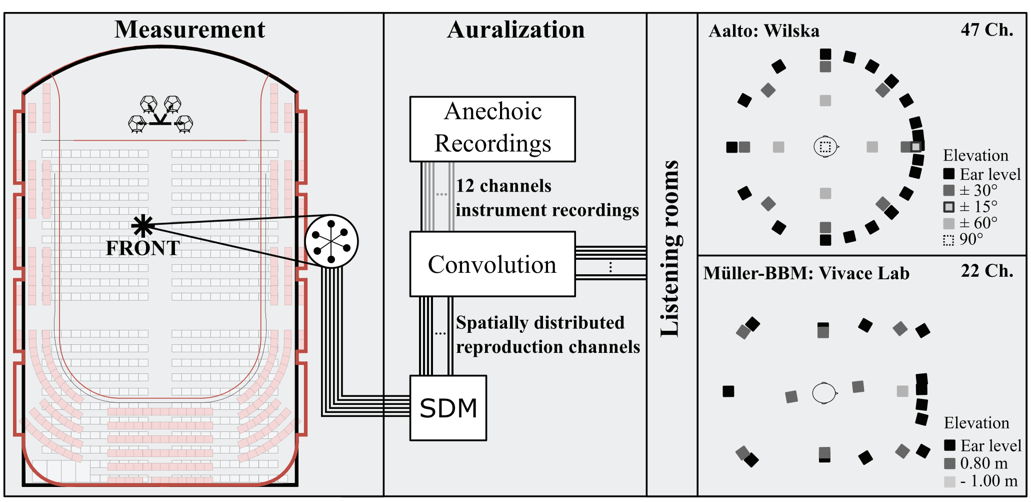

FIG. 5. (Color online) The block diagram of the auralization with the loudspeaker quartet measurements in the chamber music halls. The method for one of 12 driver channels at source position 1 on stage is shown. The process is repeated for all source channels and sources for auralizing the entire quartet.

samples and 2 dB for the remaining two samples. These levels are chosen so that listening over a longer period of time remains comfortable for the participants.

C. Anechoic music

Two short musical excerpts were recorded to study the perceptual differences between the halls. The two pieces differed, not only in terms of instruments, but also in their playing style and dynamic characteristics.

The first excerpt was a passage from *piano* to *fortissimo* in string quartet op.76 no.1, movement III (menuetto, presto), bars 23–38 (10 s duration) by F. J. Haydn. This excerpt features fast staccato playing and also includes a full stop where the reverberation tail is audible. This music piece is referred to as "staccato-strings".

The second music excerpt was a section of the wind octet serenade KV388 by W. A. Mozart where two oboes and bassoons are playing together as a quartet (movement III, trio, a mezza voce, bars 5–14). This sample was 13 s long and tranquil with legato playing. This music piece is referred to as "legato-woodwinds". Both music excerpts were considered to be representative of typical chamber music material, ensembles, and style, while still being different in terms of their sound characteristics.

To approximate the directivity pattern of a real instrument, anechoic music recordings were made inside a dodecahedral array of microphones (for string quartet production see Ref. 14) and the signals were mapped to the drivers of the dodecahedron. The approach can be used to play back signals over the loudspeaker in real time, but here the 12 microphone signals were convolved with the rendered spatial room impulse responses of each driver.

A dodecahedral measurement loudspeaker, such as the model in use, is not expected to have a flat frequency response. Overall equalization was achieved by first averaging the magnitude frequency response of drivers over all directions, measured in the anechoic chamber with a grid resolution of 5°. Then, the response was inverted and smoothed using a third-octave Gaussian kernel. Last, a minimum phase filter response was derived and convolved with the responses.

Since all instruments were recorded frontally and the dodecahedron was also measured frontally, the instrument audio signals per channel had to be rotated, which was achieved by remapping the channels such that the player with instrument would face in a reasonable direction. Depending on the instrument and source position in the quartet, a common orientation of the instruments was achieved (see Fig. 4); the only exception was the two oboes, where the players are facing forwards instead of towards the center, as would be customary. However, this angular deviation is found to be negligible in the larger context of hall comparisons.

After processing all sources on stage, the end result should resemble a realistic reproduction of a quartet in a partly occupied chamber music hall.

D. Attributes

The aim of the perceptual study was to evaluate the halls with regard to a relatively small set of well-known, pre-selected perceptual attributes, e.g., included in Refs. 15 and 16. Furthermore, we checked the agreement between listeners, especially between listeners at the two different labs. Apart from the preference rating, four attributes were selected based on previous literature, for the following reasons:

Proximity was included, because it has been previously found to be one of the most important attributes for explaining preference.[9] Also, it is related to intimacy, which is considered to be especially important for chamber music in the literature.

Envelopment was also observed to be an important contributor to preference in symphony halls for a large group of listeners. In larger halls, the degree of envelopment is typically related to the hall shape, where shoebox-shaped halls yield high scores. This relationship shall be checked in the present halls that have variations in shape.

Clarity, in turn, was found to be a driving factor of preference for another group of listeners. Furthermore, it was considered that clarity might be of higher importance for chamber music than for orchestral music, which is also hypothesized in Ref. 4. Envelopment and clarity are often both correlated to reverberance, which is why reverberance was not tested as an additional attribute.

The three attributes selected so far cover temporal and spatial aspects, but no spectral differences. Therefore, *warmth* was included in the study as well.

Investigating loudness was also discussed but it was considered that the expected perceptual differences would not yield any substantial insight. Loudness ratings were found to follow the values of the parameter strength G (see Ref. 17) or the factor analysis results shown in Ref. 18.

E. Assessors

Ten assessors per each laboratory participated in the subjective evaluation. These 20 assessors were between 25 and 63 yrs of age (average age of 37 yrs). Assessors were not screened with standard audiometry, but they did not report any self-known hearing deficits when asked. Prior to the experiment, assessors gave their informed consent. The test duration excluding introduction was on average 70 min.

At Aalto, all assessors were students or employees (Ph.D., postdoctoral, laboratory engineers) of the acoustic laboratory and were considered to be expert listeners due to general experience in participating in various listening experiments. Some of them had a background in music performance and cultural venue room acoustics. At MBBM, acoustic consultants with at least 5 yrs in the profession participated.

F. Procedure

Attribute and preference ratings were collected with pairwise comparisons, where the listener's task was to listen to and compare two stimuli at a time and choose the one in which the given attribute was more pronounced. Pairings between seven halls required 21 comparisons and with two music pieces, the total was 42 comparisons per attribute. These 42 paired comparisons were always presented in fully randomized order and the order of the attributes was also randomized. Preference ratings were collected at the end of the evaluations.

Assessors completed the comparisons with a user interface on a small touch screen. The screen was positioned on a support in front of the subject at an appropriate height for keeping the subjects looking more forward than downward, as in a concert situation. The stimuli were played back in loops and the assessors could only switch between the stimuli, input the selection, or pause the playback. The system output gain was kept constant and the subjects could not change the looped segment.

G. Data analysis methods

The pairwise comparison data were analysed with the Bradley–Terry model[19] implemented in the CompR-package.[20] In addition to the derivation of the underlying scale values, i.e., Bradley's probability scores, this implementation also enabled the segmentation of the listeners into latent classes[10,21] via the expectation-maximisation algorithm. The latent class analysis was used to investigate the potential grouping of assessors, according to preference data, as well as the attribute ratings. Akaike (AIC), Bayesian (BIC), and consistent Akaike (CAIC) information criteria scores were used to select an appropriate number of classes supported by the data. See Ref. 29 for a table of the information criteria scores.

To investigate associations between the subjective responses and the objective room acoustical parameters, correlations were calculated between attributes, preferences, and objective parameters. For the correlation analysis, the results were normalized to zero mean and unit variance and the attribute and preference data were aggregated over the two music pieces.

Finally, the perceptual space and the differences between the halls were summarized with an explorative multiple factor analysis (MFA).[22,23] MFA was used to obtain an overall view of the results in the latent perceptual dimensions spanned by the attribute ratings, and to facilitate the interpretation of the results and the comparison to the previous results obtained with large concert halls.[9]

V. RESULTS

A. Agreement between the laboratories and segmentation of assessors into latent groups

Differences between reproduction setups (e.g., number of loudspeakers), as well as between assessor panels, could potentially lead to systematic differences and discrepancy in the attribute ratings between the two laboratories. Thus, the agreement between the two sites was analyzed using correlation coefficients. Correlation was performed with the scale values derived from the combined data, including all the assessors in each laboratory. These results are tabulated in Table II.

The results indicate high correlation (cor > 0.9) between most attributes and musical excerpts, but a discrepancy between the sites in terms of clarity ratings (cor $= 0.14$ and cor $= -0.28$ for strings and woodwinds, respectively). Agreement is also slightly reduced for the attribute proximity for the legato-woodwinds music piece (cor $= 0.71$).

The low correlation for clarity required further investigation. Therefore, grouping of listeners was explored using the latent class analysis approach, to determine the number of groups that best fit the data. In this way, we could assess whether the response behaviour for certain attributes depended only on the different lab conditions, or if groups with a certain response behaviour can be identified within the complete pool of listeners. The number of segments was decided by using a combination of model selection criteria: AIC, BIC, and CAIC. Given that AIC alone would often indicate a greater number of classes than BIC and CAIC, which are more conservative, we used the average number of classes indicated by these three measures (rounded to the nearest integer). Thus, more weight was put on the more conservative criteria.

This heuristic was used to analyse the number of listener groups per attribute, taking into account responses to both music pieces. This level of analysis was chosen, because it would give an indication of the level of unanimity of listeners per each attribute. Using a fixed set of attributes and only little training, it is possible that individuals could have understood the attributes differently, or disagreed on their meaning. This analysis resulted in segmentation of assessors into two classes for all attributes except envelopment, which was best modelled with a single class. The grouping of subjects is tabulated in Table III. Note that also the preference data were analysed with the latent class approach.

Comparing the distribution of group members between laboratories reveals that the low correlation in case of clarity does not depend on the laboratory exclusively. All participants at MBBM belonged to the same group and while six listeners at Aalto showed different response behaviour, four listeners were assigned to the same group as at MBBM.

TABLE II. Agreement between the labs measured by correlations of the mean scores per each music and attribute.

Music	Attribute	Cor	p-value
Staccato-strings	Clarity	0.14	0.757
	Envelopment	0.92	0.003
	Proximity	0.92	0.003
	Warmth	0.91	0.004
	Preference	0.91	0.005
Legato-woodwinds	Clarity	−0.28	0.548
	Envelopment	0.99	< 0.001
	Proximity	0.71	0.076
	Warmth	0.98	< 0.001
	Preference	0.92	0.003

TABLE III. Grouping of assessors based on the attribute ratings (both music pieces). The ID stands for a unique identifier for each subject and the numbers on the right side of the table indicate group membership.

		Attribute				
Lab	ID	Envelopment	Warmth	Clarity	Proximity	Preference
AALTO	AS10	1	1	2	2	1
	AS11	1	1	1	1	1
	AS12	1	2	1	1	1
	AS13	1	1	1	1	2
	AS14	1	1	2	1	1
	AS15	1	1	2	1	1
	AS16	1	2	1	1	1
	AS17	1	1	2	1	1
	AS18	1	1	2	1	2
	AS19	1	1	2	1	2
MBBM	AS20	1	1	1	1	2
	AS21	1	2	1	2	1
	AS22	1	2	1	1	1
	AS23	1	2	1	1	1
	AS24	1	2	1	2	1
	AS25	1	1	1	1	1
	AS26	1	2	1	1	1
	AS27	1	1	1	1	1
	AS28	1	1	1	2	2
	AS29	1	1	1	1	1

B. Attribute ratings

Figure 6 shows the results per attribute, music piece, and latent group and Fig. 7 shows average values over both pieces.

In terms of envelopment, the halls, BL and RD, which are both shoebox-shaped, received the highest score, while the crosswise rectangular hall (BR) and the large, fan-shaped hall (PR) received very low scores under both conditions.

Regarding warmth, BL has the highest scores again, followed by the pentagonal hall MZS, which received high scores mainly amongst the second listener group that rated MZS as a warm hall with both signals.

In terms of clarity, MZS has the overall highest rating, but no hall stands out particularly strongly. Disagreement between the two assessor groups forming for clarity is strongest in case of the legato-woodwinds, which together with the unequal distribution of group members between labs, led to the low correlation shown in Table II. The first group attributed the lowest clarity to BL, while the second group rated it to be the highest.

For proximity, a large group of 16 listeners gave the highest rating to MZS in case of the staccato-strings. The same group considered BL to produce the most proximate sound for the legato-woodwinds. A smaller, second group gave a high rating to BR in case of the legato-woodwinds.

C. Preferences

As seen in Table III, the preference data were segmented into two latent groups as well. Here, there were 15 assessors in the first preference group and five assessors in the second group. For the larger group with staccato-strings, the most preferred hall was MZS and for the other group, the most favorite hall was BR. With legato-woodwinds the larger group preferred BL and RD while the smaller group liked halls BR, HD, and MZS.

D. Correlations between attributes, preference, and objective parameters

Correlations between attributes, preference, and objective parameters were investigated by means of Pearson's correlation coefficient (see Fig. 8). Perceived clarity correlates well with the clarity index C_{80} at low and mid

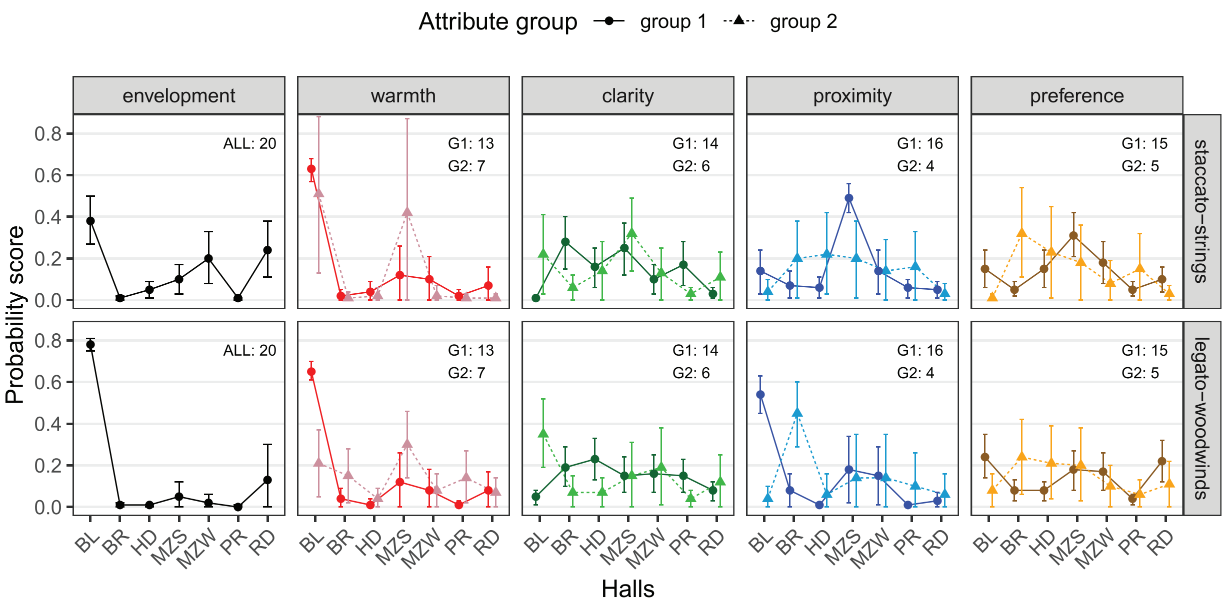

FIG. 6. (Color online) Attribute ratings by attribute and music piece. Error bars represent Bonferroni corrected 95% confidence intervals. Group assignments based on each individual attribute.

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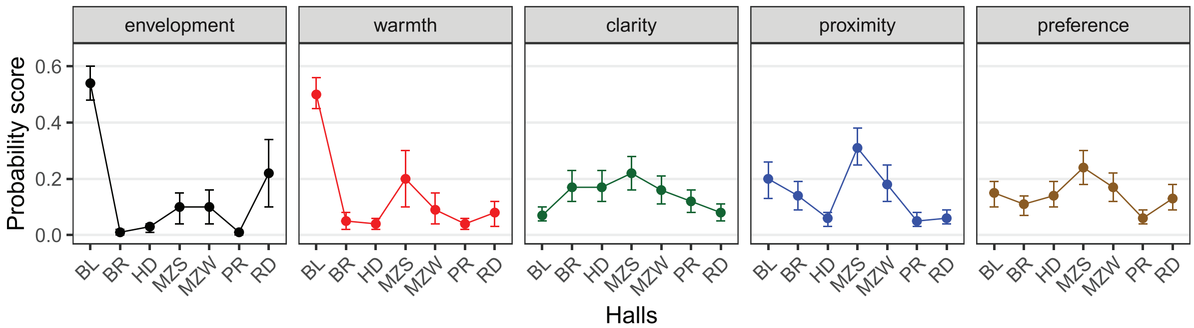

FIG. 7. (Color online) Average results per attribute averaged over the music pieces. Error bars represent Bonferroni corrected 95% confidence intervals.

frequencies, and negatively with L_J. Envelopment correlates mainly with late lateral sound level L_J and strength G. Proximity correlates positively with mid-frequency G and C_{80} and negatively with low-frequency EDT and T_{20}, i.e., strong and clear sound lead to more proximate sound. Finally, the attribute warmth has high correlation with wide-band G and L_J, but not with low frequency G. This is unintuitive since low frequency G is expected to describe the perception of low frequencies. Yet, the same observation was made in Ref. 24.

Preference of group 1 ($\frac{3}{4}$ of the assessors) is correlated with high frequency late lateral sound level L_J and early lateral energy J_{LF} as well as G. At high frequencies, there is weak negative correlation with C_{80}. Preference scores in the smaller preference group 2 correlate positively with C_{80}, and negatively with L_J, i.e., almost the same correlation as for the attribute clarity.

Inter-attribute correlations are shown in Fig. 9. Preference in group 1 is associated strongly with proximity and also weakly with warmth and envelopment. Group 2's preferences, in contrast, are only correlated with clarity and negatively with envelopment.

Another way to present associations between variables is through MFA. The analysis was done using the attribute rating data from both music pieces to construct the latent perceptual space and by including preference ratings and objective parameters as supplementary variables, meaning that they did not contribute to the calculation of the latent space. The result is plotted on two main axes in Fig. 10. Almost all of the variance in the data (89%) is explained with the first two dimensions.

The first plot on the top allows for another look at the correlations between objective and subjective parameters. With both signals, clarity is pointing to the same direction as C_{80}, and envelopment is pointing to the same direction as L_j, which high correlations already indicated (Fig. 9). Proximity is not described with any single ISO parameter.

The second plot on the bottom shows the results for preference in the same two-dimensional latent space. For legato-woodwinds, preference of group 1 is pointing almost in the same direction as proximity, warmth, and envelopment. Preference of group 2 is totally in line with clarity. For staccato-strings, the preference groups are close to orthogonal. Preference in group 1 is mainly driven by proximity and preference in group 2 is explained mostly by clarity. The most interesting finding with the MFA analysis is that proximity seems to be signal dependent while all the other attributes share the same perceptual dimensions with both music pieces.

VI. DISCUSSION

A. Preferences and assessors

In summary, these findings confirm an important result from previous studies regarding large symphony halls.[9,10,25,26] One group of listeners exists that prefers proximity, envelopment, and warmth (preference group 1) and a second group that prefers mostly clarity (preference group

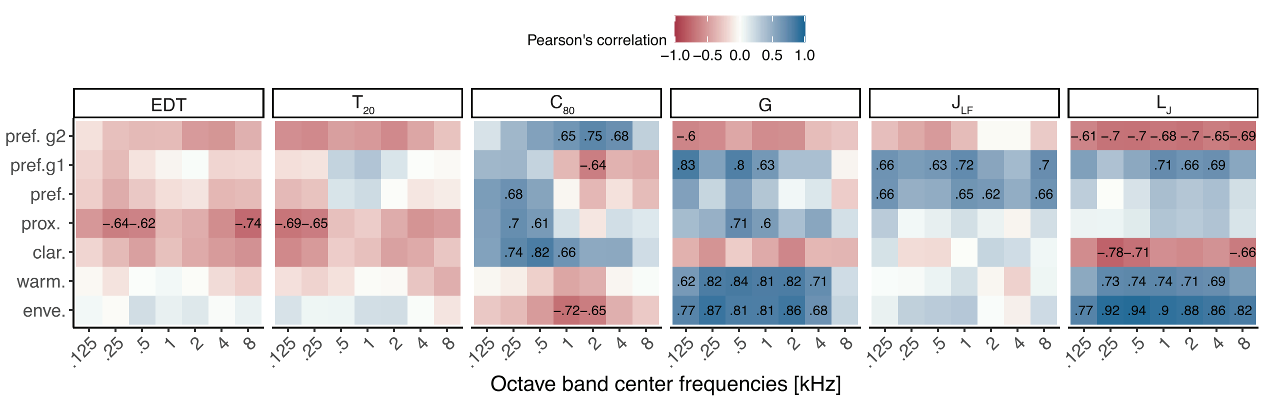

FIG. 8. (Color online) Correlations between attributes and ISO 3382-1 octave band values. Only correlation coefficients that are greater or lower than ±0.6 are shown in numbers.

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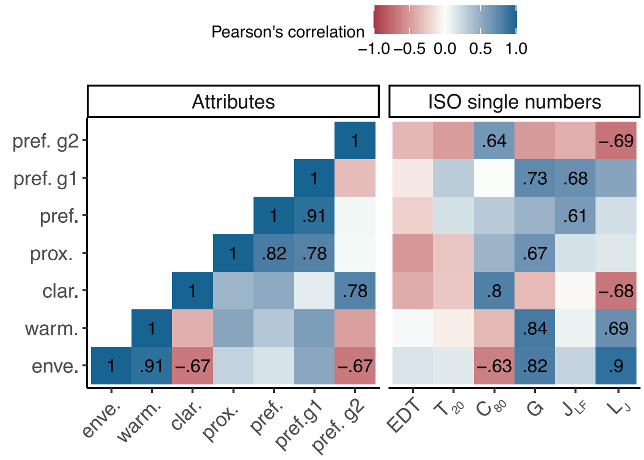

FIG. 9. (Color online) Correlations between attributes and ISO 3382-1 single number values. Only correlation coefficients that are greater or lower than ±0.6 are shown in numbers.

2). Even though one might hypothesize that clarity is more important for chamber music than for symphonic music, as often mentioned in the literature reviewed in Sec. II, the second group was the smaller one, as observed in previous studies using symphonic music. The fact that the preference groups were not dependent on the location at which the test was performed further supports the finding that preference is really an individual matter of taste.

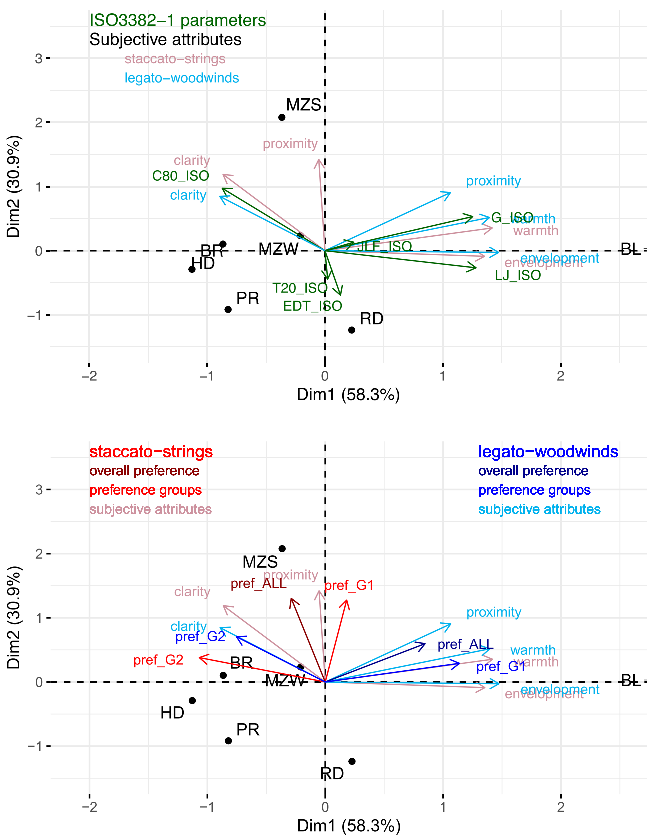

FIG. 10. (Color online) Multiple factor analysis. Red lines represent results for staccato-strings and blue lines represent results for legato-woodwinds stimulus.

In the studies of symphony halls, shoebox-shaped halls with a flat floor were usually loud, enveloping, and warm, whereas halls with inclined audience and vineyard-style halls offered less reverberation and more clarity. In accordance with these results, the least preferred hall in preference group 1 was the large, inclined, and fan-shaped hall (PR), which has low warmth, weak envelopment, and a relatively distant sound. Note that it is the largest hall with the most seats, so it is not unexpected that it does not render a proximate chamber music sound. Yet, the most preferred hall for preference group 1 was not a shoebox-shaped hall, but the more unusual pentagonal hall (MZS), where the receiver was placed in the frontal section, which is lower than the other sections of the hall [see Fig. 3(f)]. The walls surrounding this section create strong early reflections from the back and from the back/right. Late energy arrives mainly from the top. While this is an unusual situation, it appears to be favorable for people's appreciation for proximate, enveloping, and warm sound.

Upon first sight, it seems unusual that for preference group 2, the most preferred hall is a shoebox, which typically offers enveloping sound. However, in BR, the seating is arranged crosswise, with the side walls more distant than the front and back walls. It has the lowest RT as well as the lowest early lateral energy fraction, contributing to the high clarity and low envelopment, preferred by this group. The acoustics of BR is in stark contrast to the equally small shoebox-shaped hall BL, which is built in the typical orientation and has high RT. It is judged as the warmest and most enveloping amongst the tested halls.

Finally, it is worth noting that envelopment was the only attribute that was best fit by using only a single latent class that indicated good agreement among all the listeners. All other attributes seem to be interpreted in at least two different ways by the listeners, resulting in two groups. Especially with regard to clarity, the disagreement is high, which is interesting considering that clarity was expected to be an important attribute for chamber music. The reason for such segmentation of listeners is not yet known. It might depend on the background of the assessors, a lack of familiarity with rating acoustics based on the provided attributes, different interpretations of the attributes, or merely disagreement. Also, Table III reveals that the groupings of assessors for preferences and individual attributes have no clear relationship.

B. Attributes and signals

Well-known correlations between objective parameters and subjective attributes were confirmed, such as high correlation between clarity and C_{80}, as well as envelopment and L_J. For proximity, no direct correlation was found from the ISO:3382-1 parameters, but correlation to a combination of parameters could be seen. A model objectively predicting proximity could be the subject of future work.

In the case of some attributes, the halls were ranked differently with staccato-strings and legato-woodwinds. Such interrelations can be discussed based on the MFA analysis (Fig. 10). It reveals that warmth and envelopment do not depend on the signal, clarity differs to some extent, and proximity depends heavily on the playing style. While it is not possible to fully explain signal dependent differences without signal dependent auditory models, some general differences may be due to the fact that pauses in the staccato playing make it easier to attend to room acoustic differences. In case of proximity in particular, a warm and enveloping (objectively G and L_J) sound is enough to yield high proximity for the legato excerpt, but for staccato playing, some clarity is also required to evoke a proximate sound. In earlier studies,[10] other attributes, such as brightness, also were found to be an important component of clarity.

C. Other aspects

Comparing the results of different halls, one should consider that only one position in each hall was tested in this study. It is known that the acoustics can vary considerably among different seats.[27,28] Nevertheless, it remains a necessity for hall comparison to keep receiver distances constant, and due to the size of the smallest halls, the distance of 7 m was chosen (it is already the second to last row in BR). The assessment of other positions is left for future experiments. Especially, it will be interesting to see if the high ratings for MZS are also obtained in different seating areas.

Last, the choice of the occupancy simulation as a compromise is motivated by the known shortcomings of auralizing and generalizing from unoccupied measurements. It should be noted that the hall in which the lowest percentage of seats was covered (PR) was the hall with the second lowest strength, so that covering all seats could have changed it to the position of lowest strength. In the future, one could study the perceptual relevance of the acoustic influence of other audience members' heads and torsos, which is not modelled properly by the occupancy simulations with cloth.

VII. CONCLUSIONS

This study presented new measurements and subjective evaluation of seven established chamber music halls with occupancy simulation for one receiver position and two music excerpts.

Categorization of listeners by preference confirmed the emergence of two groups, where listeners in the larger group prefer proximate, enveloping, and warm sound and listeners in the other group prefer clarity. This aligns with earlier studies of large symphony halls.[10] Thus, there do not seem to be fundamental differences between the perception of chamber music halls and symphony halls in this regard.

In the future, different requirements between halls for symphonic music and halls for chamber music could be compared by auralizing orchestral and symphony music in both types of halls. Notably, even the choice of two different pieces of chamber music revealed differences in the ratings. This finding highlights that the choice of material should be considered when evaluating a hall that is intended for a certain musical genre or playing style.

As often in subjective studies, there was not one hall that is clearly preferred, as preference ultimately is individual among listeners. However, the large, fan-shaped hall tested turned out to be the least preferred for chamber music in this set of halls. Furthermore, there was one interesting non-shoebox hall which consistently received medium to high ratings in the attributes, and the highest overall preference ratings. The specific measurement position in this hall resulted in a medium to high impression of envelopment, warmth, clarity, and proximity, likely by supplying strong early reflections, as well as enveloping late reverberation.

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