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Concert halls with strong and lateral sound increase the emotional impact of orchestra music

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An audience’s auditory experience during a thrilling and emotive live symphony concert is an intertwined combination of the music and the acoustic response of the concert hall. Music in itself is known to elicit emotional pleasure, and at best, listening to music may evoke concrete psychophysiological responses. Certain concert halls have gained a reputation for superior acoustics, but despite the continuous research by a multitude of objective and subjective studies on room acoustics, the fundamental reason for the appreciation of some concert halls remains elusive. This study demonstrates that room acoustic effects contribute to the overall emotional experience of a musical performance. In two listening tests, the subjects listen to identical orchestra performances rendered in the acoustics of several concert halls. The emotional excitation during listening is measured in the first experiment, and in the second test, the subjects assess the experienced subjective impact by paired comparisons. The results showed that the sound of some traditional rectangular halls provides greater psychophysiological responses and subjective impact. These findings provide a quintessential explanation for these halls’ success and reveal the overall significance of room acoustics for emotional experience in music performance. © 2016 Acoustical Society of America.

I. INTRODUCTION

Listening to music is a source of emotional arousal.1–3 While listening, stimulation of pleasure-specific areas of the brain yields rewarding effects4 and may even lead to psychophysiological reactions like chills or goosebumps.5,6 A live symphony concert can be a most profound cultural experience, and since the late 1700s, purpose-built concert halls have gathered audiences for this purpose. The acoustic properties of such venues have been studied scientifically for more than a century. The research has identified distinct acoustic features that correspond to perceptual qualities such as the loudness, perceived source width, or the listeners’ sense of being enveloped by the sound.7–9 Certain concert halls have attained a venerable public reputation,10 and the reasons explaining the subjective preference for room acoustic conditions have attracted continuous interest.9,11–13 Although preferences have been found to correlate with mixtures of desired perceptual attributes, measured acoustical properties have not succeeded in resolving the difference between acceptable and truly excellent concert hall acoustics. We present evidence that the music in outstanding halls evokes increased emotional impact and pleasurable sensations—elemental factors that may be essential for a profound overall concert experience. Previous studies have investigated only subjects’ emotional reactions to sound events in simulated acoustic environments.14,15 Here we establish a bridge between orchestral music presentations in various concert halls and their psychological impact on listeners. Two experiments measure the psychophysiological effect and subjective impact of room acoustic conditions and show that listeners react with varying intensity to the acoustics. The results offer a substantial explanation for the acclaim of concert halls with outstanding reputations.

Emotional arousal activates the sympathetic nervous system, and emotional peaks may be observed in human physiological functions, e.g., variations in heart and respiration rate, blood pressure, or body temperature.16 The skin conductance response due to activation of eccrine sweat glands is a common measure for detecting strong emotional arousals of positive valence, and they can be linked with reactions such as shivers, thrills, or tears.5,17,18 Musical genres and compositions that evoke strong responses are highly individual,16,19 but identified excerpts known to cause, e.g., shivers or tears include many Classical and Romantic orchestral works.18 While individual notes and their interpretation by performers give form to phrases and harmonies, in other words the musical dictionary, the acoustics of the room affects the way the sound is being delivered to the audience.

At their best, the room acoustics complement the artistic expression by providing support to the acoustic instruments’ sound, binding consecutive notes together, spreading the sound wider in space, or in general, making the bare instruments sound more expressive and impressive. Preceding research has aimed to either resolve the overall acoustic quality of concert halls or disentangle preferences by using perceptual or objective room acoustic attributes.9,20–23 The most authoritative study by Beranek12 resulted in an international list in which four of the five top ranks are rectangular, so-called shoebox halls: Vienna Musikverein, Boston Symphony Hall, Berlin Konzerthaus, and Amsterdam Concertgebouw. The success of these halls from the acoustical perspective has
been mostly explained by their strong and enveloping sound and more recently by their responsiveness to music dynamics. Our study bypasses subjectively reported preference and concentrates on how room acoustic conditions affect subjects’ psychophysiological responses to music. The differences found with listening experiments between concert halls would fundamentally explain the importance of good acoustics and answer the paramount question of why some concert halls are considered better than others.

II. METHODS

We conducted two listening tests to explore the psychophysiological reactions and perception of acoustics. In these tests, the subjects listened to sound stimuli consisting of an anechoic orchestra excerpt from Beethoven’s Symphony No. 7 (Ref. 26) convolved with spatial room impulse responses measured in two receiver positions (denoted R1 and R2) in six concert halls. The sound was reproduced using a threedimensional (3-D) loudspeaker array in an acoustically treated listening room. In the first test, electrodermal activity was recorded during focused listening. In the second test with a paired comparison approach, the same subjects evaluated sound of the concert halls and selected the stimulus that they perceived as having more subjective impact. The following sections describe the listening tests in detail.

A. Concert hall measurements and spatial reproduction

The acoustics of the six compared concert halls (see Table I and Fig. 1) were measured with a loudspeaker orchestra consisting of an array of 33 sources in 24 individual channels. The loudspeaker layout and dimensions of the array correspond to a typical orchestra seating arrangement (see Fig. 2). The principal receiver was a G.R.A.S., type 50-VI 3D vector intensity probe, which consists of six omni-directional microphone capsules in three co-centric pairs arranged about the x, y, and z axes. The radius of the capsules from the probe center is 0.05 m. The spatial room impulse responses measured at 48 kHz sample rate individually from the source channels were analyzed with the spatial decomposition method (SDM). The method approximates the impulse response with plane waves and estimates the incident direction for each audio sample in the impulse response by using time difference of arrivals (TDOA) between the six capsules in the probe in very short time windows. One of the capsules also represents the omni-directional pressure signal, which is distributed to the reproduction loudspeakers using the direction estimates from SDM. The instantaneous pressure is assigned to the nearest reproduction loudspeaker without any interpolation or panning between loudspeakers.

The end result is a spatial convolution reverb from one measurement channel to 24 reproduction loudspeakers in the listening room (see Fig. 2). The same processing is applied for all sources, and the convolutions with respective anechoic instrument recordings are combined in the multi-channel output for the entire orchestra sound.

The spatial impulse response measurements provide also data for the estimation of objective room acoustic parameters. The application of figure-of-eight weighting to the octave-band filtered omnidirectional pressure and SDM direction estimates enables the calculation of the lateral energy parameters (lateral energy fraction, LER; late lateral fraction, LJ). For binaural parameters, we used dummy head measurements (Bruel & Kjær H.A.T.S.) available with the same source setup at five equally spaced positions down an off-center line beginning 7 m from the stage. Binaural receiver positions and their relations to the positions included in the listening experiments are shown in Fig. 3. Binaural measurements are absent from Helsinki Music Centre.

Because the acoustic properties depend heavily on the room geometries and materials, the sound in the included concert halls varies greatly from each other. Comparisons of the estimated room acoustic parameters confirm that the included halls with rectangular and non-rectangular typologies have different overall acoustics. Due to the measurements in unoccupied halls, the average mid-frequency reverberation times (T) range from 1.7 to 2.9 s. The ranges of other objective parameters span over several just noticeable differences. On average, the three rectangular halls have more reverberation and lateral energy and a stronger sound but less clarity (C80) than the included non-rectangular halls. These data and the ranges of parameter values correspond to earlier studies.

The acoustics of the measured concert halls were reproduced in an acoustically treated listening room. The room has a 24-channel loudspeaker system for spatial sound reproduction in 3-D. The loudspeakers are located at a 1.5 m nominal distance from the listening position. Small variations in the true loudspeaker distances were compensated for by applying the respective delays in the loudspeaker signals. Twelve loudspeakers (Genelec type 8020B) are in the horizontal plane, eight (8020B) in elevated angles, and four (1029A) below the ear level (see Fig. 2). More loudspeakers are positioned in the frontal hemisphere because the majority of the sound energy in concert halls arrives from the directions of the sound sources. The loudspeaker sound levels at the listening position were calibrated to within ±0.5 dB accuracy. The acoustical treatment of the listening room provides effective soundproofing against possible external noises.

### Table I. List of concert halls included in the listening experiments.

<table>
<thead>
<tr>
<th>Id</th>
<th>Hall</th>
<th>Shape</th>
<th>V (m³)</th>
<th>N</th>
<th>G (dB)</th>
<th>EDT (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VM</td>
<td>Vienna Musikverein</td>
<td>Rect.</td>
<td>15 000</td>
<td>1680</td>
<td>3.7</td>
<td>3.0</td>
</tr>
<tr>
<td>AC</td>
<td>Amsterdam Concertgebouw</td>
<td>Rect.</td>
<td>18 780</td>
<td>2040</td>
<td>2.7</td>
<td>2.5</td>
</tr>
<tr>
<td>BK</td>
<td>Berlin Konzerthaus</td>
<td>Rect.</td>
<td>15 000</td>
<td>1575</td>
<td>2.2</td>
<td>2.2</td>
</tr>
<tr>
<td>BP</td>
<td>Berlin Philharmonie</td>
<td>Vineyard</td>
<td>21 000</td>
<td>2220</td>
<td>1.9</td>
<td>1.9</td>
</tr>
<tr>
<td>HM</td>
<td>Helsinki Music Centre</td>
<td>Vineyard</td>
<td>24 000</td>
<td>1700</td>
<td>1.9</td>
<td>2.1</td>
</tr>
<tr>
<td>CP</td>
<td>Cologne Philharmonie</td>
<td>Fan</td>
<td>19 000</td>
<td>2000</td>
<td>1.9</td>
<td>1.7</td>
</tr>
</tbody>
</table>

*aEstimated value.*
The signal chain was comprised of an Apple Macbook Pro computer with Max/MSP listening test software, an RME Digiface multi-channel audio interface, and three eight-channel, Presonus Digimax FS DA-converters. In the second experiment, the users controlled the test with a graphical user interface on a 9.7-in. wireless touch screen (Apple Ipad 2), which was positioned on a stand in front of the listening position. The height of the screen was adjusted so that subject could operate the interface while keeping the head in natural listening orientation yet without obstructing the surrounding loudspeakers. All equipment apart from the touch screen were hidden behind a white, acoustically transparent curtain to ensure a neutral visual appearance.

The listening room has a mean reverberation time of 0.11 s, and the peak-to-peak level difference between the direct sound and the strongest reflection averaged over the 1–8 kHz octave bands (12.8 dB) complies with the ITU-R BS.1116-1 recommendation for subjective audio evaluation systems. The accuracy of the reproduction method, including the listening room, was validated by comparing the objective monaural and spatial room acoustic parameters (T, G, C80, EDT, LEF, LJ) before and after the spatial sound reproduction. In essence, we measured the listening room using the

![Diagram of concert halls](image)

**FIG. 1.** (Color online) Overlaid floor plans of the rectangular (a) and non-rectangular (b) concert halls included in the listening experiments. Abbreviations for the concert halls are explained in Table I. Drawings are aligned with respect to the receiver positions (R1 and R2) and the measurement source array on the stage. Balconies above the main audience area are drawn in different shade. Position R2 in Helsinki Music Centre (HM) is marked separately.
same microphone probe as in the concert halls and the reproduction loudspeakers as the individual sources. The convolution of the spatial responses (after SDM in Fig. 2) of the concert hall and the listening room correspond to the reproduction chain presented to the subjects. The Pearson’s correlation coefficients between parameters from the original and reproduced spatial responses for the 12 receiver positions are \( r > 0.86, p < 0.0001 \) (125 Hz to 8 kHz), and \( r > 0.96, p < 0.0001 \) (250 Hz to 2 kHz) for all parameters. At the 63 Hz octave band, the response of the listening room slightly increases the proportion of early lateral energy. Reverberation times at high frequencies are increased by 20% due to the combination of SDM analysis of the diffuse field in concert halls and the nearest-loudspeaker reproduction.\(^{29}\) However, these effects are similar in all compared positions. Because the relative values for strength and the spectral balance remain unaltered, the influence to the perception is considered small. Consequently the overall room acoustic differences remain constant also between the rectangular and non-rectangular typologies.

**B. Music signal**

The music selected for the tests was a passage from Beethoven’s 7th symphony, first movement, bars 11–18, duration 28 s. The composition belongs to the principal works in the orchestral literature, as it is one of the symphonies included regularly in concert programs.\(^ {30}\) All instrument parts were recorded in an anechoic chamber, one at a time.\(^ {26}\) The score during the excerpt contains the strings, pairs of flutes, oboes, clarinets, bassoons, French horns, and trumpets each and the timpani. To simulate the characteristic tone of a string section from one respective instrument recording, the replicated string parts were processed with an algorithm that varies the time, amplitude, spectrum, and intonation differences.\(^ {31}\) The resulting number of 16 first violins, 12 second

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**FIG. 2.** (Color online) Block diagram of the stimulus generation and loudspeaker locations in the listening room. The signal path represents the processing for a single measurement source. The corresponding procedure is conducted for other sources and respective anechoic signals. All convolutions for one receiver position are combined for full orchestra auralization. In the listening room, 12 loudspeakers are in the lateral plane, 7 in elevated directions, 1 directly above the listener, and 4 in lower elevations.

**FIG. 3.** (Color online) Illustration of the receiver positions in room impulse response measurements for binaural parameters. Position R1 and R2 in parentheses indicate the receiver positions in the listening experiments. Curly brackets span over the positions averaged in the BDR (binaural dynamic responsiveness) (Ref. \(^ {25}\)) values.

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The subjects were instructed to assume a comfortable position in for at least 5 min before the start of the measurement. Hence the electrode-skin contact was allowed to set-evoking music. In addition to high or increasing music dynamics, also very delicate passages can provide substantial emotional impact. In related previous studies, the subjects have been allowed to select music excerpts to their own individual taste. However, the purpose of the present study was not to find the excerpts resulting in the strongest psychophysiological response but instead explore how various acoustic environments affect the auditory experience. In the present case of concert hall acoustics and orchestral music, a Beethoven symphony can be considered universal. Although some subjects could find the selected excerpt nondescript, different acoustics might still render the music more engaging.

C. Experiments

Twenty-eight subjects (14 female, 14 male) participated in the tests. Their ages were between 22 and 64 yr, 40 yr on average. Their musical backgrounds ranged from ordinary music consumers to music professionals. Audiometry reported normal hearing for all subjects considering their age and occupation. All had prior experience in critical listening as the current experiments were organized in the last of five listening sessions on concert hall acoustics. Participants’ other sessions were on earlier days. The subjects were aware that the general topic in the experiments is concert hall acoustics, but the authors did not reveal any details on the stimuli. The music signal in the present experiments was different from those presented during the preceding listening sessions.

In the first test, the skin conductance of the subjects was measured with a Varioprt-B device (Becker Meditec) using a 0.5 V constant voltage. The subjects wore Ag/AgCl electrodes in the medial phalanges of the non-dominant hand’s middle and ring fingers. The contact electrolyte between the electrodes and palmar skin was a 0.5% NaCl paste. The electrodes were attached in the beginning of the test session followed by a verbal description of the test procedure to the subject. Hence the electrode-skin contact was allowed to settle in for at least 5 min before the start of the measurement. The subjects were instructed to assume a comfortable position in the seat to avoid movement during the test.

The pilot signal presented as the first stimulus in the electrodermal activity experiment contained the same music excerpt but in acoustics with considerably less impact than in the 12 positions in the test sequence. This effect was accomplished by convolving the anechoic signals with room impulse responses measured identically in yet another hall (Munich Gasteig, 19 m distance, V = 30 000 m^3, N = 2300). The large volume of a fan-shape hall and additional truncation of the impulse responses to the initial 100 ms prior to convolution purposefully rendered the sound dry and weak, only for presenting the music excerpt to the listeners.

After the pilot signal and the following silence of 15 s, the subjects listened to the actual 12 stimuli (six halls × two positions) in a randomized order, each separated again by 15 s of silence. The total length of listening, approximately 12 min, was kept short enough to reduce the possibility of major lapses in concentration or biases due to habituation. The subjects were unaware of the exact number of presented stimuli to avoid the anticipation of the end of the test sequence. At the end of the experiment, each participant was briefly interviewed regarding his or her own recollections during the test. None of the subjects reported losses or distractions of attentiveness, or unpleasant experiences.

In the second, more conventional listening test, the subjects’ task was to compare pairs of stimuli and choose the one that produced a higher overall impact on them. The term “impact” was verbally described as thrilling, intense, impressing, or positively striking. The subjects could freely switch between the two stimuli being played back synchronously. In essence, the test setting corresponds to jumping seamlessly back and forth between two concert halls while the orchestra continues an identical performance. Each hall was compared against others separately in two receiver positions at different distances. That is, different distances were not compared against each other. The total number of comparisons was 30 (six halls and two receiver positions), and the presentation order was fully randomized for each subject.

D. Analysis

The analysis of the skin conductance consisted of signal conditioning, followed by a separation of the rapidly changing phasic responses from the underlying longer-term tonic level. The signal conditioning included, first, median filtering with window length of 0.1 s, second, down sampling from 1000 to 100 Hz, and finally, a moving-average filter of 0.3 s window length. We ensured visually that the conditioning did not alter significant features of the signal but only removed possible artifacts such as measurement noise. Then the phasic skin conductance under interest was isolated from the overall conductance variation by the continuous decomposition analysis. The total responses during each stimulus were measured as the integral of phasic sudomotor nerve activity driver (ISCR) within a selected time window as proposed by Benedek and Kaernbach. The processing was conducted in MATLAB environment with LEDALAB package (version 3.4.6c).
An example of the skin conductance from one subject after the continuous decomposition analysis is illustrated in Fig. 4. The top-left panel visualizes a spectrogram of the orchestra music signal. The following panels, from left-to-right, top-to-bottom, show the continuous phasic conductance level during the concert hall stimuli presented in random order. The first stimulus is the pilot signal, which causes a sudden increase in skin conductance due to a sound starting after at least 2 min of silence. The increasing intensity in the music after 12 s elicits varying peaks in the response. Toward the beginning of the following stimulus, the expectation of the next sound causes the conductance to remain elevated. The subsequent stimuli elicit varying responses. However, in some cases, late stimuli might elicit a strong response, such as in the given example. These observations are congruent with the electrodermal measurement guidelines.33

The dataset contains a total of 324 measurements gathered from 12 stimuli with 27 subjects. Data from one original subject were discarded due to a gradually declining electrode contact during the measurement. ISCR values were converted to logarithmic scale, and inter-individual differences in ISCR ranges were standardized following a general recommendation, as

$$SCR = \frac{\log(1 + ISCR) - \text{mean}\{\log(1 + ISCR)\}}{\text{sd}\{\log(1 + ISCR)\}},$$

where sd stands for standard deviation. For clarity, SCR denotes standardized logarithmic skin conductance responses in the discussion.

The subjects may have responded strongly to only one or a few stimuli while other stimuli evoked little response. This contrast emphasizes the distribution tails in the raw data. Despite the standardization, data do not fully comply with the requirements imposed for one-way analysis of variance (ANOVA). We conducted the primary statistical analysis with the non-parametric Kruskal–Wallis test with various grouping approaches for the 12 listening positions, including two hall types (rectangular and non-rectangular), listening distance, and background data. In addition, we double-checked the statistical significance of the main effects using ANOVA.

Electrodermal measurement is a subject to various challenges in comparison to traditional listening tests. Psychological habituation occurs when the subjects become increasingly familiar with similar stimuli presented repeatedly. Evaluation of the habituation is complex because decreases in the electrodermal activity can depend simultaneously on the stimuli and
habitation. In the literature, threshold of habituation has been proposed as two or three consecutive stimuli that do not elicit sufficient responses.33 This kind of criterion might lead to unnecessarily omitted data, particularly with the present experiment as some of the presented stimuli are likely not to elicit noticeable responses. Therefore no data were omitted due to possible habituation. Instead, randomizing the presentation order was used as a precaution against result biasing. Furthermore possible habituation does not cause strong false positive responses that would artificially increase the average ISCR rating. Slight variations in the attentiveness by the listeners would have a similar effect. However, none of the subjects reported about lapses of concentration during the test. The number of stimuli presented during the experiment was kept small compared to other similar studies.37

Paired comparisons from the second experiment result in a choice frequency matrix, which can be analyzed in several ways. We calculated the probabilities of choosing a certain hall over others with the Bradley–Terry–Luce (BTL) model.38,39 It estimates the scale values that underlie the observed choice frequencies. The analysis model by Courcoux and Semenou suggests against segmenting the subjects into groups based on impact, and provides the statistical significance for the differences between halls.40 This approach also enables testing of hypotheses about perceived magnitudes in the framework of standard statistical theory. Grouping by hall geometry is accomplished by adding the rows and columns of corresponding listening positions together in the choice frequency matrix. A comprehensive overview on comparison models and their application is discussed by Choisel and Wickelmaier.41

Earlier studies have pointed out that listeners could be categorized according to individual preferences.20,22,42 The present study does not classify listeners based on their possible preferences but instead treats them as equal samples of ordinary concert-goers to reach more generic results, albeit at the expense of increased variance due to inter-individual differences.

In addition to the analysis on listening experiment results, we compared the mean SCR and subjective impact rating to objective room acoustic parameters with Pearson’s correlation coefficients. The analysis by ISO3382-1 standard parameters is augmented with binaural parameters of binaural quality index (BQI, i.e., inverse of early interaural cross-correlation12) and binaural dynamic responsiveness (BDR).25

The large number of statistical tests between listening test data and objective parameters may lead to false positive discoveries. The Bonferroni-type corrections to p values can be conservative and thus prone to false negatives (type II error). Furthermore the objective room acoustic parameters are not entirely independent, especially over adjacent octave bands. For these reasons, we applied the Benjamini–Hochberg step-up procedure43 to control the false discovery rate in the correlation analysis.

III. RESULTS

Both receiver positions considered, 16 subjects (59% of all subjects) exhibited their highest SCR in either the Vienna Musikverein (VM) or Berlin Konzerthaus (BK) [see Fig. 5(a)]. Apart from Cologne Philharmonie (CP) R1, all other positions ranked within the top half by mean SCR, are from rectangular halls. The Kruskal–Wallis one-way ANOVA for normalized SCR revealed that the types of concert hall geometries (rectangular or non-rectangular) had statistically significant differences [$\chi^2 = 6.71$, $df = 1$, $p = 0.01$, see Fig. 5(a)] with a 0.05 significance level. Other statistically significant differences exist across all 12 presented positions in concert halls ($\chi^2 = 24.21$, $df = 11$, $p = 0.01$), receiver distance (position R1 or R2) ($\chi^2 = 8.63$, $df = 1$, $p = 0.003$) as well as four combinations of receiver distance and hall geometry ($\chi^2 = 15.40$, $df = 3$, $p = 0.002$). The rectangular VM R1 ranked highest, and the surround hall CP R2 ranked lowest with a significant difference in their mean SCR rank identified by a post hoc Tukey–Kramer multiple comparisons test. Additional significant differences are shown with brackets in Fig. 5(a). In contrast to other halls, Berlin Philharmonie (BP) and Helsinki Music Centre (HM) elicited marginally higher mean responses in their positions R2 further from the stage than in R1. We did not observe significant differences between individual subjects, presentation order or between the six halls with the two positions combined.

In the second experiment, VM provided prominently more impact than the other halls, followed by BK in the front position R1 [see Fig. 5(b)]. The rank order of the halls by highest impact is changed in R2, where VM and Amsterdam Concertgebouw (AC) fall behind BK, although there are no significant differences between the rectangular halls. Similarly to the SCR measurement, impact in BP was relatively higher in position R2 than in R1. However, HM did not follow the same pattern, and subjective impact in HM R2 was negligible compared to other halls. Unlike in the SCR measurement, subjects experienced relatively little impact in both positions in CP. Both experiments suggest together that the acoustics provided by the included shoebox-type rooms provide significantly higher emotional impact. The SCR results also suggest that the listening position has an effect of magnitude similar to the hall typology [see Fig. 5(a)]. Analysis of the experiment results and ISO3382-1 objective room acoustic parameters estimated from the concert hall measurements reveals that the parameters related to the sound strength and envelopment are generally associated with the increased emotional impact of concert hall acoustics. Complete sets of Pearson’s correlation coefficients are provided in Tables II and III. With all halls and both positions included, low- and mid-frequency strength (G) has a strong statistically significant correlation with the mean SCR ($r > 0.7$, $p < 0.05$). Furthermore, the parameter for late lateral energy (LJ) shows significant positive correlations throughout the frequency bands ($r > 0.5$, $p < 0.05$). In R1 positions analyzed separately, the low-frequency strength ($r > 0.7$), and the early binaural incoherence12 (BQI; $r \geq 0.8$, $p < 0.05$) suggest the most prominent relation to the mean SCR. However, the applied Benjamini–Hochberg correction indicates that these correlations do not quite reach statistical significance. In general, high values for BQI suggest that the early reflected sound arrives from lateral
directions, resulting in a reduced interaural cross-correlation. The BDR is an objective measure for the variation in perceptual balance between the direct sound and early reflections due to the non-linearities in the orchestra sound and human spatial hearing at the high frequencies. This effect has been found to be generally more pronounced at larger distances. The high correlation coefficient ($r = 0.87$, $p < 0.05$) observed in R2 between BDR and SCR suggests the potential importance of the dynamic and spatial responsiveness of the acoustics to the music. Correlations with other parameters remain at a moderate level in this condition.

Subjective impact follows the general trend of correlations with objective parameters similarly to mean position-wise SCR as discussed in the preceding text. Because the two positions were not mixed in the paired comparison experiment, Table III presents correlations for R1 and R2 separately. The highest positive correlation coefficients are observed with sound strength, interaural incoherence, or late lateral energy (G, BQI, LJ; $r \geq 0.6, p < 0.05$). All correlations with $p < 0.05$ were found significant also with the Benjamini–Hochberg correction. Objective parameters describing reverberance (i.e., reverberation time T, early decay time EDT) are traditionally the first factors considered in objective and subjective acoustical analysis. While the correlations with the impact are positive using a linear model, the respective correlations are only moderate. Apart from a few exceptions, the correlation coefficients between the clarity parameter ($C80$) and both mean SCR and subjective impact are negative. This underlines the overall importance of strength and envelopment over high articulation in emotional impact.

An additional correlation analysis was conducted between the listening test data and the objective parameters estimated from the concert hall responses including the effect by the spatial sound reproduction. Those results are in agreement with the ones presented in the preceding text; this
TABLE II. Pearson’s correlation coefficients between mean SCR results [Fig. 5(a)] and selected room acoustic parameters in frequency bands. Correlations are averaged over two octave bands for more robust analysis. Correlations significant also with the Benjamini–Hochberg correction at the $\alpha = 0.25$ false discovery rate are emphasized in boldface. Parameters listed in the header denote strength (G), clarity (C80), early decay time (EDT), reverberation time (T), late lateral strength (LJ), lateral energy fraction (LEF), inverse of early interaural cross-correlation (BQI), and binaural dynamic responsiveness (BDR) (Ref. 25).

<table>
<thead>
<tr>
<th>Room acoustic parameter</th>
<th>Hz</th>
<th>G</th>
<th>C80</th>
<th>EDT</th>
<th>T</th>
<th>LJ</th>
<th>LEF</th>
<th>BQI</th>
<th>BDR</th>
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<tr>
<td></td>
<td>63–125</td>
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<td>0.41</td>
<td>0.47</td>
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<td></td>
<td>125–250</td>
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**aStatistically significant correlations at the $p < 0.05$ level.**

**bStatistically significant correlations at the $p < 0.01$ level.**

is predictable considering the minor acoustic influence by the reproduction system.

IV. DISCUSSION

The principal findings prove that with the same orchestral music, the intensity of listeners’ arousal and subjective impact varies depending on the concert hall and that the included classical rectangular shaped concert halls evoked higher subjective impact and emotional response than the other types of included concert halls. These results are in agreement with earlier hypotheses and assumptions.

Earlier studies have suggested that perceptual proximity or intimacy has a major effect on subjective preference. The difference in mean SCR between positions R1 and R2 demonstrates that the physical proximity does indeed have an effect on psychophysiological responses to listening to music. For many members of the audience, an important motivation for attending a concert is to listen to music and elicit emotional experiences; our findings show that some halls offer relatively strong experience also in seats further back down the hall. The results indicate that the average emotional response evoked by the orchestra sound in front of a shoebox concert hall is reduced by the same proportion when moving to a position further away in a hall of similar typology or when having the same seat but with the acoustics of non-rectangular halls included in the experiment [see fourth group in Fig. 5(a)].

Preceding subjective listening tests have identified the division of individual acoustic preferences into multiple groups. Some listeners prefer the strong and enveloping sound that is traditionally associated with the shoebox halls. In contrast, others tend to find a well-articulated sound, often provided by halls without prominent reflecting surfaces or rich reverberance, more important. Here the included non-rectangular halls (BP, CP, and HM) had a comparatively low subjective impact on listeners, and only CP R1 elicited a high mean SCR. That position has a highly articulated sound or rich reverberance, more important. Here the included non-rectangular halls (BP, CP, and HM) had a comparatively low subjective impact on listeners, and only CP R1 elicited a high mean SCR. That position has a highly articulated sound or rich reverberance, more important.

Correlations are averaged over two octave bands for more robust analysis. Correlations significant also with the Benjamini-Hochberg correction on a $\alpha = 0.25$ false discovery rate are emphasized in boldface.

TABLE III. Pearson’s correlation coefficients between mean subjective impact [Fig. 5(b)] and selected room acoustic parameters in frequency bands. Correlations are averaged over two octave bands for more robust analysis. Correlations significant also with the Benjamini-Hochberg correction on a $\alpha = 0.25$ false discovery rate are emphasized in boldface.

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**aStatistically significant correlations at the $p < 0.05$ level.**

**bStatistically significant correlations at the $p < 0.01$ level.**


Jukka Päätynen and Tapio Lokki
SCR in BP and HM, the same effect is observed with the subjective impact in BP as well as in BK and AC. A possible explanation for this phenomenon is the change in the balance between direct and reflected sound. In particularly reverberant halls, such as VM, the effect by the room can be perceived already near the orchestra in R1. In contrast, in halls where the geometry does not provide substantial early reflections or reverberation, the acoustic response in the front positions is dominated by the direct sound. With increasing distance, the reflected and reverberant sound becomes relatively stronger in comparison to other components of the acoustic response, also supporting higher strength.45,46 In VM, position R2 can be perceived as too reverberant, especially when unoccupied, while BK and AC retain a sufficiently defined sound. Along with the generally negative correlation coefficients between the clarity parameter and the experiment results, these remarks suggest that enveloping, and reverberant, room presence is an essential part of the overall impact to listeners.

The reverberation in unoccupied halls can be longer than in an authentic concert situation with the seated audience. The bare seats with minimal upholstery have a low absorption especially in VM, and the reverberation time during concerts is estimated as approximately 0.5 s shorter compared to the condition presented in the listening tests.10 Without audience, reverberation in R2 may be found excessive. Therefore the influence by occupied reverberance to the current results would be estimated to marginally reduce the impact in R1 due to the decrease in the room presence and increase the impact in R2 as the masking from the reverberation is reduced.

Beranek has published the most authoritative studies on the subjective quality of concert halls.10,12 Based on surveys with conductors, critics, and expert listeners, several dozen concert halls were rank-ordered based on their subjective acoustic quality. While the present experiments represent only a small overlapping subset of halls included in his surveys, a clear pattern emerges between current results and Beranek’s rank order. Four halls, VM, BK, AC, and BP, appear in this order within Beranek’s highest ranked 20 halls. In the present experiments, the higher rated positions by the SCR and subjective impact in each hall concur directly with Beranek’s rank ordering.

V. CONCLUSIONS

The primary hypothesis in this article was that the acoustics in concert halls contribute differently to the emotional impact elicited by the performed music. The hypothesis was tested in two listening experiments where the subjects listened to an orchestral music excerpt reproduced in the acoustics of different concert halls. The principal findings from the tests indicated that different acoustics has a significant effect on the psychophysiological responses as well as subjective impact. Overall the subjects considered the presented halls with rectangular typography having a more impressive sound than other rooms compared in this study. Furthermore, positions closer to the orchestra were found to elicit stronger emotional responses. The results of the subjective impact and psychophysiological responses complement each other.

Earlier research has demonstrated that room designs favorable for lateral reflections tend to increase the perceived envelopment, strength, and width of sound as well as enhance the dynamic range. Objective parameters related to these attributes were found here to correlate with the subjective impact. According to previous international surveys of concert halls,11,12 classical shoebox-shape halls, such as Vienna Musikverein, Berlin Konzerthaus, or Amsterdam Concertgebouw, have been generally considered to create the most preferred acoustic impression. Earlier studies have connected the acoustical success to an enveloping, strong, and resonant sound. Such factors were found to contribute also to the increased emotional response and subjective impact, although none of the associated room acoustic parameters alone appeared to be sufficient for completely explaining the elicited emotional impact in all investigated conditions. The outcome of this study calls for research integrating the fields of acoustics and psychology to establish a means of further exploring and predicting the connection between emotional responses and discrete properties of the sound field.

ACKNOWLEDGMENTS

The research leading to these results has received funding from the Academy of Finland, Project Nos. 257099 and 289300. The authors thank Dr. Philip Robinson for discussion and corrections, Jussi Hakala for discussions on electrodermal activity measurements, and Antti Kuusinen for discussions on statistics.
