SUBJECTIVE IMPACT OF CONCERT HALL ACOUSTICS

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1 INTRODUCTION

The audience in concerts gathers to enjoy listening to music. Although ordinary listeners may pay only little attention to the room acoustics in classical concerts, it has an inseparable part in the overall experience, since room acoustics convey the sound of the instruments from stage to the listeners. At its best, acoustics can, for example, enhance the musical expressivity by binding notes together[1], or spatially expand the sound to envelop the listener[2]. One of the main reasons to listen to music, or to attend a concert in-situ, is the emotional impact that the music can deliver. Most people can unanimously state that music performed in a room sounds more interesting than the same piece played in an anechoic chamber. Similarly, a concert hall with outstanding acoustics can increase the impact of the performance and enhance the overall experience.

The researchers of psychology and behaviour have recognized that, for many people, music is a stimuli that provides pleasurable feelings[3]. Certain types of music, particular pieces[4], or specific music structures[5] have been shown to trigger particularly strong emotional responses. In turn, the strongest reactions may manifest themselves in psychophysiological effects such as shivers or goosebumps[4]. Such reactions derive from the activation of sympathetic nervous system, and the intensity of the emotional reactions can be monitored by multiple means, such as measuring the skin conductance, heart rate, or respitory rate[4]. While the psychology of music is a complex area in the first place, in concerts the music perception is even more convoluted, as the combination of music and room-acoustic effects enters the listeners' ears.

One of the foremost aims in room acoustic design is to give spaces the acoustical properties that best suit their intended purposes. In case of performance venues, the design is often guided by architectural limitations, clients' requirements, and experience of the pracitioner, among several other factors. Large-scale projects tend to be touted with superior acoustics, but the long-term success will be eventually weighted by the audiences' experiences. In this sense, the acoustics of a concert hall should enhance the performance for a more profound enjoyment of the listener.

With the experiments presented in this paper, we propose that the acoustics of different concert halls have a varying influence to the emotional impact of listeners. The results suggest that the degree of subjective impact depends significantly on the general geometry of the hall. More precisely, greater impact is observed with rectangular concert halls in comparison to contemporary surround-design halls. The results are compared in light of standardised objective parameters, and the discussion is augmented by analysis on the characteristic geometry differences between hall types.

2 METHODS

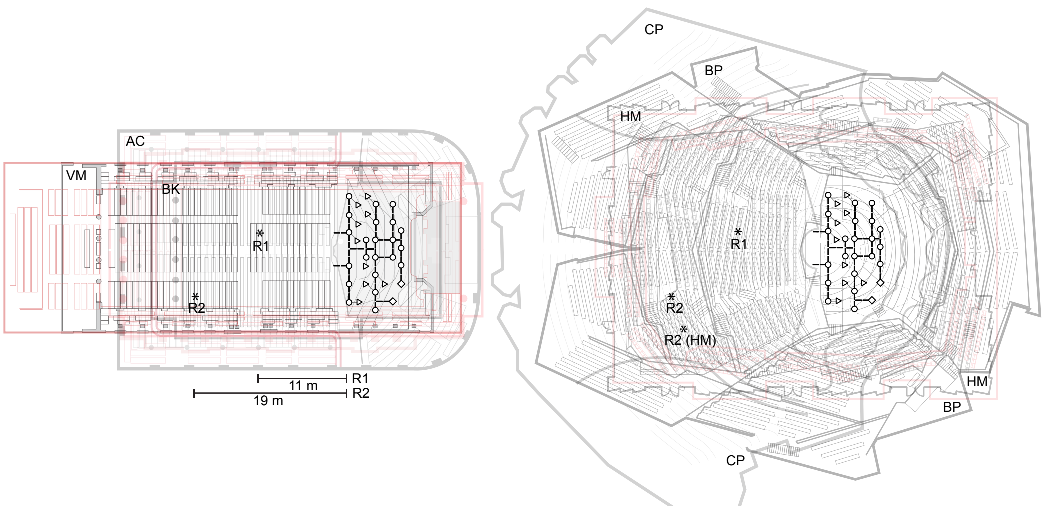
The experiments consist two listening tests, where the subjects listen to a set of orchestra music stimuli reproduced in the acoustics of measured European concert halls. In the first test, the subjects only listen to the music samples with different room acoustics while their electrical skin conductance is monitored from their fingertips. In the second test the subjects evaluate the acoustics according to the perceived subjective overall impact. The results from the tests are analyzed with statistical methods applicable for skin conductance data and paired comparisons.

Twenty eight subjects participated in the tests to represent a typical classical concert audience. Their ages were between 22-64 years, and 40 years 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 on listening tests, as they had participated in other similar listening sessions on earlier days. The subjects were only told that the tests are related to room acoustics.

The tests utilize room-acoustic measurements from six European halls, which are listed in Table 1. Three halls represent the classical shoebox-shape, and three others are of other types. From each hall, two respective receiver positions from the front stalls (denoted R1) and rear parterre (R2) were selected for the tests, see Fig. 1.

Id	Hall	Shape	V [m^3]	N	G [dB]	EDT [s]
VM	Vienna Musikverein	Rect.	15000	1680	3.7	3.0
AC	Amsterdam Concertgebouw	Rect.	18780	2040	2.7	2.5
BK	Berlin Konzerthaus	Rect.	15000	1575	2.2	2.2
BP	Berlin Philharmonie	Vineyard	21000	2220	1.9	1.9
HM	Helsinki Music Centre	Vineyard	24000	1700	1.9	2.1
CP	Cologne Philharmonie	Fan	†19000	2000	1.9	1.7

Table 1 List of European concert halls in the listening experiments. V, N, G, and EDT denote volume, number of seats, average strength, and average early decay time, respectively. Measured values for G and EDT are averages from 500 and 1000 Hz octave bands over 24 source channels and both measurement positions. († estimated)



a) b)

Figure 1 Floor plans of the three shoebox concert halls (a) and non-shoebox halls (b). R1 and R2 indicate the receiver positions included in the listening experiments. The floor plans are aligned by the loudspeaker orchestra shown on stage, and the scales are equal. Balconies above the main audience area are drawn in different shade.

2.1 Hall measurements and auralization

The concert halls were measured with a loudspeaker orchestra, consisting of an array of 33 sources[6] in 24 individual channels[7]. Using logarithmic sine sweeps at a calibrated output level, the room impulse responses were recorded with a G.R.A.S. type 50-VI 3D vector intensity probe at 48kHz sample rate. Its six omni-directional capsules are arranged in three co-centric pairs on perpendicular axes. The distance between opposing microphones is 0.1 m. Each spatial room impulse response was analyzed with the Spatial Decomposition Method (SDM)[8]. The method approximates the room impulse response with plane waves, and estimates the incident direction for each audio sample in the response using time-difference of arrival (TDOA) between the six microphones 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 loudspeaker without panning or interpolation between loudspeakers[9]. The end result is a spatial convolution reverb from one measurement channel to 24 reproduction loudspeakers in the listening room. 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. Such an auralization aims to give the subject a state-of-the-art impression of listening to an orchestra performance in various measured concert halls.

We estimated the ISO3382-1 standard objective parameters using the same omni-directional pressure for analyzing the listening test results. Instead of using figure-of-eight microphones, the directional energy parameters were estimated using the combination of directional data from SDM and omni-directional pressure. Additional binaural parameters were obtained from impulse responses recorded with a Bruel & Kjær H.A.T.S. dummy head. However, the binaural receiver positions do not fully correspond to the listening positions, and binaural measurements are absent from Helsinki Music Centre.

2.2 Listening experiments

The listening tests were organized in an acoustically treated listening room, where 24 loudspeakers surround the listening position in 3-D configuration for spatial sound reproduction. Since in conventional concert situations most of the sound energy arrives from the front directions, more loudspeakers are located in the frontal hemisphere for more accurate directional reproduction. The nominal distance of the loudspeakers was 1.5 m. The large amount of absorption on the walls and in the ceiling of the listening room yields a reverberation time of about 0.1 s at the middle frequencies. The linoleum-over-concrete floor was covered with a carpet around the listening position.

The music signal was an anechoic excerpt from Beethoven's Symphony no. 7, I movement, bars 11-18, with the full orchestra. The string sections were synthesized[10] from the single anechoic instrument recordings[11], and the resulting complement of strings corresponds to a typical number of musicians in professional orchestras. The excerpt begins in *piano* with alternating long notes with the woodwinds, and ascending scales with the strings. A prominent *crescendo* with ascending *tutti* scales culminates in imposing major chords in *fortissimo*. The ascending *crescendo* scales can be a considerable source of emotional impact[12] to many listeners, while a symphony by Beethoven represents a rather universal orchestral work.

In the first test, the subjects were instructed to concentrate on listening to a series of music signal in the two positions in each of the six concert halls in fully randomized order. During listening, the subjects wore a pair of small electrodes in their middle and ring finger tips of the non-dominant hand. We expected that continuosly measured skin conductace would show varying activity depending which concert hall and which position the subjects are listening to. A 15 s period of silence was inserted between automatically played stimuli. In addition, the very first stimulus with every subject was an introductory, non-impactful presentation of the same music excerpt, which was rendered in another measured concert hall.

The second listening test followed a traditional paired comparison method. The subjects were asked to listen to a pair of stimuli at a time, and choose the one that they perceived having the higher subjective impact. The experimenter explained the term *impact* before the test using bywords like thrilling, more intense, or positively striking, to ensure the correct interpretation of the task. The subject could freely switch between the two stimuli, which corresponds to jumping back and forth between two concert halls with the identical orchestra performing continuously in a loop. Different receiver positions were not compared against each other. That is, only the respective positions were compared with combinations of all halls. Therefore, the total number of comparisons was 30 (six halls and two receiver positions). Again, the presented pairs were fully randomized.

2.3 Analysis

The skin conductance of the subjects varies depending on their emotional excitation. The captured skin conductance signal is a superposition of two different effects. First, the long-term variations cause gradual, so-called tonic conductance changes with a time scale of minutes. Second, so-called phasic responses occur more rapidly as the skin conductance response (SCR) to stimuli within few seconds. As we are interested only in the rapid responses, i.e. reactions to different presented concert hall acoustics, we need to isolate the phasic responses from the measured overall conductance. After low-pass and median filtering the raw measurement signals, we applied continuous decomposition analysis with Ledalab toolbox by Benedek and Kaernbach[13] in Matlab environment. An example SCR signal from one subject during listening is shown in Fig. 2. The first stimulus (denoted PILOT) causes a strong initial increase in SCR. The next stumulus (CP R1) is the first proper concert hall. The subsequent stimuli elicit varying degrees of responses. Despite of several repetitions of the same music excerpt, the last presented stimulus (VM R1) triggers a prominent response. Such observations are in agreement with SCR guidelines[14]. Data from one subject were discarded due to failing electrode contact, and the SCR dataset contain a total of 324 measurements (12 stimuli $\times$ 27 subjects).

The variations in the conductance are triggered by sudomotor nerve impulses. The applied analysis method estimates the nerve impulses underlying the phasic SCR via deconvolution operations. In essence, the amount of nerve activity corresponds to the degree of emotional impact elicited by the stimuli. We used the integral of the nerve activation within accepted time windows as the test metric. Because the resposes vary greatly between individuals, values across 12 stimuli from each subject were standardized in the manner of z-score. In the following, SCR denotes these standardized values.

The paired comparisons from the second experiment yield square matrices, where choises for certain stimulus over another is indicated by non-zero elements in the respective row and column. Accumulating the matrices over all subjects is a straightforward analysis approach. Instead, we adopted a more advanced method for calculating the probability of choosing one hall over others. Bradley-Terry-Luce (BTL) model[15,16] estimates the scale values that underlie the observed choice frequencies. Statistical significance in the differences between halls were analyzed with the model by Courcoux and Semenou[17]. By adding together respective matrix rows and columns, we can analyze the probabilities for higher impact by different hall types, receiver positions, and the combination of the hall type and position. Choisel and Wickelmaier[18] have presented a detailed overview on comparison models and their application.

3 RESULTS

The results from the skin conductance experiment indicate that the physiological reaction depend on the acoustics of the concert hall. The highest mean SCR among all subjects was observed with the front stalls of Vienna Musikverein, and the lowest level at the parterre in Cologne Philharmonie. Most subjects (6) also exhibited their strongest response in VM R1. Figure 3a shows the mutual order of individual positions and concert halls. The differences between all positions and halls are not statistically significant, as the results and responses by listeners have large variances. Combining all

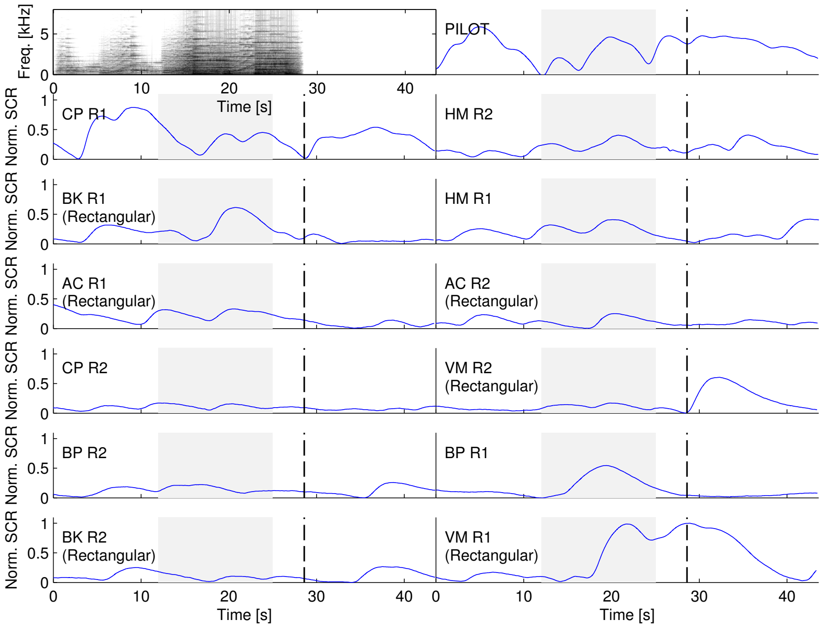


Figure 2 Phasic skin conductance from one subject during the listening test. Top-left panel shows a spectrogram of the stimulus signals. The orchestra crescendo begins at time of 12.5s. The shaded area in the conductance plots indicates the time window of accepted responses. Dashed vertical line shows the end of audio in the stimulus sequence.

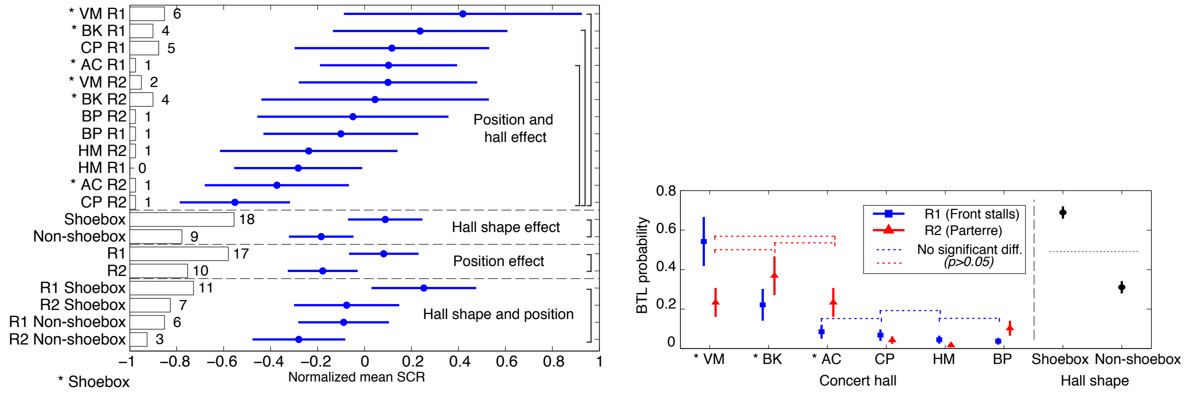
positions in the two hall types shows that listening to music in the acoustics of shoebox concert halls elicit a stronger psychophysiological response than non-shoebox rooms. Two-thirds of the subjects also experienced their strongest response with shoebox hall acoustics. Similarly, the difference in the SCR between front stalls and parterre positions is statistically significant.

The results from the paired comparison test are in agreement with the skin conductance measurement. In the front stalls positions, Vienna Musikverein and Berlin Konzerthaus were considered to have significantly higher subjective impact than other halls. In R2, the subjects observed high impact in all shoebox halls, while CP and HM produced only negligible impact. With the responses aggregated over two hall types, the difference is substantial for the advantage of shoebox rooms.

In general, the results suggest strongly that the degree of emotional impact by orchestra music is connected to the acoustics of the concert hall. In order to analyze the possible connection between the impact of acoustic and objective metrics, we conducted a correlation analysis between the test results and objective room-acoustic parameters in octave bands. SCR measured in all positions correlates the strongest with strength parameter G and late lateral fraction (LJ) at 125-4000 Hz, where the Pearson correlation coefficient $r^2 > 0.6$. In R1, the correlation coefficient between SCR and 1-IACC80 (BQI[19,20]) is $r^2 > 0.87$ above 1 kHz. In the parterre position R2, the most highest correlation $r^2 > 0.86$ was found with the binaural dynamic responsiveness (BDR) at 1-4 kHz. Recently, BDR has been proposed as the objective metric for music dynamics perception[21]. Correlations in the subjective impact are similar to the SCR. Values of 1-IACC80 correlate particularly strongly with the impact, and in R1 the correlation cofficients above 1 kHz exceed 0.95. Interestingly, clarity parameters C80 have general negative correlation coefficients in both tests.

4 DISCUSSION

Our experiments suggest that, while the music material itself is the principal source for emotional impact, the surrounding acoustics may have a significant contribution to the overall experience. Earlier



a) Skin conductance response, Test 1 b) Subjective impact, Test 2

Figure 3 Means and 95% confidence intervals from the SCR measurement (a) and paired comparison test (b). The horizontal bars on the left side indicate the number of subjects whose highest SCR value was with the respective position. The following three panels show the results grouped by room geometry (rectangular or non-rectangular), receiver distance (R1 or R2), and their combinations, respectively. Rectangular halls (Rect.) are denoted with an asterisk (*). Panel (b) shows the results from the second experiment for the subjective impact by different concert halls. The vertical axis indicates the probability in Bradley-Terry-Luce model for choosing one over other alternatives. In panel (a), brackets indicate significant differences ($p < 0.05$), while in panel (b) the dashed brackets indicate non-significant differences ($p > 0.05$).

research have shown that adequate sound level and certain amount of spaciousness are desired factors in concert hall acoustics. The early lateral reflections have often been cited beneficial for the overall acoustic impression. Based on the results, higher strength and lateral energy appear to be among the acoustic properties that elicit emotional responses in the listeners.

Early reflections contribute to the total strength, and reflections from lateral directions in turn decrease the interaural cross-correlation. Indeed, the inverse of inter-aural cross correlation appeared as a more accurate estimator for SCR and subjective impact than the lateral energy fraction (LEF). Due to the geometry in narrow rectangular halls with flat or slightly sloping floor, they are favorable for the development of lateral energy throughout the room impulse response[22]. Hence, the benefit from the lateral energy offers a direct explanation for the results in favour of the shoebox halls. The connection of interaural cross-correlation is also in agreement with earlier surveys. Hidaka et al. proposed in 1995[19] that the general level of 1-IACC, computed from the early response at the middle frequencies, could serve as an rough indication of the acoustical quality of the concert hall.

The reverberation is typically one of the foremost aspects observed in concert hall acoustics, but the sheer reverberation time did not have major influence to the results. Instead, the direction of late reverberant energy showed repeatedly significant correlations with the perceived impact. Also this finding has a close connection with the room shape, upper volume, and seating. The vineyard design aims at placing audiences in a relatively short distance from the stage and with good sight lines to the orchestra. With the sufficient seating capacity and modern limitations for seating density, a common solution is to place the audience in multiple sections around the stage. In order to secure the sight lines, the floor inclination of the upper sections has to be increased. In essence, this approach increases the audience absorption at the upper volume of the hall. Consequently, the audience covers more of the surface visible from the sources on stage. Furthermore, the ceiling, representing a larger proportion of the total first-reflecting surface, often directs the reflections to the audience area. Together these features reduce the overall lateral energy, and its benefits. In contrast, more scarce sightlines allow the audience placement to more horizontal surfaces, such as in traditional shoebox halls. Overlaid cross-sections in Fig. 4 illustrate this principle. In the included shoebox halls (Fig. 4a) the upper volume is free of audience absorption, which allows the late reverberation to develop through high-

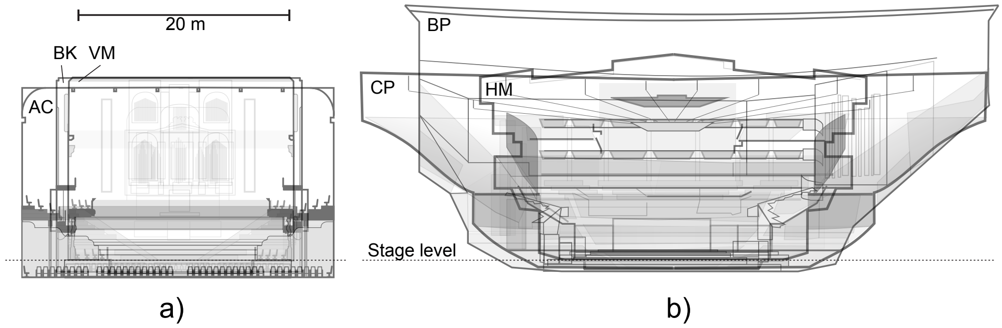


Figure 4 Cross sections of the six concert halls in scale, aligned by the elevation of the stage front. a) Shoebox halls. b) Non-shoebox halls.

order reflections. In contrast, in halls with alternative designs (Fig. 4b), the strongly inclined audience areas may prevent the high-order lateral reflection paths. While the reverberation time remains within the intended limits, the direction of late energy may not be optimal for the desired envelopment.

The negative correlation between clarity measures and the listening test results is also an intriguing finding that cannot be directly explained. Earlier studies have shown that some listeners prefer clear and articulating acoustics, while others seek for full and majestic sound[7,23]. However, in this study such a clear division into contrasting preference groups was not found. In both tests, positions with enveloping and full sound received the highest responses by prominent margin. Cologne Philharmonie R1 has a quite strong and articulated sound. However, it is not very enveloping in comparison to VM and BK. Still, the bass and timpani sound in the peak of the crescendo are powerful, which may contribute to the high mean SCR. In the second test, the same position provided only low impact.

The most authoritative rank order of several dozen concert halls has been gathered by Beranek[20] from conductors and other experienced listeners. Although our experiments contain only some of the halls included in his surveys, we can notice a clear pattern between the present study and Beranek's rank order. The results suggest that certain halls, primarly Vienna Musikverein and Berlin Konzerthaus, are above other compared concert halls based on the SCR measurements and subjective impact. On the same criteria, these two leading halls are followed by Amsterdam Concertgebouw and Berlin Philharmonie. Also these halls appear in the respective order within Beranek's highest ranked 20 halls. This connection suggests that the emotional impact influences the overall preference in room acoustics.

Together the experiment results suggest that the subjective impact experienced by the subjects and the elicited psychophysiological responses correspond to a certain extent. In the light of correlations with objective parameters, ratings for SCR and impact are prominently driven by a sound which combines sufficient level and spaciousness. The sound level in general may be influenced by both the acoustics and music. In music, sound level is an inherent, often varying, component of the musical context, and the dynamic level of music has shown to contribute to various emotional expressions[24,25]. Instead, the spatial aspects are not traditionally associated to the music itself, other than the physical positions of the instruments. Still, spaciousness may enhance the aesthetic value of music without directly influencing its context. The emotional effect by the direction and movement of sound source can be traced back to the human evolution and survival, and shift of attention[26]. The exact reason for the enhancement of impact and emotional response by spatial sounds in music remains unresolved.

5 CONCLUSIONS

This paper presented experiments which showed that the emotional response and impact experienced by listeners depend on the concert hall acoustics. The results suggested that near-orchestra positions elicit stronger psychophysiological responses than positions further away, and that the acoustics provided by, for example, shoebox-shape concert halls are more likely to enhance the impact of the listened music. Hence, such conditions serve better the original meaning of music: pleasure or emotional experience. Correlation analysis between the listening test results and objective metrics of the room impulse responses indicate that the strength of sound, low interaural cross-correlation, and late lateral energy together predict acoustic conditions with high impact.

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6 REFERENCES

1. J. Meyer. *Acoustics and the Performance of Music*. Springer, New York, NY, USA, 2009.
2. W. V. Keet. The influence of early lateral reflections on the spatial impression. In *Proc. 6th International Congress on Acoustics*, volume 3, pages E53--E56, Tokyo, Japan, 1968.
3. L. Dubé and J. Le Bel. The content and structure of laypeople's concept of pleasure. *Cognition & Emotion*, 17(2):263--295, 2003.
4. V. N. Salimpoor, M. Benovoy, G. Longo, J. R. Cooperstock, and R. J. Zatorre. The rewarding aspects of music listening are related to degree of emotional arousal. *PloS one*, 4(10):e7487, 2009.
5. J. A. Sloboda. Music structure and emoptional response: some empirical findings. *Psychology of Music*, 19:110--120, 1991.
6. J. Pätynen. *A virtual symphony orchestra for studies on concert hall acoustics*. PhD thesis, Aalto University School of Science, November 2011.
7. T. Lokki. Tasting music like wine. *Physics Today*, 67(1):27--32, 2014.
8. S. Tervo, J. Pätynen, and T. Lokki. Spatial decomposition method for room impulse responses. *J Audio Eng. Soc.*, 61(1/2):16--27, Mar. 2013.
9. J. Pätynen, S. Tervo, , and T. Lokki. Amplitude panning decreases spectral brightness with concert hall auralizations. In *Proc. 55th Audio Eng. Soc. conference, Helsinki, Finland*, Aug. 27-29 2014. Paper no. 49.
10. J. Pätynen, S. Tervo, and T. Lokki. Simulation of the violin section sound based on the analysis of orchestra performance. In *IEEE Workshop on Appl. of Signal Processing to Audio and Acoustics (WASPAA 2011)*. IEEE, Oct. 16-19 2011.
11. J. Pätynen, V. Pulkki, and T. Lokki. Anechoic recording system for symphony orchestra. *Acta Acust United Ac*, 94(6):856--865, Dec. 2008.
12. D. Huron. The ramp archetype and the maintenance of passive auditory attention. *Music Perception*, 10(1):93--92, 1992.
13. M. Benedek and C. Kaernbach. A continuous measure of phasic electrodermal activity. *Journal of Neuroscience Methods*, 190:80--91, 2010.
14. W. Boucsein, D. C. Fowles, S. Grimnes, G. Ben-Shakhar, W. T. Roth, M. C. Dawson, and D. L. Filion. Publication recommendations for electrodermal measurements. *Psychophysiology*, 49:1017--1034, 2012.
15. R. A. Bradley and M. E. Terry. Rank analysis of incomplete block designs: I. The method of paired comparisons. *Biometrika*, 39:324--345, 1952.
16. R. D. Luce. *Individual choice behaviour: A theoretical analysis*. Wiley, New York, NY, USA, 1959.
17. P. Courcouxand M. Semenou. Preference data analysis using a paired comparison model. *Food quality and preference*, 8(5):353--358, 1997.
18. S. Choisel and F. Wickelmaier. Evaluation of multichannel reproduced sound: Scaling auditory attributes underlying listener preference. *J Acoust Soc Am*, 121(1):388--400, 2007.
19. T. Hidaka, L. L. Beranek, and T. Okano. Interaural cross-correlation, lateral fraction, and low- and high-frequency sound levels as measures of acoustical quality in concert halls. *J Acoust Soc Am*, 98(2):988--1007, 1995.
20. L. L. Beranek. Subjective rank-orderings and acoustical measurements for fifty-eight concert halls. *Acta Acust United Ac*, 89(3):494--508, 2003.
21. J. Pätynen, S. Tervo, P. W. Robinson, and T. Lokki. Concert halls with strong lateral reflections enhance musical dynamics. *Proc Natl Acad Sci Am*, 111(12):4409--4414, Mar. 2014.
22. M. Long. What Is so Special about Shoebox Halls? Envelopment, Envelopment, Envelopment. *Acoustics Today*, 5(2):21--25, 2009.
23. M. Barron. The subjective effects of first reflections in concert halls --- the need for lateral reflections. *J Sound Vib*, 15(4):475--494, 1971.
24. G. C. Bruner. Music, mood, and marketing. *the Journal of marketing*, 54:94--104, 1990.
25. P. N. Juslin. Emotional communication in music performance: A functionalist perspective and some data. *Music Perception*, 14(4):383--418, 1997.
26. A. Tajadura-Jiménez, A. Väljamäe, E. Asutay, and D. Västfjäll. Embodied auditory perception: the emotional impact of approaching and receding sound sources. *Emotion*, 10(2):216--229, 2010.