DYNAMIC RESPONSIVENESS IN CONCERT HALLS AS SOURCE OF EMOTIONAL IMPACT

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1 INTRODUCTION

Acoustics of concert halls is a complex field that traditionally crosses over the subjective and objective evaluations. These means aim to predict the subjective preference for particular acoustic conditions via perceptual attributes and objective measures of the physical properties of rooms [1,2,3]. Although the perceptual descriptors vary slightly between studies depending on the compared acoustic conditions as well as the applied music excerpts [3], the most typically reported perceptual aspects are loudness, reverberance, spaciousness and envelopment, clarity, proximity/intimacy, brightness, and bass [4]. As a distinct property shared by many studies [5,6,7,8], they assume that the music exciting the acoustic response is a perceptually stationary signal. However, recent research has adopted alternative directions for resolving the challenge in assessing the quality of concert spaces. Rather than directly rating the characteristics of the acoustic transmission, latest studies have been oriented more towards the more fundamental functions of music [9], i.e. emotional experience evoked by music listening [10,11], and the perceived expressivity of the musical content [12] (p. 6). These studies have identified that, first, the same music excerpt performed through different concert hall acoustics appears to produce a varying intensity of emotional pleasure [13]. Second, another study has indicated that different concert halls have the virtue of augmenting the expressivity of music by expanding the loudness contrasts as well as enhancing the spaciousness perception along dynamically varying music [14]. We hypothesise that the emotional impact, and therefore the listening pleasure in concert halls, is influenced by the expressivity of the music performed in different room acoustics. Here, we investigate the connections between subjective impact from music listening and the expressivity-intensifying factors of concert hall acoustics.

The close relationship between dynamics and emotional impact is not only supported by our recent research. Indeed, there are much older proposals, which are as follows. Beranek wrote: "*listening is enhanced immeasurably by the dynamic response of the concert hall*" [15] (p. 509), and Meyer followed along the same lines claiming: "*a convincing tonal development in forte succeeds only in acoustically good halls [...] spatial expansion of the sound are of great significance for an emotional experience*" [16] (p. 199). This paper aims to offer validation for the above statements by merging the results from three experiments: first, with a recently introduced approach on the perceived transmission of musical expressivity [14], second, by subjectively experienced emotional impact in different acoustics [13], and third, from a psychophysiological angle by measured and self-reported emotional reactions [13]. These datasets collected in listening experiments have been analyzed individually in their respective studies, but here we combine the results so that different subjective and perceptual aspects can be represented in a common perceptual factor space.

2 METHODS

The data subjected to the statistical analysis are gathered from listening experiments that have been reported separately in preceding publications [13,14]. Both listening tests included the same group of 28 subjects who represented a mixture of professional musicians, music amateurs, and active audience members in concerts. The mean age of the subjects was 39.6 years with the individual variation between 22-64 years. Audiometry was conducted in early stages of the listening test procedure to confirm that the hearing levels were typical regarding subjects' age and occupation. Details of the subject selection is reported in Ref.[17].

The listening test data was collected by subjective evaluation of concert hall auralizations that were based on spatial room impulse response measurements from a wide-area array of sources on stages, multi-channel convolution of anechoic orchestra excerpts, and reproduction through 3D loudspeaker array in acoustically treated listening room. Measurements in six unoccupied concert halls were included in the studies: Vienna Musikverein (abbr. VM); Berlin Konzerthaus (BK); Amsterdam Concertgebouw (AC); Helsinki Music Centre (HM); Cologne Philharmonie (CP); and Berlin Philharmonie (BP). The sound source in each hall was an identical array of 33 two-way loudspeakers on the stage, arranged to simulate a typical orchestra seating. Two receiver positions at the stalls (denoted R1 and R2) were chosen from each hall in such a manner that the physical distances (11 and 19 m) in relation to the front line of the orchestra was identical in each hall in the respective position.

Swept sinusoid measurement signals from each source were captured with an open six-microphone array. The subsequent spatial analysis of the room impulse responses was conducted with Spatial Decomposition Method (SDM)[18]. Spatially decomposed room impulse responses were convolved with anechoic orchestra music signals[19,20] for reproduction of each measured condition. Different music excerpts were used in each experiment. The stimuli were presented to the subjects in a quiet, acoustically treated room (RT_{mid}=0.11 s) with a 24-channel spatial loudspeaker system. The entire processing chain is illustrated in Fig. 1. Room-acoustic measurements, analysis, and reproduction were identical in both studies combined here, and details of the system are reviewed in Refs.[14,17].

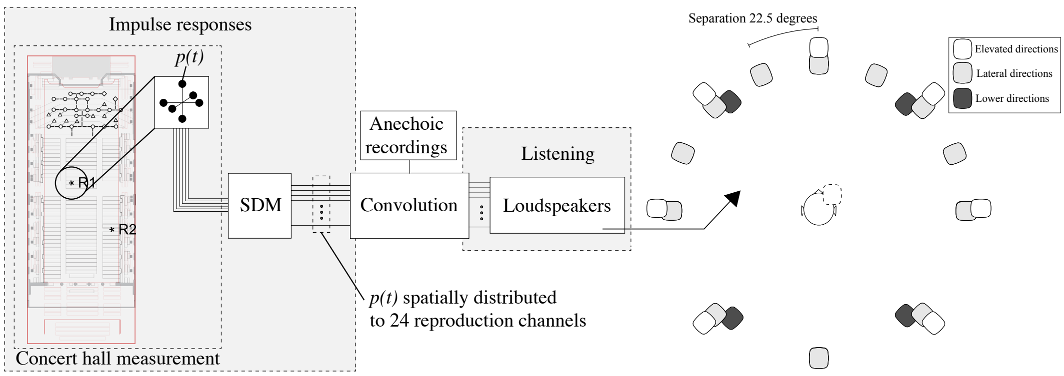

Figure 1 Block diagram of the spatial room impulse response measurement arrangement, block diagram for the stimuli generation and spatial audio reproduction.

2.1 Experiment A: Dynamic responsiveness and dynamic attributes

Subjective assessment focusing on how the acoustics contribute to the transmission of musical expressivity is a recent approach in research on room acoustics[14]. This method could be positioned between the traditional ratings of preference and collecting perceptual attributes. After all, musical expressivity is generally considered a key factor in communicating and eliciting emotional responses in music[12,21].

In this experiment, the signal presented to the assessors contained a sudden change in the music dynamics that was created by joining two orchestral segments (bars 41-43 and 53-55 from Bruckner's Symphony no. 8, II movement) fluently as continuous music. The former bars includes orchestra playing in piano, whereas the latter bars the texture is written in the same tonality in forte. Over the entire passage, the instrumentation remains unchanged, which makes the constructed signal useful for studying the perception of music dynamics change. More detailed analysis of the applied music signal is provided in Ref.[14].

With the clear dynamic change included in the signal in the concert hall auralizations, the assessors' task in paired comparison was to indicate the stimuli with the more prominent contrast in the sudden step of music dynamics. An option for no perceivable difference was also given. In addition, the subjects described their principal reason for the current choice by writing concisely the foremost difference between the pair of dynamic changes on a paper form in Finnish language. The authors refrained from providing details regarding the stimuli, or direct cues for possible differences in order to avoid biasing the assessors' judgements with the test instructions. After the experiment, the answer sheet was reviewed with each participant for resolving possible unclear definitions, and to ensure the correct interpretation. Finally, the experimenters assigned the written attributes into groups of perceptual factors for detailed analysis of the paired comparison results. In the present study, we included paired comparisons between six halls in two receiver positions separately, which results in 30 pairs for each assessor, and the accompanying perceptual attribute classification for each pair.

2.2 Experiment B: Psychophysiological measurement for emotional impact

Of the reviewed series of listening tests, this experiment differed the most from conventional listening tests on room acoustics. It is known that emotional responses can be measured from the variations in skin conductance response (SCR) due to the activation of sympathetic nervous system[22]. Here, the participants' skin conductance response was recorded with a Varioport-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[23] with a 0.5% NaCl paste as contact electrolyte. The experiment did not contain any interaction, and the continuous skin conductance signal during active listening was recorded synchronously with the automatic control of the signal playback. Complete details of the procedure are laid out in Ref.[13].

The music selected for this experiment was a 28-second passage from Beethoven's 7th symphony, first movement, bars 11-18. The dynamic and tonal developments during the passage are the main reasons for selecting this passage, which begins softly with woodwind chords and ascending major scales with strings, and culminates to a prominent crescendo with dominant scale, leading finally to a tonic degree with a full orchestra in fortissimo. With the gradually increasing intensity, the excerpt was expected to evoke strong attention[24] and incite psychophysiological reactions. Here, with the identical orchestra performance presented in different concert hall acoustics, a stronger reaction to the crescendo would suggest a more profound emotional response, higher impact, and thus, a greater pleasure for the listener. The stimuli had 2-second fade-in and fade-out times to reduce a startling effect due to a sudden start of sound.

The test sequence consisted of twelve auralizations (all six halls in positions R1 and R2). They were preceded by a pilot stimulus familiarizing the subjects with the signal in auralization of another concert hall, which was measured identically at a more distant receiver position but the reverberation tail was truncated[13]. All stimuli were presented in randomized order and separated by 15 s of silence. The length of the actual experiment (circa 12 minutes) was relatively short to avoid the possibility of major lapses in concentration or loss of responses 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. In the concluding interview, none of the participants reported losses of attentiveness or unpleasant experiences.

The raw skin conductance recording was filtered to remove signal artefacts and processed with Ledalab package in Matlab environment for separating the short-time phasic responses to the stimuli from slower change of tonic levels. The final single-value metric for the psychophysiological reactions was the standardized logarithm of integral of estimated phasic driver[13] as recommended in the electrodermal measurement guidelines[23]. The dataset contained a total of 324 measurements (12 stimuli $\times$ 27 subjects), as the data from one subject was discarded due to declining electrode contact, and arithmetic mean was used as the mean SCR data for each room-acoustic condition.

2.3 Experiment C: Self-reported subjective impact with paired comparisons

In this experiment, participants evaluated the same Beethoven's 7th symphony passage with crescendo in different halls' acoustics, but with a paired comparison technique as in experiment A. The subjects' task was simply to choose the stimulus that they felt producing a higher overall impact on them. The term "impact" was verbally described as thrilling, emotionally more intense, impressing, influential, or positively striking. Hence, the aim was to investigate similar effects than in the psychophysiological measurement in experiment B, not the preference. This experiment yielded a total of 30 paired comparisons for each assessor. Details of ths experiment have been reported in Ref. [13].

3 ANALYSIS

The data collected from three listening experiments consists of subjective evaluations and measurements. Apart from the SCR dataset, two other comparisons were conducted over the included concert hall conditions separately in each position. That is, the subjects did not compare receiver positions within one hall, or different positions across two halls. Hence, it is feasible to investigate the receiver positions as separate cases. Gathered SCR measurements were comparable across included combinations of halls and positions, but the total SCR results were separated to the groups of respective receiver positions.

Paired comparison data were analyzed using the Bradley-Terry-Luce (BTL) model for estimating the choice probabilities for given alternatives as in Refs [13,14]. As described with Experiment A, perceptual attributes were collected parallel to the paired comparison. The paired comparisons were grouped according to the category of the attribute (such as loudness, brightness, etc.) to respective groups based on the given attribute, and these separately aggregated paired comparison groups were analyzed with the BTL model.

Reduction of perceptual attributes into a lower number of salient factors is an often-used technique with subjective evaluation [25]. The foremost approach in analyzing the underlying similarities between perceptual criteria is the principal component analysis (PCA). However, the present case includes descriptors of dynamic responsiveness that are derived as subsets of the overall paired comparison data. Hence, PCA is not ideal in treating such partially associated variables. Multiple factor analysis (MFA) has two notable advantages: First, MFA has the direct capability to denote certain attributes as supplementary variables. This means that such variables do not affect the factor solution but they can be included for further statistical analysis. Second, MFA enables a convenient way to assign grouping variables for individuals, i.e. concert halls and their basic typology in this case. For these reasons, MFA is regarded more powerful approach for the current scenario, although some results could be reached even with a trivial correlation analysis. The analyzed dataset contains a total of nine items — overall rating for perceived dynamics, six attributes for dynamics perception, rating for subjective impact, and psychophysiological response. Dynamics attributes were denoted as supplementary variables. In addition, the halls were assigned to two groups respective to their generic typology of rectangular (AC, BK, VM) or non-rectangular (BP, CP, HM) geometry. Naturally, the number of MFA components equals the three quantitative (i.e. non-supplemental) variables. The statistic analyses are conducted in R environment using FactoMineR-package [26].

4 RESULTS

MFA procedure indicates that three variables — overall dynamics, subjective impact, and psychological effect — are highly similar perceptual aspects. In receiver positions R1 and R2, the first MFA component covers 86.9% and 79.7% of total variance, respectively. Corresponding second MFA components represent 12.3% and 15.9% of the variance. All eigenvalues for position R1 are 2.59, 0.37, and 0.05, while the eigenvalues for position R2 are 2.39, 0.48, and 0.13. First two MFA components account cumulatively for 98.3% and 95.6% of the total variance for the two receiver positions. Together

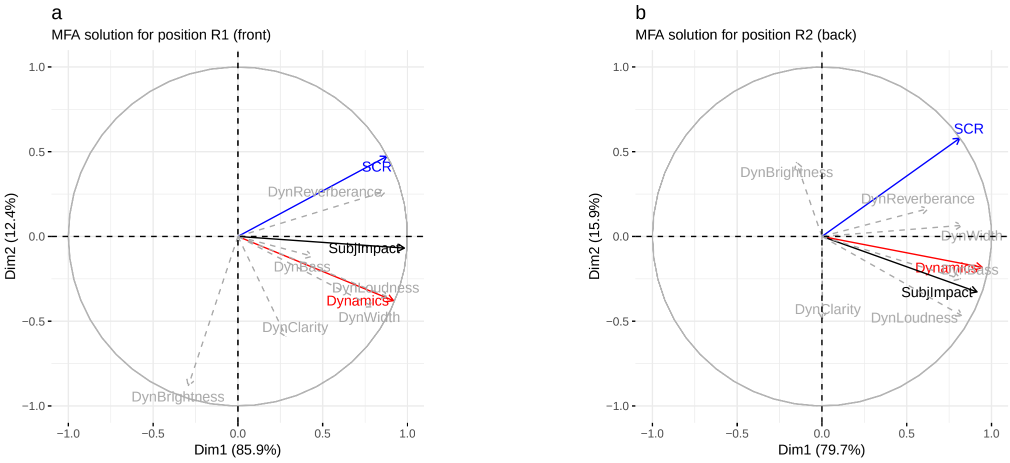

Figure 2 Multiple factor analysis for receiver position separately. Supplementary variables are plotted with dashed symbols.

with rapidly descending eigenvalues, high cumulative variances suggest that the dynamics perception as well as emotional impact by acoustics can be represented as a nearly unidimensional perceptual factor.

The MFA solution of the variables is shown in Fig. 2 together with the supplementary variables of dynamic responsiveness attributes. In position R1, we can notice that the subjectively reported impact is positioned approximately between the psychophysiological measure (SCR) and the overall dynamics responsiveness (see Fig. 2a). Dynamic loudness, i.e. perceived dynamic range of concert hall, as well as perceived spatial dynamic responsiveness (denoted with DynLoudness, DynWidth, and DynReverberance in the figure, respectively) become all mapped near the general direction of the main variables. However, music dynamics-related variation in sound clarity and spectral brightness are not well represented by the principal MFA dimension. The same observations apply also for position R2 further away from the orchestra (see Fig. 2b). The most noticeable difference here is the slightly stronger deviation of SCR variable from the dynamics and subjective impact variables. However, the similarity of the three variables remains prominent as MFA component 2, orthogonal to component 1, still represents only 15.9% of the total variance. While the visualized variables are in moderate angle, it is important to note that their strongest directions lie on the primary MFA component covering a minimum of 80% of the variance.

Investigation of individual halls and their typologies reveals interesting findings. Figure 3 visualizes the positions of the included concert halls over MFA dimensions 1-2. The main differentiating aspect between rectangular and non-rectangular geometries in position R1 is the subjective and emotional impact, shown in Fig. 3a. Three halls within the rectangular group are evenly separated by the direction of the dynamic responsiveness. The confidence ellipses at confidence level 0.95 nearly separate the hall typologies, although the overlap in this factorial space includes hall AC. In contrast, the hall types become clearly distinguished in R2, shown in Fig. 3b. Here the directions of dynamics and subjective impact correspond strongly with the separation between rectangular and non-rectangular type means, while individual halls are ordered along the axis of SCR variable. We can observe from individual halls that VM and BK appear to provide particularly strongly perceived response to dynamics as well as subjective impact. Still, it should be noted that the contribution of the vertical component 2 in the MFA plots is minor compared to the horizontal first component.

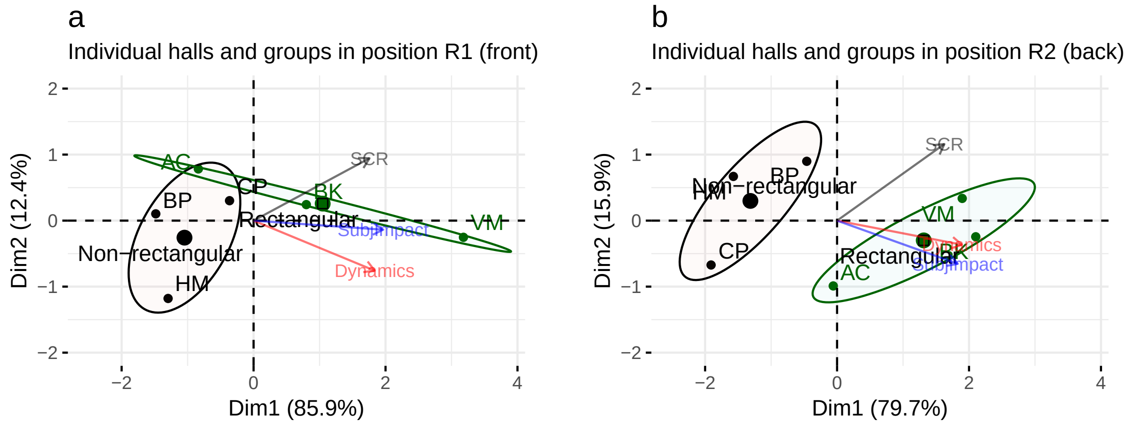

Figure 3 Individual and group plot of the compared concert halls. Variable directions from Fig. 2 are overlaid using a length scale of 2.

5 DISCUSSION AND CONCLUDING REMARKS

The outcome of the multiple factor analysis suggested that the perceived responsiveness by room acoustics to music dynamics, psychophysiologically measured emotional impact, and subjectively evaluated impact are quantitative factors that together are capable of differentiating concert hall types, and in most cases also individual concert halls. With the current varying selection of room-acoustic conditions, the variables on subjective impact (self-reported) and psychophysiological response (measured) are closely oriented in the factorial space. This suggests that the paired comparison approach could well be used for studying the influence of acoustics to the emotional impact of music performance when direct measurement of emotions-related psychopysiological responses is not possible.

Earlier publications demonstrated that the music dynamics can vary between concert halls in both measured[27] or perceived domains[14]. Current analysis showed that the experienced emotional impact by music follows the degree of the dynamic responsiveness by the concert hall's acoustics. This outcome provides evidence for an underlying link between dynamic responsiveness and emotional impact. Further on, this suggests that the rooms' capability to contribute to the expressivity of performed music could be a key factor in emotionally profound concert experiences.

The unoccupied state of halls in measurements introduced varying degree of deviation from the acoustic properties of the occupied state. The foremost change should occur most likely in the late reverberation of the presently included rectangular rooms. While the dynamics-related variation in reverberance was observed as one of the more prominent variables, moderate decrease in that aspect is estimated to have only minor influence on the MFA solution, and lead to a subtle increase in the overlap between hall groups. However, the authors find it unlikely that the use of auralizations from unoccupied measurements would dramatically influence the overall findings of the current nature.

Compared to the more traditional studies where explaining and estimating subjective preference by perceptual attributes has been challenging, the current approach presents a relatively direct relation between the magnitude of dynamic responsiveness as a perceptual attribute, and a more general concept of emotional experience. However, this investigation does not include subjective preference, and incorporating subjective ratings of concert halls in the analysis of salient perceptual factors is expected to yield further understanding on the relation of emotional impact, music dynamics, and room-acoustic preference.

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