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Binaural dynamic responsiveness in concert halls

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ABSTRACT

The standard objective parameters aim to describe the linear effects of concert hall acoustics to an arbitrary excitation signal. However, neither the music signals from acoustic instruments nor the spatial hearing by the listener behave linearly. For instance, louder playing disproportionately excites higher harmonics more than harmonics near the fundamental frequency, resulting in a different tone color. Moreover, binaural directional hearing emphasizes high frequencies more when the sound arrives from the sides of the head rather than from the median plane. These premises lead to a hypothesis that the perceived dynamic range of identical performances varies between different concert halls. It is possible that concert halls that better convey musical dynamic changes would be preferred. This paper presents facts that contribute to the non-linear behavior in otherwise linear concert halls.

1 INTRODUCTION

Objective room acoustics is an essential part of the evaluation of the acoustics of performance venues. In practice, current evaluation methods are entirely based on the energetic inspection of the room impulse responses at frequency bands as proposed by the applicable standard[1]. The room impulse response is measured with equipment having preferably very linear responses with regard to output and recording levels.

Usually the room acoustics is examined as a linear process. However, both the music sources and human receivers are far from that. A natural instrument, not to mention a full symphony orchestra, behaves rather differently from a linear measurement sound source. Instead of high-quality microphones, the human receivers have a complex hearing system that reacts differently to directional sounds, and in an even more complex way to several copies of the original sound.

Combined effects with non-linear sources and non-linear receivers should be investigated carefully in order to have a more complete understanding on the perception of concert hall acoustics. Some published papers discuss room acoustics from the perspective of either binaural hearing or music signals, but very rarely with both of these aspects. More often, however, the room acoustic is considered to be comprised solely of the room impulse response, disregarding the non-linear effects altogether.

In this paper, the background is on a hypothesis that, not only the spatial effects, but also the dynamic range of performed music perceived by the listener is larger in some halls than in others.

This paper overviews briefly the effects and interactions related to the binaural dynamic responsiveness, including the sound of the orchestra and the binaural hearing. First, this article reviews earlier work related on these themes. Then, experiments employing existing data are presented before discussion and conclusions.

2 EARLIER RESEARCH ON RELATED TOPICS

During the past half a century, scientists and practitioners alike have learned from numerous studies that the decay rate of sound, for instance, is not the overriding objective parameter for describing the acoustic conditions in concert halls. Instead, much of the research interest has been redirected toward the directional analysis of the early sound field. Lateral early reflections have been found to increase the subjective sense of spaciousness[2], and also objective binaural loudness[3].

Standardized strength parameter *G* indicates the omnidirectional point-to-point amplification in an enclosure at the receiving position. However, it neglects the direction of the incident sound for which human hearing is sensitive. The sound direction is perceived based on the binaural cues. The distance between the ears and the curvature of the head delay the signal to the contralateral ear causing time differences. Also, the shape of the pinnae as well as the shadowing effect of the head cause inter-aural level differences between ears and alter the frequency response depending on the direction of the arriving sound[4]. For a sound arriving at both ears, summation of sound level is calculated with specific equations[5]. Clearly, the binaural gain differs from the traditional omnidirectional gain. Despite the major difference between sound amplification in omnidirectional and binaural conditions, not many papers have linked binaural loudness with concert hall acoustics, or the interaction between binaural loudness and spatial aspects.

Subjective effects of lateral sound energy were closely studied by Barron[6] in 1971 and Barron and Marshall[7] in 1981 . Conclusions from experiments with variable reflection levels and delays were that a higher amount of early lateral energy increases the spatial impression. The results eventually led to the lateral energy fraction measure (LEF). Although Barron and Marshall briefly discuss the effect of listening level, they concentrated on analyzing the effects of direct-to-reflection level ratio.

One of the seminal papers on the combined effect of lateral sound and the absolute sound level was published by Keet[8]. He connected the terms spatial responsiveness and apparent source width (ASW) with results from listening experiments that there is a relationship between ASW and the absolute presentation level of the signal. A decade later, a principal publication on the subject was presented by Kuhl[9]. Along with a wide range of reviewed literature, the paper presented experiments where orchestral music was played from a loudspeaker on stages of six concert halls. The level of spaciousness was studied in relation to, not only the early energy in binaural impulse responses, but also with artificially modified sound level. The results show a linear increase in the spatial impression index along the rising sound pressure level.

Morimoto and Iida have otained similar results[10] in studies of ASW. They used binaural sound pressure levels and inter-aural cross correlation (IACC) for determining absolute levels. Their findings suggest that in subjective ASW, a 2.6 dB rise in A-weighted binaural sound pressure level equals to an increase of 0.1 points in the (1-IACC) index. These results have been later discussed by Marshall and Barron in a review of the preceding work on spatial impression[2].

Using a slightly different perspective, Blauert and Lindemann have studied spatial effects of sound fields with low and high-pass filtered reflections[11]. They found out that the broadening of auditory image occurs only if early lateral reflections contain frequencies above 3 kHz. The frequency-dependency had been also brought up by Barron and Marshall[7] (Fig. 19), citing that low or high-frequency lateral reflections produce different spatial effects, namely envelopment and source broadening.

In the earlier studies the change in spatial impression with binaural sound level has been achieved by artificially altering the presentation level of the stimuli. A real orchestra, however, does not work linearly. Instead, the playing dynamics drastically change the sound spectrum. Dynamics being one of the principal expressive effects in Classical and contemporary orchestral music[12], it can be thought of as a separate, yet fundamental dimension in the musical information along pitch and timbre. On this basis, conveying the dynamic information to the listener unimpaired should be of paramount importance.

A recent study with subjective evaluation of nine halls suggested that there are aspects in the acoustic conditions that cannot be explained by the standardized objective parameters[13]. These factors include descriptors such as intimacy or proximity. Since the perception of detail in sound or image can be thought to relate to the distance of the communication, it is possible that increased detail, or dynamic range in music, corresponds to intimacy. Notably, proximity tends to drive strongly the overall subjective preference of acoustics[13]. Therefore the overall topic is a highly interesting area of research.

3 DYNAMICS, BINAURAL HEARING, AND EARLY REFLECTIONS

An overview of the earlier research points out that a majority of the work has concentrated on studying the subjective effects of changing the parameters of the early reflections or the presented signal. The following sections present analyses on dynamic responsiveness of the symphony orchestra and spectral sensitivity of the binaural directional hearing. Last, temporal development of the directional energy is visualized with examples of measured concert halls.

3.1 Dynamic spectral changes in orchestral music

A general effect with higher playing dynamics is the intensification of the instrument sound. With regard to the topic of this paper, an even more important phenomenon is the non-linear increase in the overall spectrum. With most orchestra instruments, the higher harmonics are excited more with a more forceful playing style. The degree of the emphasis at higher harmonics depends on the instrument, and it is the strongest with brass instruments. This effect is well-known, and it has been demonstrated for individual instruments e.g. by Luce[14] and Fabiani[15]. Meyer[16] (p. 317) has presented an octave-band analysis of orchestra performance during a recorded crescendo. However, a precise overall dynamic spectral change for a full orchestra is not found in the literature. Next, such a study is presented briefly.

Analysis of spectral effects in symphony orchestra playing dynamics is given in Fig. 1. First, the spectrum of the radiated sound energy in three instructed dynamics (*p*, *f*, and *ff*) is calculated from the anechoic orchestra instrument measurements[17]. Two octaves of A-major triads were recorded with all instruments. Hence, the effect of the dynamics is captured equally for all instruments. The overall effect is obtained by summation of the instrument spectra in respective numbers of instruments in a typical symphony orchestra. Consequently, the analysis represents the dynamic effect of the whole orchestra. These results are shown in Fig. 1a. It should be noted that instead of the principal region of directivity commonly used when recording orchestras, the power response data is averaged from measurements around the instruments.

Second, similar analysis is performed with a publicly released record of orchestral music. A prominent challenge using orchestral music is that the played notes should not change much with the

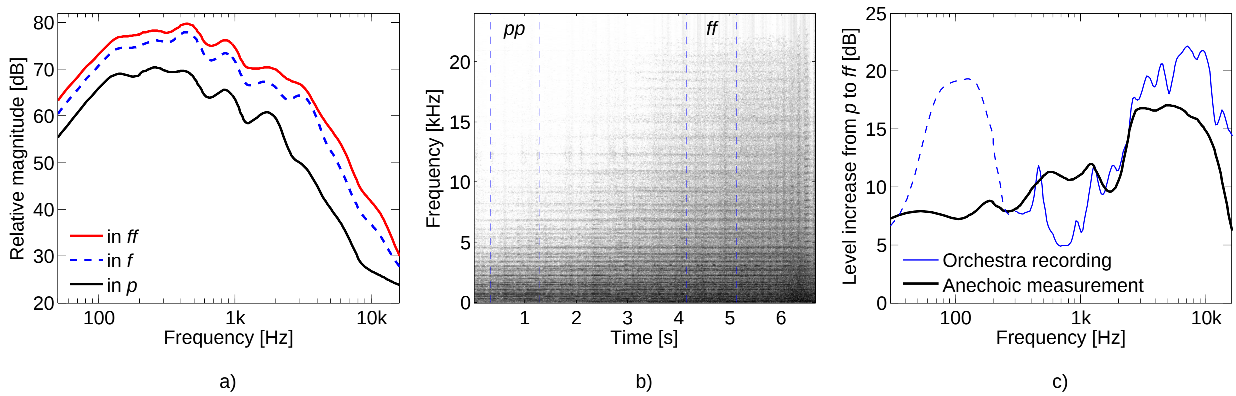

Figure 1: Analysis of the orchestra spectrum with regard to the playing dynamics. a) Mean power responses of symphony orchestra instruments recorded with three dynamics in an anechoic chamber. b) Spectrogram from a publicly released orchestra recording with a crescendo. Darker shade indicates more sound energy. c) Comparison of frequency responses with regard to dynamics. Thick solid line is the difference between *p* and *ff* curves in Fig. 1a. Thin solid line shows the difference between selected segments in Fig. 1b. One-third octave smoothing is applied to plotted curves.

dynamics. A suitable passage is found in, for instance, the third movement of Bruckner's Symphony no. 4, where a long crescendo is played with fairly constant pitches throughout the score. Figure 1b shows a spectrogram of eight bars of *tutti* crescendo, and two selected segments of the passage in two dynamics. The spectrogram indicates a clear increase of high frequencies along the crescendo.

The results from both analyses are compared in Fig. 1c, where it is seen that the general shape of the orchestra recording curve corresponds to the laboratory measurement. While the curves in Fig. 1a seem to be nearly identical visually, the subtraction reveals that in comparison to low frequencies, the magnitude above at mid frequencies (400-2k) or above 2 kHz increase by factors of 1.5 and 2.0, respectively. The low frequency emphasis in the orchestra recording is most likely due to an intensifying timpani tremolo. Using the data from the principal radiation directions instead of power responses, the dynamic spectral responsiveness would match the orchestra recording at high-frequencies even better.

3.2 Directional hearing

It is a well known effect that the frequency content entering the ear canals depends on the direction of the incident sound. The shading of the head, shapes of the pinnae, and the reflections from the listeners body cause alterations in the HRTFs. Along many other effects, one prominent effect is the emphasis of the high frequencies at the ear on the same side that the sound is arriving from. This information was recently applied for showing the benefit of having a higher binaural loudness in such experimental concert hall geometries that provide lateral early reflections[3].

Here the phenomenon of the increased binaural loudness over frequencies is visualized with the HRTF measurements in the CIPIC database[18] in the manner of Lokki et al.[3]. Calculation of the binaural frequency response $L(\theta, \phi, f)$ for single azimuth θ and elevation angle ϕ employs equations for binaural loudness[3,5]:

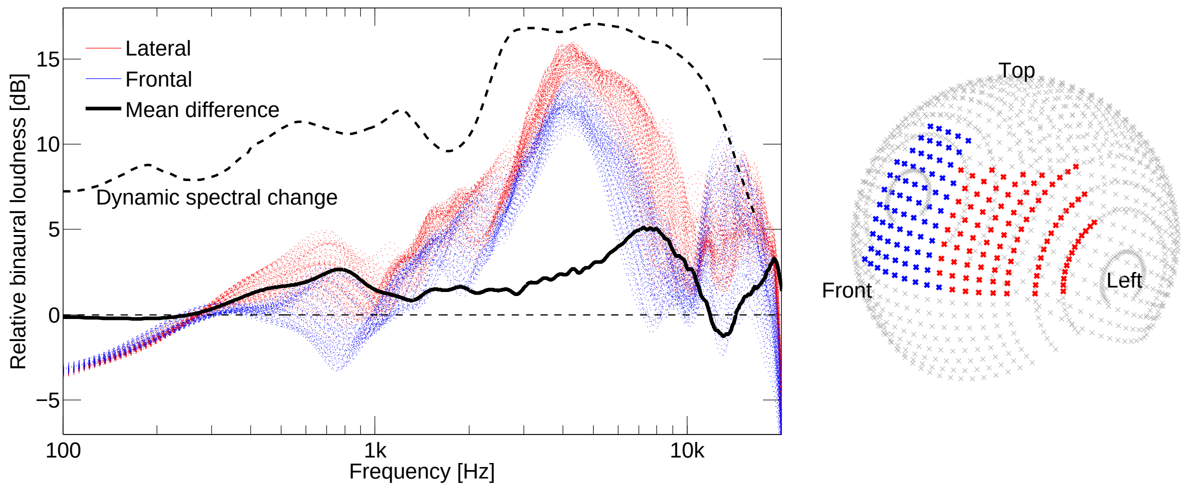

Figure 2: Comparison of the binaural loudness at frontal and lateral directions using mean of CIPIC HRTF database. (Left panel) Binaural loudness in selected angles with the difference between the average loudness in frontal and lateral regions. The curve for dynamic spectral change is the same as in Fig. 1c. (Right panel) Regions for frontal and lateral angles in the CIPIC measurement angles.

$$L(\theta,\phi,f) = g + log_2\left(\sum_{l,r} 2^{H^{(s)}_{l,r}(\theta,\phi,f)/g)}\right), \tag{1}$$

where

$$H^{(s)}_{l,r}(\theta,\phi,f) = 10log_{10}\left(\frac{1}{N}\sum_{s=1}^{N}\left|\mathcal{F}\{h^{(s)}_{l,r}(\theta,\phi,t)\}\right|^2\right). \tag{2}$$

The CIPIC subject is denoted by s. Binaural gain factor[5] g =3 dB. Data is averaged over N =45 human subjects in the database. $h_{l,r}$ and $\mathcal{F}$ denote a pair of head-related impulse responses for the left and right ear, and Fourier transform, respectively.

Figure 2 demonstrates the comparison of the binaural loudness over frequencies in a group of incident angles at the front and side. The right-hand side panel shows the regions of selected angles with different shades representing the frontal and side directions. The respective curve clouds for frontal and side binaural loudness are plotted in the left-hand side panel with respective shades. The difference of the curve cloud averages is shown with the thick line. It is rather evident that the binaural loudness at high frequencies benefits from the reflections from the side, as proposed by Lokki et al.[3]. It is noteworthy how well the shape of the dynamic spectral change of the orchestra sound (from Fig. 1c) follows the lateral binaural gain increase at high frequencies, and the general shape binaural frequency response.

3.3 Early reflections in concert halls

World-renowned concert halls have been measured on several instances by various research teams during the past decades. However, most of the published data is presented as standardized objective parameters[19] that obscure the detailed acoustic features in the halls.

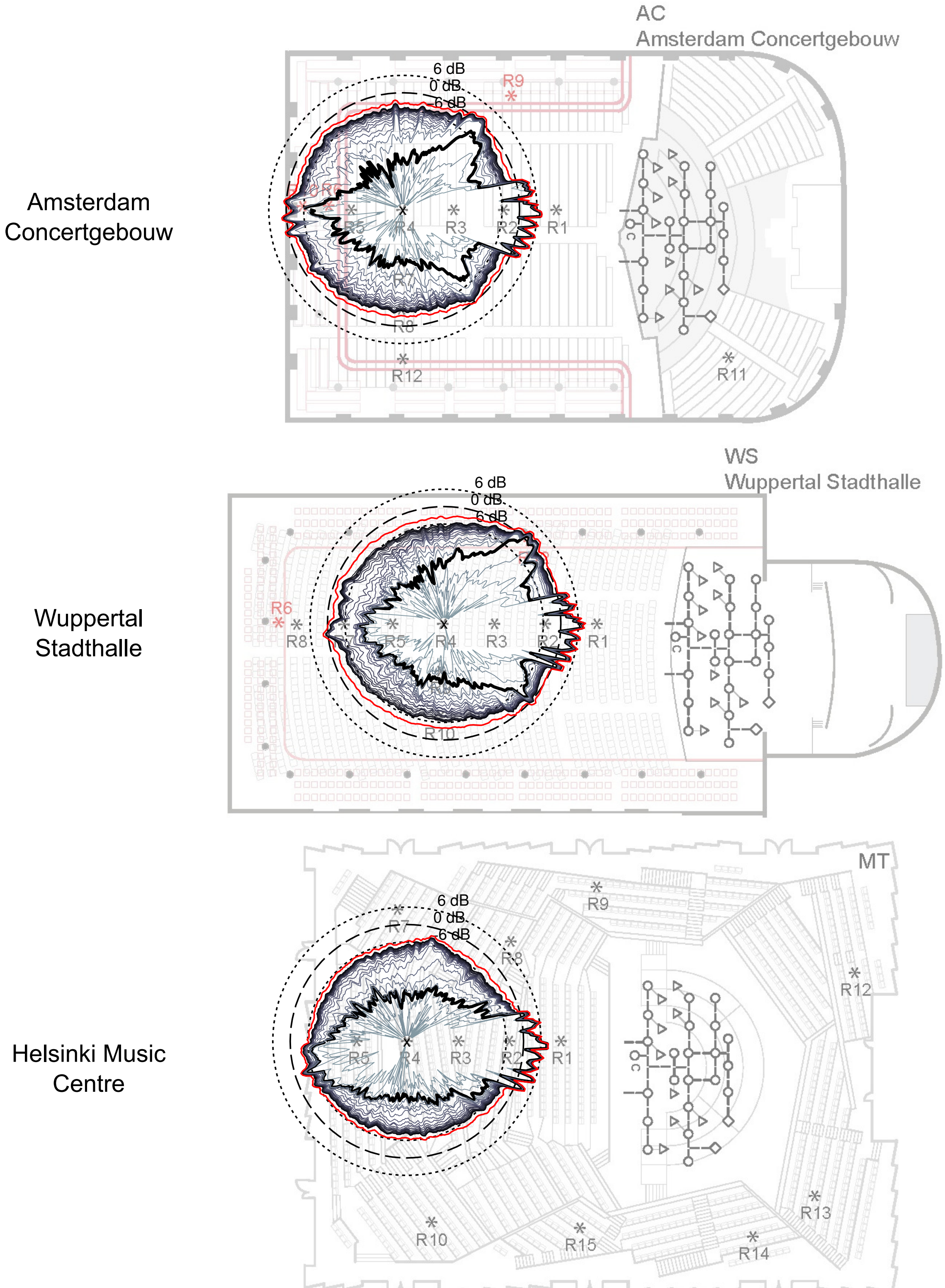

Figure 3: Spatio-temporal analysis from three halls. Receiver distance in each hall is 19 meters from the front line of the loudspeaker orchestra. The bold black curve indicates the wide-band cumulative spatial energy distribution at 30 ms after the initial direct sound.

Selected measurement results from concert hall measurements with the loudspeaker orchestra are presented in the following using spatiotemporal visualizations. A detailed description of this method is given by the present authors[20]. In short, the expanding polar curves indicate the energy in each direction cumulating over time, averaged over all 25 source channels on stage. The innermost curve shows the energy distribution in the direct sound (first 5 milliseconds). The next curves outside that show the distribution within increasing time steps of 10 ms up to the 200 ms. Thus, the inner thick curve visualizes the spatial energy distribution after the first 30 ms in the room impulse responses. The outermost red curve represents the final lateral energy distribution of the full impulse response.

Figure 3 demonstrates the development of the spatial energy distribution in the lateral plane in three concert halls. Measurement distance of 19 m from the front line of the loudspeaker orchestra is kept constant. Two topmost diagrams show the analysis from shoebox halls of different widths, and the bottom diagram is from a measurement of a vineyard-design hall with a raked audience area. By comparing the energy distribution after 30 ms (thick black curve), it can be noticed that the effect of early reflections from the sides is prominent in shoebox halls. Due to the larger width of Amsterdam Concertgebouw, the early reflections continue arriving approximately 20 ms later than in the narrower Wuppertal Stadthalle. In contrast, the geometry in the bottom hall does not provide noticeable early reflections to the current receiver position. In general, the total energy from the sides tends to be 3-5 dB higher in the shoebox halls.

4 DISCUSSION

The experimental analysis confirms that the spectral response of a full orchestra is not linear with respect to the playing dynamics. A study on the anechoic instrument recordings suggests that the high frequencies are emphasized prominently compared to lower frequencies. It is probable that the presented data underestimates the true dynamic spectral response for two reasons. First, the measured instrument spectra were from the power responses, that is, averaged from all directions around the source. Most orchestra instruments have a primary region of directivity at higher frequencies. Thus, a similar analysis for data e.g. from the frontal hemisphere would increase the high-frequency content a higher dynamics. Second, playing in anechoic conditions do not allow the performer to fully exploit the dynamic range of the instrument. Consequently, the quieter dynamics in natural playing conditions have potentially even more low-pass filtered characteristics. In general, the current estimates for dynamic responsiveness corresponds roughly to the frontal measurements of individual instruments in the literature[14]. By coincidence, the band of the largest spectral change occurs at the same frequencies at which the early reflections have been found to produce the most spaciousness and preference[11].

Binaural loudness results indicate that early reflections arriving from the side emphasize frequencies where the non-linearity in the dynamic spectral responsiveness are the highest in the orchestra sound. With respect to the direct sound or a ceiling reflection, the gain at the frequency band of the highest dynamic spectral change is approximately 2-5 dB. The given example, however, shows the situation in only a single side reflection. In concert halls with rectangular geometry, parallel side walls provide first-order lateral reflections from both sides. The binaural loudness with nearly symmetric side reflections is left for future research. Still, one could predict that the combined effect of two lateral reflections is higher than shown for one reflection. In addition, classical shoebox-type halls are shown to exhibit early lateral second-order reflections from the under the side balconies[21]. On the other hand, it does not seem to be difficult to find more positions that provide even less early lateral energy in vineyard halls[21].

The original hypothesis of binaural dynamic responsiveness was experimented with informal listening. The experimental results from the test suggests that the contribution of early reflections to perceived loudness is different depending on the music dynamics. Hence, the dynamic range of loudness seems to be wider when early reflections are present. This gives some tentative base for the proposed effect of binaural dynamic responsiveness.

The directional analysis from three measured concert halls points out the lateral sound differences encountered in actual performance spaces. Given the differences in the early sound fields between a vineyard hall and shoebox halls, it is evident that the spaces convey the important high-frequency band of the orchestra dynamics differently (see Fig. 3), provided that the surface materials are equal. The amount and spatial distribution of early sound energy alone suggests that the halls differ also by their spatial impression, as cited in the literature on the Amsterdam Concertgebouw[6,19].

The aspect of auditory masking has been intentionally left outside the scope of this paper. Nevertheless, it is an important part of the binaural perception, as many non-linear masking phenomena contribute to the general topic[22].

5 CONCLUSIONS

This paper has presented preliminary research on the hypothesis of binaural dynamic responsiveness. The authors claim that in concert halls with favorable geometry the perceived dynamic range of sound level in the music performance is expanded due to interaction between non-linearities in the source signal and spatial binaural hearing. The results from the analyses on anechoic instrument measurements and orchestral music recording, HRTF database, and concert hall measurements indicate that the frequency region with the most changes with music dynamics is affected by the binaural directional frequency response.

Earlier research has studied early lateral reflections in detail, and the desired qualities in concert halls advocate for the already-known spatial benefits of lateral reflections. In addition, the advantages of lateral reflections extend potentially much further. The dynamic spectral effects are believed to have a much more significant part in overall acoustic impression than previously thought from the results of experiments with linear presentation level changes. This research area calls for more attention in the future, formal listening tests in addition to present topics in order to study the binaural dynamic responsiveness in detail and showing that at higher music dynamics the loudness-increasing effect by the lateral reflection is emphasized.

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