INTERNATIONAL SYMPOSIUM on MUSICAL and ROOM ACOUSTICS

ISMRA 2016

September 11-13, 2016

La Plata, Buenos Aires, Argentina

Evaluation of Concert Halls / Opera Houses
ISMRA2016-72

Why do some concert halls render music more expressive and impressive than others?

Tapio Lokki
Aalto University, Finland, Tapio.Lokki@aalto.fi

Abstract

Research on musical acoustics and room acoustics is very seldom performed together. This is quite strange, as it is well known that musical instruments sound unpleasant in anechoic spaces. A musical instrument needs reverberation to sound enjoyable, and therefore room acoustics is an essential part of music. Room acoustics not only reverberate the sound, but also change the timbre of musical sounds. Moreover, reverberation is an integral component of music that binds together individual notes, helps to form phrases, and carries on the harmony between phrases.

This paper ties together musical and room acoustics. The directivity of musical instruments and the spectral changes according to played dynamics are reviewed. These issues are linked to the basics of concert hall acoustics to explain why room acousticians who design concert halls should also understand these fundamental aspects of musical instruments and their sounds. In addition, recent findings in concert hall acoustics are explained in light of the acoustics and concert halls that best support the music. In other words, what room acoustics features convey the important spectral changes to the audience as well as possible?

Keywords: Auditorium acoustics, dynamics, musical acoustics, seat-dip effect

INTERNATIONAL SYMPOSIUM on MUSICAL and ROOM ACOUSTICS
ISMRA 2016
September 11-13, 2016
La Plata, Buenos Aires, Argentina

Why do some concert halls render music more expressive and impressive than others?

1 Introduction

A concert hall is a special venue dedicated to performing and listening to music. The hall reverberates the sound emitted by musical instruments to make musical performance more loud, rich, and full-bodied. The reverberation also colors the sound by emphasizing some frequencies more than others, i.e., the hall changes the timbre of instrument sounds. Therefore, the hall affects to music in both the frequency and the time domains. This paper focuses mainly on frequency domain effects.

Engineers often use a source-medium-receiver model to explain a process. In the case of a concert hall such a model is presented in Fig 1. Traditionally, room acoustics research is concentrated only on the medium part of this communication process. The ISO3382-1:2009 standard [1] has been created to objectively measure room acoustical features, which include reverberation time, clarity, strength, etc. The ideas behind the standard have been presented already long time ago, see e.g. [2]. The standard acknowledges all these measures to be frequency dependent and therefore, octave or one third-octave band analyses are recommended. Moreover, the standard eliminates variability in measurements by defining that measurement loudspeakers and microphones should be omnidirectional, i.e., emitting/capturing the same amount of sound energy from all directions at all frequencies. This is reasonable for repeatability, and for the comparison of measurements performed by different researchers.

From a technical point of view the ISO3382-1:2009 standard is valid, but room acoustics researchers like to predict the acoustics of a hall with as few numbers as possible, and often only a few parameters at mid frequencies are considered. This routine is really misleading, as traditional room acoustical parameters are not sophisticated enough to predict all salient subjective impressions. There are at least three reasons why commonly applied objective measures are insufficient. First, the typical source (an orchestra) and, receiver (human listener)

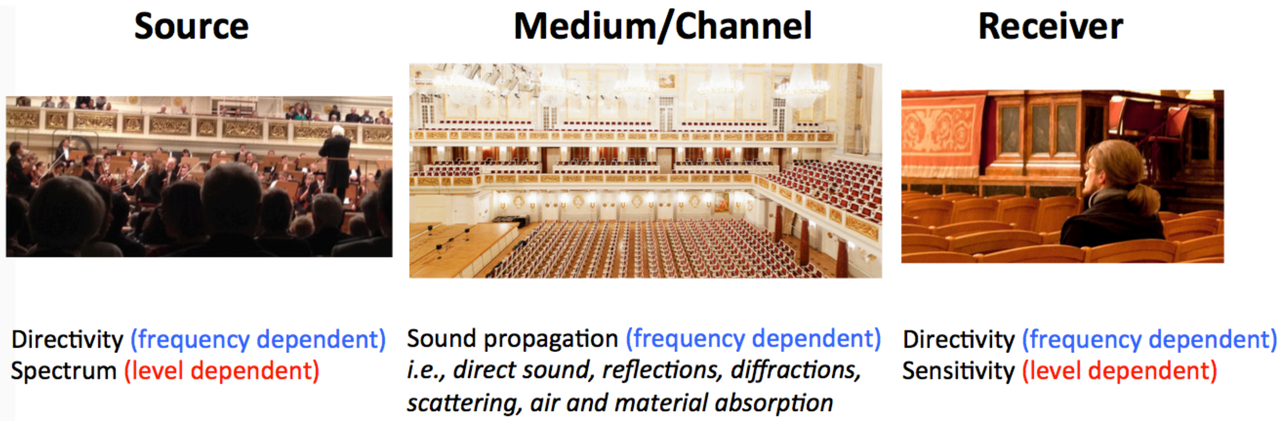


Figure 1: Source - Medium - Receiver communication process for a concert hall.

both have frequency and level dependent features that are not captured in impulse responses measured according to the standard. Second, averaging of results of all source-receiver combinations (typically a few sources and many listening positions) does not correspond to the reality in which we have dozens of sound sources (musical instruments) on stage and only one listener at one single seat. Third, results are often presented only at mid frequencies or at a frequency range that is definitely inadequate from the perception point of view, as illustrated in this paper.

This paper concentrates mainly on the frequency and level dependent issues of both musical instruments and human listeners in order to better understand the big picture of concert hall acoustics. In addition, room acoustical phenomena that affect those frequency and level dependent features are reviewed.

2 Sources and receivers in a concert hall

2.1 Musical instruments as sources

The sound sources on stage are musical instruments and human voices. The size of the ensemble varies from a solo instrument, e.g., a grand piano, to large orchestras and choirs consisting of hundreds of musicians. Regardless of the ensemble size, every single sound source shares two important features from a room acoustics point of view, namely frequency dependent radiation patterns [3, 4] and level dependent spectra [5, 3, 6].

Musical instruments radiate sound to all directions, but the spectrum varies with direction. The low frequencies are more or less omnidirectionally radiated while the radiation pattern is more unequal the higher the frequency. The radiation pattern is defined by the geometry and the properties of the radiating parts of the instrument. For example, the main radiators in string instruments are the f-holes and the body. In brass instruments, all sound is emitted from the bell and woodwinds radiate sound from the open tone holes as well as from the bell. A grand piano and percussion instruments have probably the most complex radiation properties. All in all, the radiation patterns do not depend on the played dynamics [4]. In other words, the radiation pattern is frequency dependent and naturally varies between played notes, but the radiation at one single frequency is always the same if that particular frequency is excited. This concept is important to understand and is separate from the level dependent characteristics of musical instruments.

In musical acoustics research the level dependency of instrument spectra is well understood [3]. For example, a brass instrument excites many more harmonics when played in *fortissimo* than in *pianissimo*, resulting in different timbre. Nevertheless, such spectral changes are almost totally ignored in room acoustics research, and only recently has it been found to be important [6, 7, 8]. Figure 2 illustrates the spectral differences of *piano* and *fortissimo* of a full orchestra, analysed from commercial recordings. The data are taken from 29 recordings[1] of Bruckner's 4th Symphony (bars 19-26, III movement) and the plot shows the spectra of an orchestra playing a long crescendo practically without changing the played notes. The plot in the right shows the dynamic range and highlights the large differences at different frequencies. At low frequencies the larger dynamic range is due to timpani playing really loudly, and at high frequencies the difference is related to the emphasized higher harmonics. In many cases the spectral differences can be even larger as loud instruments (gran cassa, timpani, tuba, trombone, trumpet, piatti) are silent in *piano* passages, but join the *fortissimo*, which makes the difference really large.

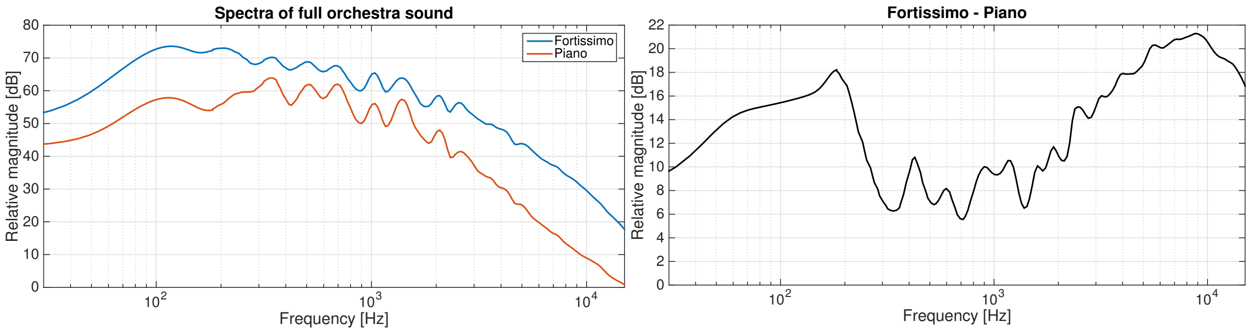


Figure 2: Left: The spectra of a full orchestra sound in different dynamics. Right: the spectral change between *fortissimo* and *piano*.

2.2 Human listeners as receivers

Similarly to the sound sources, human listeners have two important features; frequency dependent directivity [9, 10] and level dependent sensitivity, the latter of which is generally known in the form of the equal loudness contours [11].

Frequency dependent directivity has been under active research for several decades. Head-related transfer functions (HRTF) [9, 10] describe the effect of the body and the outer ear to the frequency response of sound and these direction-dependent functions have been measured, modeled, and applied in studies related to binaural technology [12]. From the room acoustical point of view the HRTFs show how the human head colors reflections from different directions. Figure 3 illustrates the mean difference between a reflection from the frontal direction (e.g., from ceiling or from clouds above the orchestra) and the lateral direction (e.g., a reflection from a side wall or from a balcony overhang). Note that the plot shows binaural level, which is a power sum of both ears [13]. The spectra illustrate how a human head emphasizes the level of lateral reflections much more than median plane reflections [14]. Analogously to the directivity of musical instruments, the HRTF functions are independent of the level of excitation signal.

Correspondingly to the level dependent spectra of musical instruments, human hearing has also level dependent sensitivity. Equal loudness contours [11], plotted in Fig. 4 describe the level of different frequencies producing as loud perception as 1 kHz tone at a certain level. These

[1] Commercial recordings are usually compressed and therefore the overall level difference is quite modest. In-situ in a concert hall the dynamic range could be even 60 dB [3].

contours are defined only for single tones and it is not known exactly to what extent they apply for complex wideband sounds. Anyhow, it is evident that level dependent sensitivity particularly affects our perception of low frequencies.

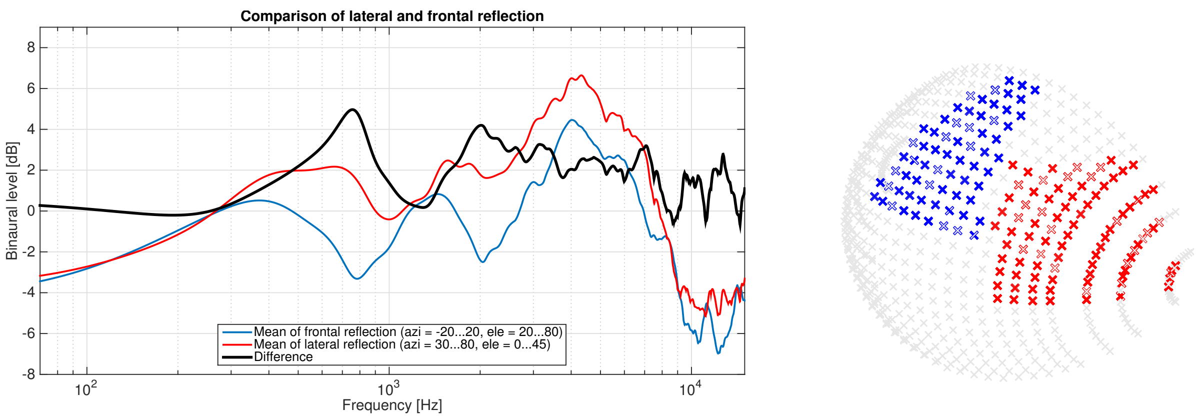


Figure 3: Left: Binaural level for reflections from lateral and frontal directions. The responses are means of all colored directions illustrated on the right.

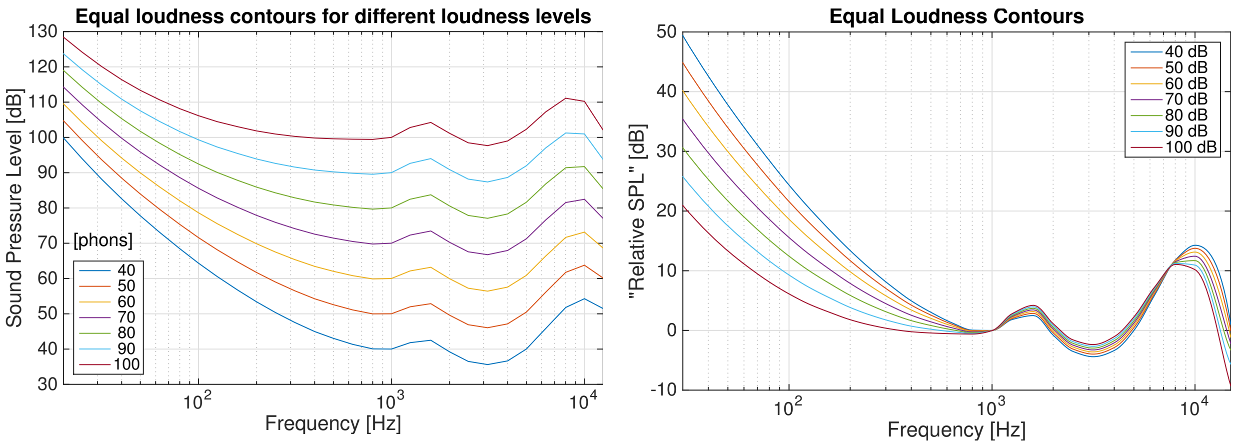


Figure 4: Left: Equal loudness contours according to ISO226 standard. Right: The same contours level aligned at 1 kHz.

2.3 Combination of level dependent features

Figure 5 combines the level dependent effects together. The spectrum of an orchestral *piano* is added to the equal loudness contour of 40 phons and the spectrum of an orchestral *fortissimo* is added to contours varying from 60 to 100 phons. The figure illustrates that in addition to the level increase the overall frequency response flattens remarkably. The relative change in spectra is highlighted in the right plot, which shows all responses level aligned at 1 kHz. The largest change is at low frequencies below 200 Hz, but also frequencies over 3 kHz are pronounced. These frequency regions are thus important and they should be considered more carefully in concert hall acoustics research. From the engineering point of view the defined parameters at mid frequencies are good, as the level dependency (see Fig. 1) is minimal, but from the perception point of view, current mid frequency parameters do not describe how a hall renders the broadband music.

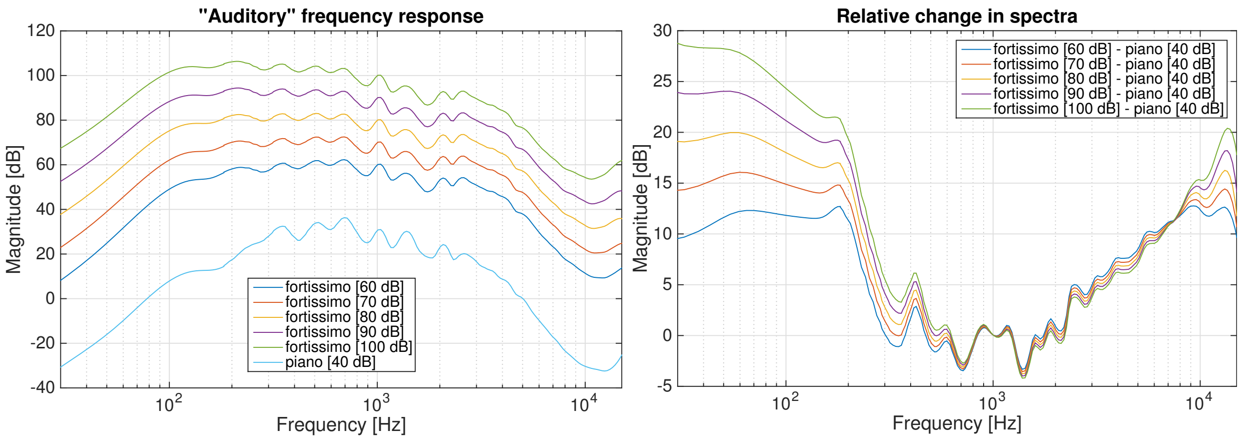


Figure 5: Left: Equal loudness contours combined with spectra of an orchestra. Right: Relative changes in spectra, contours level aligned at 1 kHz.

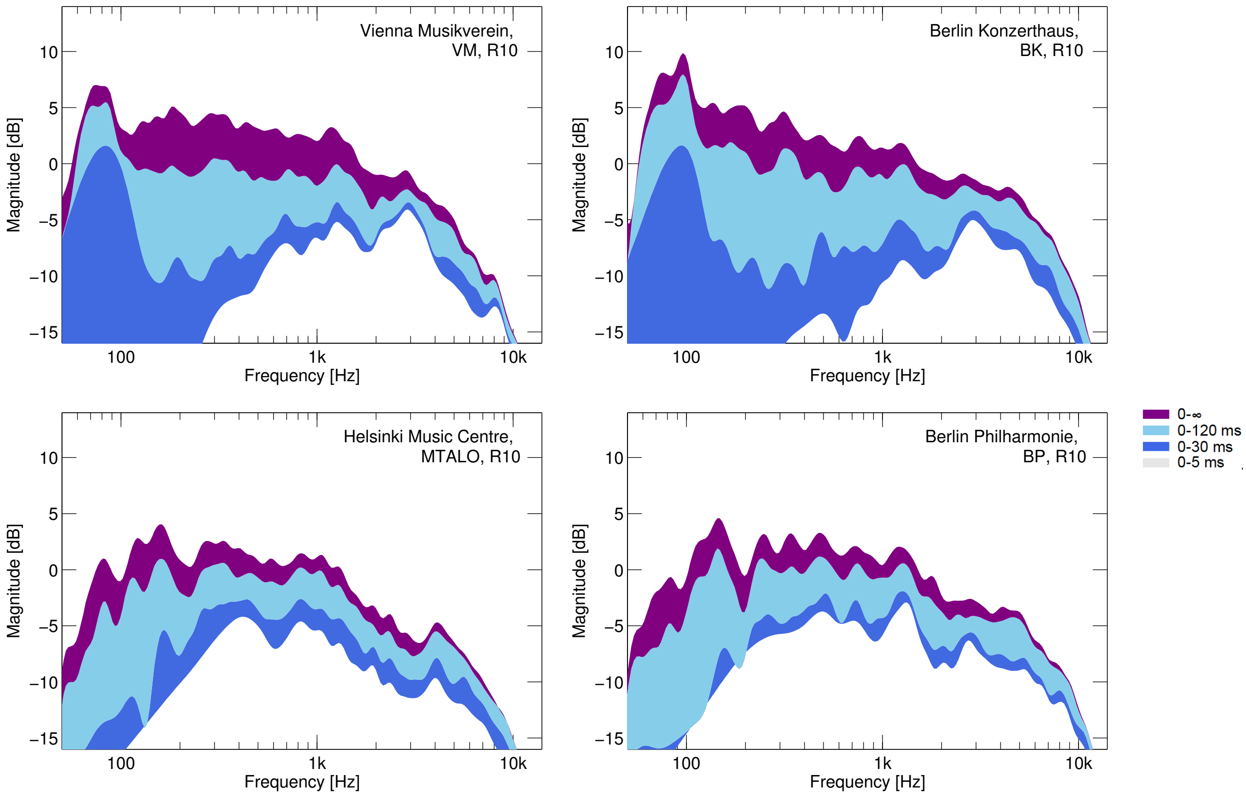
3 Concert hall as a transmission channel for music

A concert hall acts as a frequency dependent transmission channel in the source-medium-receiver communication process (Fig. 1). A hall conveys the sound from the stage to the listeners directly and through the reflections that form the reverberation. The shape of the hall defines the reflection patterns, and the frequency content of these reflections is further modified by the absorption properties of the surface materials. In addition, propagation through air attenuates the high frequencies. As an example, Fig. 6 shows the frequency responses, measured at 19 meters distance from the stage, of four different concert halls as a function of time. It is clearly seen that the frequency response changes when as the analysis window includes more and more reflections. The perceptual significance of the change in the frequency response needs more research, but it is assumed that it has connections to perceived spaciousness and dynamics. The presented measurements were made with directive sources (the loudspeaker orchestra [15]) and an omnidirectional microphone.

Note that the perception of acoustics is also related to temporal and spatial features of reverberation. However, the following discussion is concentrated on the spectral features of room acoustics.

3.1 Concert hall acoustics and low frequencies

At low frequencies both sources and receivers are more or less omnidirectional due to long wavelengths, thus the bass response is not affected at all by the directivities of instruments and listeners. Nevertheless, there are remarkable differences in the low frequency responses between different concert halls, as seen in Fig. 6. The main reasons for low frequency attenuation is material absorption, stage construction, and the seat dip effect [17, 18]. The sound propagating at a grazing angle over the seating area bends between the chairs and reflects from the floor, thus forming interference at low frequencies. The main dip in the frequency response due to this interference occurs between 100 and 200 Hz, depending on the seat type and inclination of the floor [19]. When the seat dip frequency is high, close to 200 Hz, the interference is positive below 100 Hz resulting in strong boost of really low frequencies, as seen in Fig. 6. The perceptual consequences of the seat dip effect are not yet fully understood, but it is sure that over 10 dB differences in the level of low frequencies occur between halls. When looking at Fig. 5 it is obvious that if the hall does not emphasize low frequencies there might be problems to hear bass instruments or they might sound weak.



Source: (Lokki et al., 2015, ref. [16])

Figure 6: Frequency responses (computed from indicated time windowed impulse responses) of four concert halls. The responses are averages of 24 source channels on stage and the receiver position is equally far away from the stage in each hall.

3.2 Concert hall acoustics and high frequencies

Material and air absorption change the high frequency content of the music in a concert hall. Moreover, frequency and level dependent features listed in Fig. 1 affect the loudness of high frequencies perceived by the listener.

At high frequencies all instruments are directional and therefore, e.g., the orientations of the instruments on stage are important. The direct sound is usually directed to the audience (instead of seats behind or on the side of the orchestra), optimizing the powerful high frequencies for the listeners. Reflections from walls, ceiling, and other elements have less high frequency energy. Nevertheless, reflections are perceptually important and therefore the direction of the reflections are important to give as much high frequencies as possible, as depicted in Fig. 3.

In addition, the real power in *fortissimo* comes from the higher harmonics [3], as shown in Fig. 2. If a hall attenuates these high frequencies too much, the dynamic range of the music is reduced and brilliance of high instruments is lost [6]. Therefore, the lateral early reflections are crucial for spatial and dynamical responsiveness of a hall [20]. One aspect, which requires more research, is the diffusors on the walls. They are often used to distribute the sound to a wider area, but they might also reduce the high frequencies in reflections [21].

4 Concert halls and music

Preference studies on concert hall acoustics have found out that the preferred halls sound warm, strong, proximate, and bright among other things [22, 23, 24, 25, 26, 27]. It is evident that the presented phenomena are related to these subjective perceptions. The warm sound requires enough low frequencies also below 125 Hz octave band, which is the lowest traditionally used. In our opinion, the 63 Hz octave band is really important for bass, and the lowest frequencies really make an impact on music. Brightness and brilliance is definitely related to high frequencies even up to the 8 kHz octave band. Again, a frequency region that is often ignored. Figure 5 also illustrates that both low and high frequencies are really important for large dynamics, which is evidently a key aspect for expressiveness in music. Large dynamics make music expressive and have impact on listeners, as recently shown with psychophysiological measurements [28].

We need to understand much better how the combination of orchestra, concert hall, and human hearing works together. The traditional path of explaining differences between halls exclusively with measured and modeled monaural parameters at mid frequencies is not sufficient.

Acknowledgments

This research has received funding from the Academy of Finland, project no. [257099]. In addition, I like to thank the whole Virtual Acoustics research team at Aalto University for their hard work.

References

[1] ISO 3382-1. Acoustics – measurement of room acoustic parameters – part 1: Performance spaces. International Standards Organization, 2009.

[2] J. S. Bradley. Contemporary approaches to evaluating auditorium acoustics. In Proc. AES 8th International Conference, pages 59–69, Washington, D.C, USA, May 3-6 1990.

[3] J. Meyer. Acoustics and the Performance of Music. Springer (New York), 2009.

[4] J. Pätynen and T. Lokki. Directivities of symphony orchestra instruments. Acta Acustica united with Acustica, 96(1):138–167, 2010.

[5] D. A. Luce. Dynamic spectrum changes of orchestral instruments. Journal of the Audio Engineering Society, 23(7):565–568, 1975.

[6] J. Pätynen, S. Tervo, P. W. Robinson, and T. Lokki. Concert halls with strong lateral reflections enhance musical dynamics. Proceedings of the National Academy of Sciences of the United States of America (PNAS), 111(12):4409–4414, 2014.

[7] T. Lokki and J. Pätynen. The acoustics of a concert hall as a linear problem. Europhysics News, 46(1):13–17, 2015.

[8] T. Lokki. Concert halls – conveyors of musical expressions. In Proceedings of the ICA 2016, Buenos Aires, Argentina, September 5-9 2016.

[9] H. Møller. Fundamentals of binaural technology. 36(3-4):171–218, 1992.

[10] H. Møller, M.F. Sørensen D. Hammershøi, and C.B. Jensen. Head-related transfer functions of human subjects. 43(5):300–321, 1995.

[11] ISO 226. Normal equal-loudness-level contours. International Standards Organization, 2003.

[12] J. Blauert. Spatial Hearing. The psychophysics of human sound localization. MIT Press, Cambridge, MA, 2nd edition, 1997.

[13] V. P. Sivonen and W. Ellermeier. Directional loudness in an anechoic sound field, head-related transfer functions, and binaural summation. 119(5):2965–2980, 2006.

[14] T. Lokki and J. Pätynen. Lateral reflections are favorable in concert halls due to binaural loudness. Journal of the Acoustical Society of America, 130(5):EL345–EL351, 2011.

[15] J. Pätynen. A Virtual Symphony Orchestra for Studies on Concert Hall Acoustics. PhD thesis, Aalto University School of Science, 2011.

[16] T. Lokki, J. Pätynen, S. Tervo, A. Kuusinen, H. Tahvanainen, and A. Haapaniemi. The secret of the Musikverein and other shoebox concert halls. In The 9th International Conference on Auditorium Acoustics, Paris, France, October 29-31 2015.

[17] T.J. Schultz and B.G. Watters. Propagation of sound across audience seating. Journal of the Acoustical Society of America, 36(5):885–896, 1964.

[18] G.M. Sessler and J.E. West. Sound transmission over theatre seats. Journal of the Acoustical Society of America, 36(9):1725–1732, 1964.

[19] H. Tahvanainen, J. Pätynen, and T. Lokki. Analysis of the seat-dip effect in twelve european concert halls. Acta Acustica united with Acustica, 101(4):731–742, 2015.

[20] A. H. Marshall. A note on the importance of room cross-section in concert halls. Journal of Sound and Vibration, 5(1):100 – 112, 1967.

[21] T. Lokki, J. Pätynen, S. Tervo, S. Siltanen, and L. Savioja. Engaging concert hall acoustics is made up of temporal envelope preserving reflections. Journal of the Acoustical Society of America, 129(6):EL223–EL228, June 2011.

[22] R.J. Hawkes and H. Douglas. Subjective acoustics experience in concert auditoria. Acustica, 24:235–250, 1971.

[23] G.A. Soulodre and J.S. Bradley. Subjective evaluation of new room acoustic measures. Journal of the Acoustical Society of America, 98(1):294–301, 1995.

[24] A.G. Sotiropoulou and D.B. Fleming. Concert hall acoustic evaluations by ordinary concertgoers: II, Physical room acoustic criteria subjectively significant. Acustica, 81(1):10–19, 1995.

[25] T. Lokki, J. Pätynen, A. Kuusinen, and S. Tervo. Disentangling preference ratings of concert hall acoustics using subjective sensory profiles. Journal of the Acoustical Society of America, 132(5), 2012. 3148-3161.

[26] A. Kuusinen, J. Pätynen, S. Tervo, and T. Lokki. Relationships between preference ratings, sensory profiles, and acoustical measurements in concert halls. Journal of the Acoustical Society of America, 135(1):239–250, 2014.

[27] T. Lokki, J. Pätynen, A. Kuusinen, and S. Tervo. Concert hall acoustics: Repertoire, listening position and individual taste of the listeners influence the qualitative attributes and preferences. Journal of the Acoustical Society of America, 140, 2016. In press.

[28] J. Pätynen and T. Lokki. Concert halls with strong and lateral sound increase the emotional impact of orchestra music. Journal of the Acoustical Society of America, 139(3):1214–122, 2016.