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Analysis of the Seat-Dip Effect in Twelve European Concert Halls

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Summary
The effect of low-frequency attenuation due to seats is measured with a loudspeaker orchestra in twelve European concert halls and studied with the help of time-frequency and spatiotemporal analysis methods. The methods show consistent results with previous findings on the seat-dip effect and offer further explanations to the attenuation bandwidth and correction. The attenuation bandwidth is found to depend on the floor inclination and seat design. In addition, the spatiotemporal analysis shows that uniform accumulation of spatial energy is beneficial for the correction of the seat-dip effect. This implies that contrary to previous suggestions, no distinct ceiling or lateral reflections correct the seat-dip effect. The shoebox-shaped halls seem to provide more reflections from all directions compared to other hall shapes.

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1. Introduction

As sound travels across a concert hall, it attenuates due to spherical spreading, and at high frequencies also due to air absorption. Additionally, sound travelling at near-grazing angles over the seats (below 15° or so) undergoes an excess attenuation at low frequencies, known as the seat-dip effect [1, 2]. The effect is prominent in the direct sound.

Although the effect is present in all auditoria with seats, no disturbing lack of bass in concert halls has been reported before the discovery of the effect in the New York Philharmonic Hall in 1964 [3]. In fact, many concert halls built prior to that have a rectangular shape that is generally characterised with a rich bass in the stalls [4]. Recent psychoacoustic research suggests that the initial seat-dip effect may even be beneficial for the perception of bass given that the lack of bass in the direct sound is compensated by later arriving sound that contains the bass [5, 6]. This phenomenon is referred to as the seat-dip recovery or correction. The recovery and perception of the seat-dip effect have gained less attention than the study of its origin and elimination in previous research.

An additional shortcoming in the research on the seat-dip effect is related to the assessment of the effect. Namely, concert halls are analysed objectively with measurements that lead to many room acoustic descriptors listed in the ISO 3382-1:2009 standard [7] such as reverberation time and strength. As the parameters span several octave bands and generally discard octave bands below 125 Hz, they tend to describe the seat-dip effect and its recovery inadequately [8, 9]. Furthermore, the source positions on stage are typically sparse while measuring. Recently, Pätynen *et al.* [8] presented loudspeaker orchestra measurements and complementary analysis methods that provide more details than standard measurements and room acoustic descriptors on the the recovery and the seat-dip effect in general.

This paper further applies the time-frequency and spatiotemporal methods presented in [8] for assessing the seat-dip effect in concert halls. Measurements with a loudspeaker orchestra in twelve European concert halls are analysed with a particular focus on the recovery of the seat-dip effect. The first part of the paper verifies the new analysis methods by comparing the results to existing literature on the seat-dip effect. Furthermore, the width of the seat-dip attenuation is linked with the seat type and floor inclination. The second part of the paper analyses the recovery of the seat-dip effect which is mostly influenced by the concert hall geometry. The results show that early reflections arriving uniformly at all directions are beneficial for the recovery.

2. Background

Important parameters that describe the seat-dip effect include main attenuation frequency, bandwidth, and initial attenuation magnitude. The main attenuation dip lies between 80–300 Hz, and the attenuation bandwidth can extend up to 1 kHz [1, 2]. The excess attenuation develops within a few milliseconds after the direct sound, and it can initially be as strong as −20 dB [10, 11].

The mechanism of the seat-dip effect can at least qualitatively be predicted from scattering over a periodic struc-

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ture and considering the seating area as an absorbing layer over a rigid floor [12]. The origin of the main attenuation dip can be described in both frequency- and time-domain. In the frequency-domain, the main attenuation dip is considered to occur due to a vertical resonance between the seats defined by the seat height [2]. However, the resonance model fails to explain the time-varying behaviour of the seat-dip effect [11]. In the time-domain, the main attenuation results from the destructive interference between direct sound with diffraction from the seat backrests reflected off the floor between the seats [10, 13]. Hence, the seat backrest height corresponds to a quarter wavelength of the main attenuation frequency [14]. Furthermore, additional diffraction from the seat backs extend the attenuation up to 1 kHz. In essence, the main attenuation frequency depends on the seat height and whether the seats have underpasses (open seats) or not (closed seats) [12].

The seat-dip effect has been investigated for over 50 years [1, 2] and the studied properties include: seat height [1], receiver and source position [1, 2, 14, 15, 16], audience [2], azimuth and elevation angles of incidence [1, 14, 15, 17], absorption of seats and the floor [11], seat upholstery [18], and seat underpasses [2, 13, 15, 19]. In addition to measurements in concert halls, the seat-dip effect has been studied with scale models [1, 11, 14], various numerical methods [11, 16, 20, 21], and room acoustics modelling methods, such as the finite-difference time-domain method (FDTD) [19, 22].

Various suggestions have been made to reduce the seat-dip effect. Solutions, such as raked floor [1, 2], resonant absorbers between seats [5, 16], and pits under the seats [11], focus on removing the effect altogether. Although not entirely successful in eliminating the effect, these solutions can still control the frequency and level of the attenuation. It has also been suggested that the seat-dip attenuation could be masked by increasing the reverberation at low frequencies [2, 23], but reverberation time seems to have little influence on the perceived strength of bass [24] or the threshold of perception of the low-frequency attenuation [5].

More importantly, strong early reflections have been found to remedy the seat-dip attenuation [8, 14, 25] and to increase the perceived strength of bass [26]. Bradley [14] proposed strong ceiling reflections to correct the attenuation; however, these reflections may colour the sound [5]. Furthermore, according to Pätynen et al. [8] ceiling reflections arrive typically before the seat-dip attenuation is corrected. Subsequently, Pätynen et al. concluded that halls providing distinct lateral reflections best correct the seat-dip attenuation.

The above-mentioned studies on the recovery of the seat-dip are related to the objective correction of the frequency response over time. The objective analysis and the perception of the seat-dip effect have been linked in a few occasions. The effect is generally considered to hamper the audibility of bass [14, 27]. Barron and Marshall [28] observed that spatial impression is reduced in the presence of lateral reflections that include the seat dip attenuation.

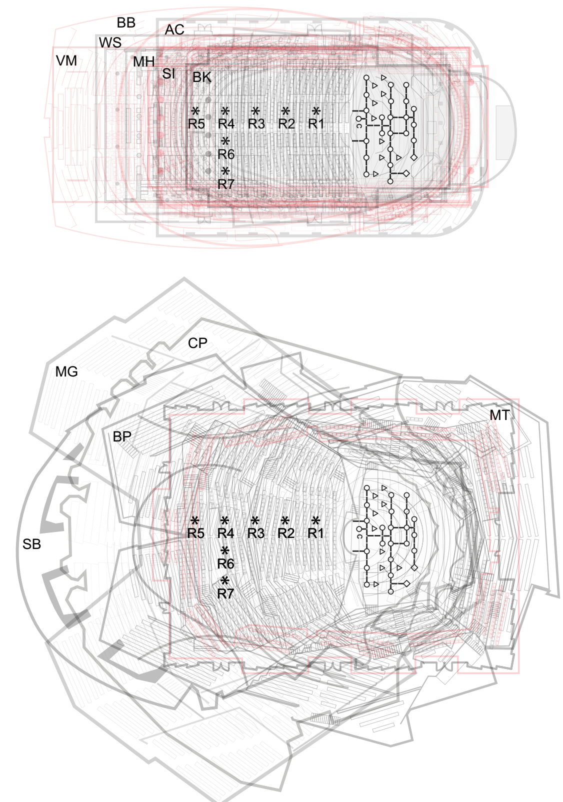

Figure 1. The plans of the studied concert halls superimposed according to hall type with the loudspeaker orchestra measurement set-up and the receiver positions R1-R7 illustrated. The front position labelled by *C* represents the conductor.

Davies et al. [5] obtained a threshold of audibility for the seat dip to be −3.8 dB in the 200 Hz octave band of the early energy over 0 to 80 ms. Recently, Walther et al. [6] hypothesised that more bass may be perceived when direct sound lacks bass and the early reflections retain it. Moreover, halls with a lower main attenuation frequency seem to have a lower perceived level of bass compared to halls with a higher attenuation frequency [29].

3. Methods

3.1. Measurements

Twelve concert halls around Europe were measured unoccupied using a loudspeaker set-up that simulates a symphony orchestra [30]. The measured concert halls with their geometrical and seat properties are listed in Table I. Seven receiver positions were chosen so that the distance between the conductor position and the microphone probe was fixed in all halls (7, 11, 15, 19, and 23 m, and 4 and 8 m to the right at the distance of 19 m). The conductor position *C* and the receiver positions R1-R7 are shown on the hall plans in Figure 1. In a few halls R6 and R7 were not measured.

The loudspeaker orchestra consisted of 34 two-way loudspeakers (Genelec) set on stage to closely approxi-

Table I. The properties of the measured concert halls. S Shoebox, C Curved shoebox, F Fan, V Vineyard.

Abbr.	Name	Hall type	Floor type	N seats	Seat upholstery	Seat backrest height (cm)	Seat underpass (cm)
AC	Amsterdam Concertgebouw	S	flat	2040	heavy	65	19
MH	Munich Herkulessaal	S	flat	1300	light	58	28
VM	Vienna Musikverein	S	flat	1700	very light	69	21
WS	Wuppertal Stadthalle	S	flat	1500	very light	40	40
BK	Berlin Konzerthaus	S	flat	1600	very light	56	37
BB	Brussels Palais des Beaux-Arts	C	flat	2150	quite heavy	57	24
SI	Lahti Sibeliustalo	C	raked	1250	quite heavy	55	15
SB	Stuttgart Beethovenhalle	F	flat	2000	very light	43	42
CP	Cologne Philharmonie	F	raked	2000	light	75	30 (blocked)
MG	Munich Gasteig	F	raked	2400	heavy	67	15 (blocked)
MT	Helsinki Musiikkitalo	V	raked	1700	quite heavy	67	33 (blocked)
BP	Berlin Philharmonie	V	raked	2200	quite heavy	70	closed

mate the position and directivity of the symphony orchestra instruments [30]. The configuration is superimposed on the hall plans in Figure 1. The measurement set-up deviates from that of the ISO 3382-1:2009 standard which enforces the use of omnidirectional sources for concert hall measurements and defines sparse source positions on stage [7]. However, there are few reasons why the seat-dip effect measured with the loudspeaker orchestra corresponds quite accurately with the seat-dip effect obtained in actual concert situations. First, the study of the seat-dip effect benefits from averaging several sources, since the effect depends strongly on source and receiver location. Second, measurements show that the applied Genelec loudspeakers can be considered omnidirectional below 1 kHz [8]. Finally, the differences in measured total sound energy between concert halls are of a similar magnitude independent of whether a real orchestra or the loudspeaker orchestra is employed [30].

The loudspeakers were connected to 25 source channels, thus nine channels combined two loudspeakers together. This was done to better approximate the directivity of the string instruments [30]. A swept sinusoidal excitation with sampling rate of 48 kHz was played from each source channel and the responses were recorded with a six-channel intensity probe (G.R.A.S. Type 50 VI). The topmost microphone used in the monaural analysis was set to 1.15 m above the floor, which represents the height of the ears of the average seated listener.

3.2. Analysis

The measurements were analysed with recently developed spatiotemporal and time-frequency visualisation techniques, so far applied for studying the seat-dip effect in Finnish concert halls [8]. These techniques were particularly successful in the analysis of the seat-dip recovery, and its connection to hall geometry. For the analysis, the frequency responses of all sources were averaged at one receiver position in order to achieve a more realistic representation of an orchestra. Such averaging yields visually smoother spatial responses and reveals more general results that more easily interpreted [8].

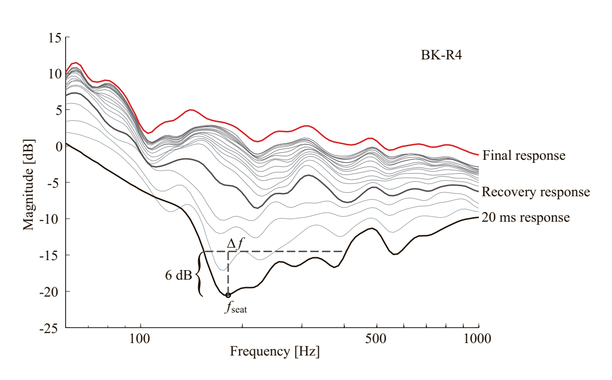

Figure 2. Illustration of the time-frequency visualisation and the definitions of terms used in this paper in Berlin Konzerthaus at receiver position R4 (BK-R4). The final frequency response is computed at 2 s and is scaled to correspond to the standard G-values. The thin grey lines represent the 10-ms increments in the time window, so it can be seen that in this case the recovery time is 60 ms.

In the time-frequency visualisation, the monaural impulse response is first windowed with a rectangular window function starting at the arrival of the direct sound at increasing 10-ms time steps and then transformed by the discrete Fourier transform. In this way, the cumulative energy of the impulse response can be studied simultaneously in both time- and frequency-domain. A rectangular window was chosen for simplicity, because using time windows with varying fade-in and fade-out times (such as Hamming or Hann) yielded negligible differences in the frequency responses (±0.2 dB) [8]. The frequency response over the full impulse response, i.e., the final response, was scaled to correspond to standard strength G -values, computed in the free field at the distance of 10 m.

The spatiotemporal visualisation, on the other hand, adds information on the accumulative distribution of sound energy at the measurement location. In this case, the directional analysis was performed using the unconstrained least-squares solution of the time-difference-of-arrival estimates between the microphones in the probe, as presented by Tervo *et al.* [31].

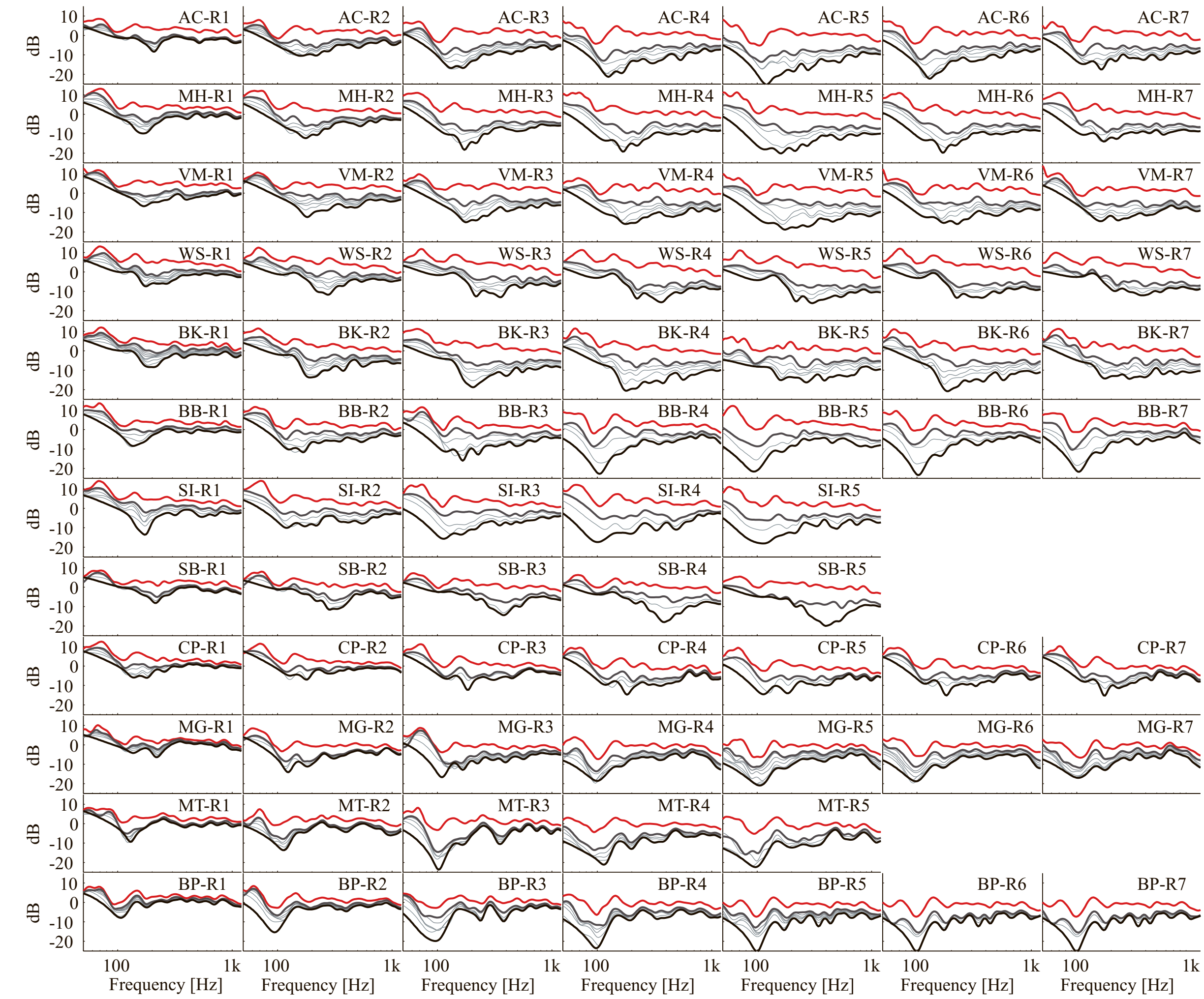

Figure 3. Time-frequency responses of the analysed concert halls scaled to correspond to the standard strength G values. The 20-ms time window is plotted with a black line, and the thin grey lines refer to the 10-ms increments in the time window. The bold grey line denotes the recovery time window. The red curve refers to the final frequency response. The frequency responses were 1/3-octave smoothed.

An example of the time-frequency visualisation is plotted in Figure 2. The applied time window starts at 20 ms, by which the seat-dip attenuation has already developed. This is plotted as the bold black curve. The grey curves denote the 10-ms increments to the time window. The recovery response (bold grey) is defined as the time frame when the magnitude at the maximum attenuation frequency f_{seat} has its maximum increase compared to the magnitude at 80 Hz. Quantifying the recovery imposes challenges due to the wide extend of the recovery and the non-linear recovery rate. Here 80 Hz was chosen as a reference, as the flatness of the low frequency response was of interest. Other possible definitions for the recovery time are listed in [8].

The final frequency response is computed over the full impulse response with a time window of 2 s at the receiver position. In addition, the terms illustrated in Figure 2 comprise the maximum attenuation frequency of the seat-dip effect f_{seat}, attenuation bandwidth Δf measured at 6 dB above the maximum attenuation, and Q-value, which is defined as the ratio $f_{seat}/\Delta f$. A higher Q-value indicates a narrower attenuation around the frequency of the maximum attenuation, and it can thus be used to quantify the attenuation bandwidth.

4. Comparison to previous results

4.1. Distance and angle of incidence

The time-frequency development of sound energy in the measured concert halls at the receiver positions around the stalls is shown in Figure 3. It is notable that at all positions the seat-dip effect has emerged by the first 20 ms. The main attenuation frequency f_{seat} generally lies between 100-200 Hz, with two exceptions: WS and SB. The seats in both halls are removable, light-weight chairs with high underpasses that seem to cause very little seat-dip attenuation. In WS at the closest receiver positions R1 and R2, the main attenuation dip occurs around 200 Hz but at the farther receiver positions, defining an attenuation dip becomes difficult. In SB, the dip occurs at around 400 Hz, which is considerable higher than in the rest of the halls. Rather than being related to the seats, the dip in SB is more likely caused by floor reflections since most receiver positions are located on the aisle rather than between the seat rows.

Previously, it has been shown that increasing the source-receiver distance increases the attenuation, but has a little effect on the maximum attenuation frequency [1, 2]. The present measurements confirm both results. First, Figure 3 shows that the attenuation frequency shifts with distance only in a few halls. Second, Figure 4 shows how the magnitude of the excess attenuation at 20 ms generally decreases with distance in the studied concert halls, when the spherical spreading loss $1/r$ has been compensated. In some concert halls such as CP and WS, the attenuation magnitude after distance compensation shows a positive value due to the fact that the 20-ms time window contains first reflections from the floor, stage, and/or back wall in addition to the direct sound.

Additionally, closer to the source the excess attenuation varies less between halls than farther from the source, and this is due to geometrical differences between the halls. In some halls, the farthest receiver position (23 m) is located under the balcony or close to a booth wall; thus the attenuation does not necessarily follow the decreasing trend. With the measurements at the farthest receiver position excluded, the excess attenuation correlates relatively highly with distance (correlation coefficient $\rho = 0.54$). Application of the Kruskal-Wallis test verifies the presupposition; the excess attenuation at f_{seat} depends significantly on the distance ($H(3) = 12.93, p < 0.005$).

The maximum attenuation frequency f_{seat} has previously been found to decrease with increasing vertical (elevation) angle of incidence [2, 14]. This means the angle between the arriving sound and the plane formed by the tops of the seat backs. Similarly, among the studied concert halls f_{seat} depends significantly on whether the floor is raked or not ($H(1) = 24.22, p < 0.001$) and thus on the vertical angle of incidence. More specifically, at R2-R7 in SI, CP, MG, MT, and BP, and at R4-R7 in BB, the vertical angle of incidence increases due to the raked floor, and the f_{seat} at those positions occur at the low end of attenuation frequency range, at around 100 Hz. However, the low f_{seat} may occur due to both increased vertical incidence angle and increased seat back height, as the stepwise-raked floor partially blocks the seat underpasses. This is discussed in the following section.

In addition to the vertical angle, a slight rise in the maximum attenuation frequency has been observed with decreasing the horizontal (azimuth) angle of incidence [2, 14]. In the present study, no such effect can be observed when comparing receivers R4 and R6-R7 located on a horizontal line, and this is probably due to averaging many source positions on stage.

As a matter of fact, most features of the seat-dip effect have previously been measured with one or few source positions on stage. However, averaging many source po-

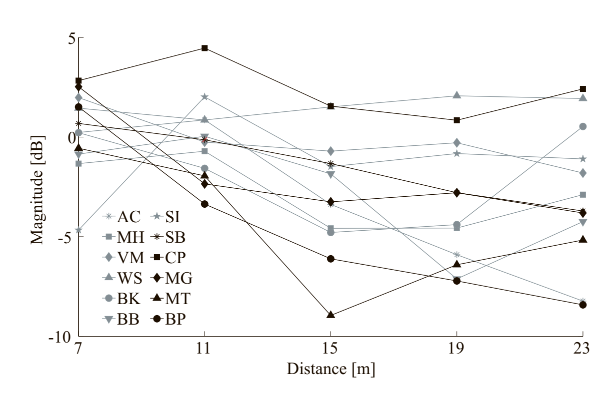

Figure 4. The magnitude of excess attenuation due to the seat-dip effect at 20 ms for all measured concert halls when spherical spreading loss $1/r$ is compensated. The shoebox-shaped halls are depicted with grey lines and non-shoebox-shaped halls with black lines. The attenuation magnitude decreases with distance.

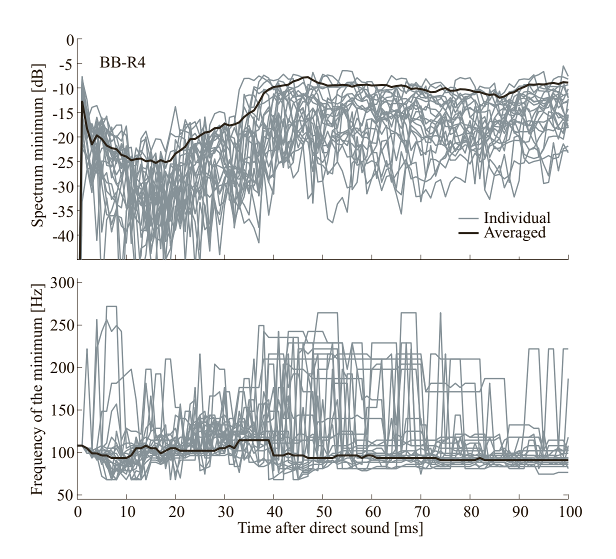

Figure 5. The difference between measuring the seat-dip effect with individual sources (grey curves) and with sources averaged (black curve) at 1-ms increments after the direct sound in BB at receiver position R4. The plot on the top shows the magnitude of the spectrum minimum and the bottom plot shows the frequency at which the minimum occurs. The frequency responses were 1/12-octave smoothed.

sitions on stage diminishes the seat-to-seat variance of the seat-dip effect, and may thus yield perceptually more relevant results, as real concerts involve more than one source. An example of the comparison between 24 individual sources and the average of the sources is provided in Figure 5, which shows the magnitude of the spectral minimum and its frequency at 1-ms increments after the direct sound. The analysis is similar to that of Davies *et al.* [13]. The individual responses depend quite strongly on the source position, and they are not as smooth as the average response. Especially the frequency of the spectrum minimum seems to follow no particular trend with the in-

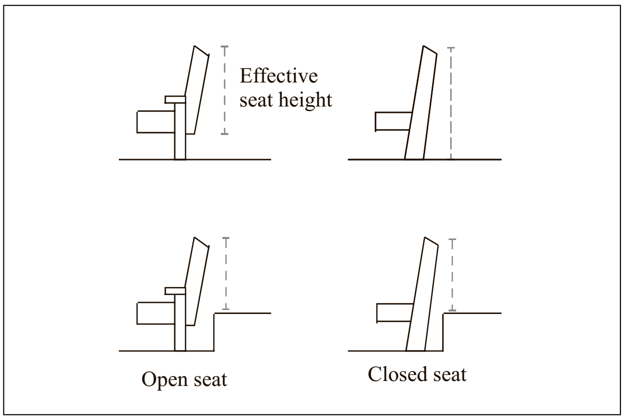

Figure 6. The effective seat height with open and closed seats on flat and stepwise raked floors. The height that determines the resonator frequency is typically measured from the top of the seat back to the ground whereas the effective seat height depends on the seat backrest height.

dividual responses, but with the full loudspeaker orchestra it can be seen that minimum frequency is rather stable.

4.2. Seat type

Sessler and West [2] proposed a closed seat to act as a quarter-wavelength resonator and an open seat (with underpass) as a half-wavelength resonator. The maximum attenuation frequency f_{seat} due to this resonance is determined by the seat height (top of the seat back to floor). In reality, f_{seat} seemed to settle somewhere between these two resonator frequencies depending on the height of the seat underpass. In the time-domain, Ishida [10] proposed the maximum seat-dip attenuation to be caused by the interference of direct sound and the sound that is first diffracted from the seat top and then either (1) reflected off the floor when the seat backrest extends all the way to the floor, or (2) reflected off the seat bottom in the case of the seat with an underpass. The arrival time of the diffracted sound determines the maximum attenuation frequency, so that the seat backrest height corresponds to a quarter-wavelength of the attenuation frequency. The backrest may be extended or shortened by the stepwise-raking floor as illustrated in Figure 6. In this research, it is called the effective seat height.

Figure 7 represents the measured and the above-mentioned theoretical maximum attenuation frequencies f_{seat} in the twelve concert halls. The f_{seat} seems to follow quite well the theory that the seat backrest height corresponds to a quarter-wavelength of maximum attenuated frequency (effective seat height). Some error is introduced by the fact that the path length depends also on the spacing of the seat rows and the width of the seat row [13, 14]. In other words, the paths are three-dimensional [14, 20].

Furthermore, the exceptions to the theory on effective seat height appear to have an explanation. In CP, almost half of the seat height is blocked by the floor steps, which reduces the effective seat height to one-half of the original height. This has been already taken into account in the estimation. The receiver position R1 closest to the stage in AC and MG does not have any seats in front, and the destructive interference is observed due to a floor reflection. The attenuation frequency is thus higher at R1. In VM, all the receiver positions are close to the aisle, which may shorten the diffraction path to the receiver, and thus increase f_{seat}. In BK, reflections from balcony overhangs (R5) and the side wall (R7) may distort the seat-dip effect. In BB at R4–R7 the measured values of f_{seat} settle below the theoretical values because the raked floor blocks the seat underpass almost completely, thus increasing the effective seat backrest height to correspond to almost a full seat height (top to floor). The same happens in SI at R2–R5. In SB, the theory does not apply since the receivers are located in the aisle. In CP at R5, the seat in front is blocked less than the others, so that the effective seat height increases and f_{seat} decreases.

4.3. Audience

The seat-dip effect is studied here with unoccupied halls, as it has previously been concluded that the audience does not have a considerable effect on the seat-dip attenuation [2]. To confirm this, additional measurements with loudspeaker orchestra were performed in a shoebox-shaped multi-purpose concert hall (Logomo, Turku) that features a raked floor in the stalls and a capacity of 1100 people. The concert hall incorporates a reverberation enhancement system and is therefore acoustically very dry itself. The lightly upholstered seats have a height of 0.81 m and an underpass of 0.19 m, blocked by the raked floor. Six rows in front of the receiver at R2 and two rows behind the receiver were occupied by altogether 100 people.

Figure 8 shows the frequency response of the occupied and unoccupied measurements at 20 ms and at 2 s, as well as the time-frequency development of both occupied and unoccupied measurements. As it can be seen, the final frequency response remains mostly unaltered between the occupied and the unoccupied hall, and below 300 Hz their time-frequency development differs slightly. At 20 ms, the main differences in the level occur between 100–2000 Hz with a maximum difference of 3 dB at 420 Hz.

5. Seat-dip recovery and concert hall geometry

5.1. Time-frequency development

The work of Pätynen et al. [8] on the temporal development of the frequency response and the seat-dip effect is extended in this section in order to investigate the attenuation recovery. The seat-dip attenuation recovery time can be computed several ways [8]. Here, the recovery time is defined as the time frame when the magnitude at the maximum attenuation frequency has its maximum increase compared to the magnitude at 80 Hz. In most of the halls studied, the seat-dip attenuation recovers between 50-110 ms, but occasionally the recovery is incomplete. An example of this can be observed in Figure 3 at BB-R4, where the final frequency response retains a dip at f_{seat}.

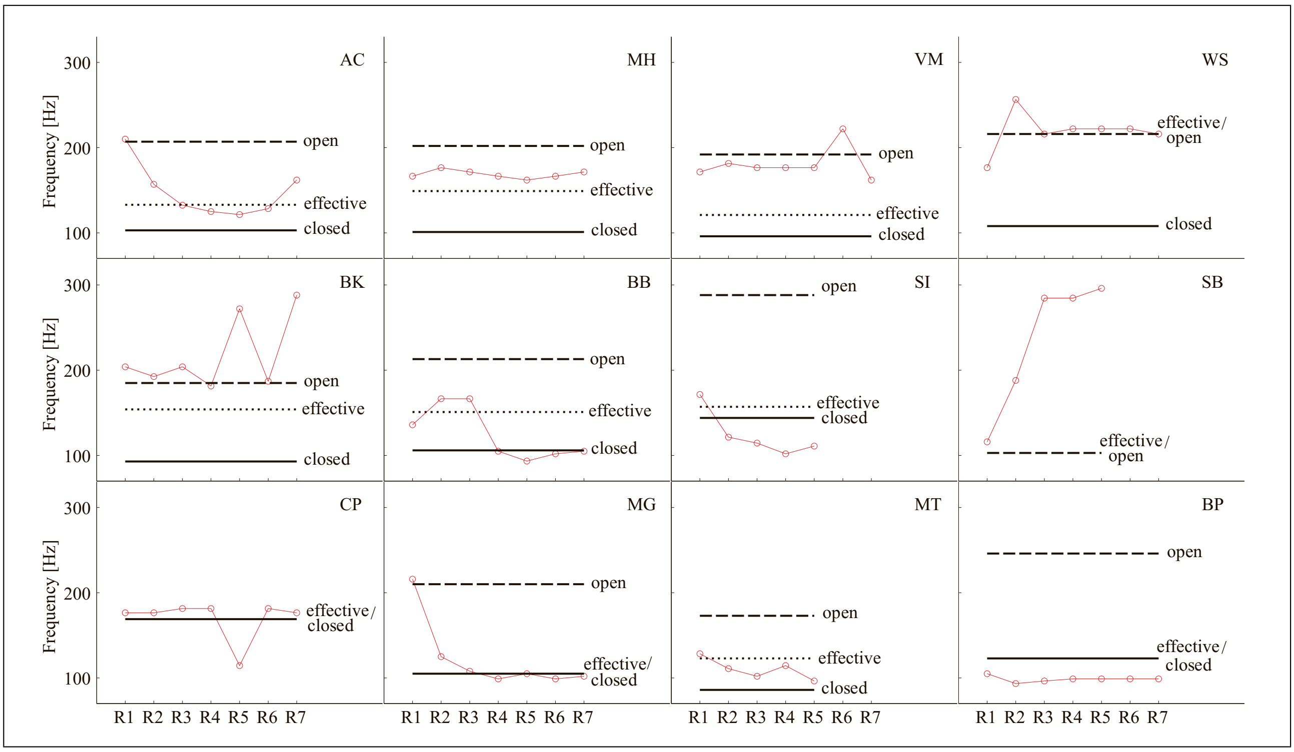

Figure 7. The measured maximum attenuation frequencies f_{seat} at 20 ms after the direct sound. The theoretical estimates according to the theory of resonance (open/closed) and theory of effective seat height are also plotted. The frequency range of SB is from 200 to 400 Hz.

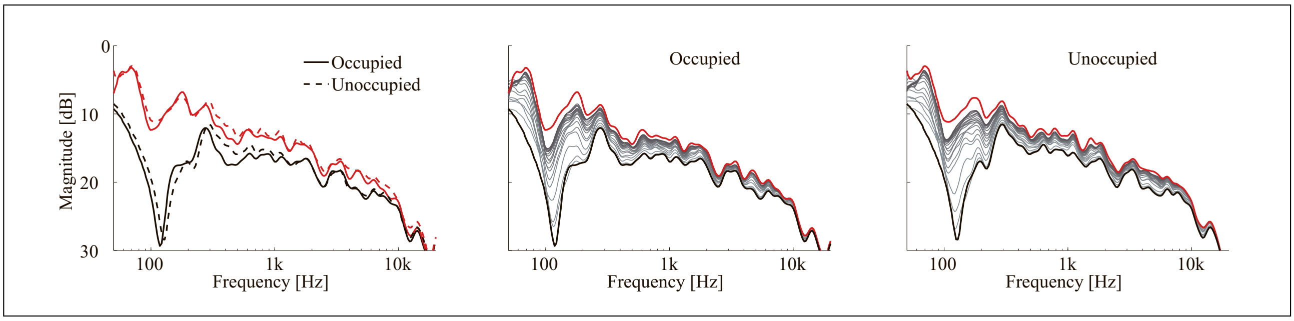

Figure 8. Frequency response at 20 ms and 2 s after the direct sound in occupied and unoccupied concert hall and the time-frequency development with 10 ms increments in both cases. The frequency responses were 1/3-octave smoothed.

In order to study the recovery, the geometrical properties of the concert halls are examined as they provide the non-grazing-angle reflections that generally retain the low frequencies. Figure 9 shows the 20-ms and the final frequency response of the concert halls divided into two categories according to hall geometry: shoebox-shaped and non-shoebox-shaped. WS and SB have been excluded because of their exceptional seat-dip effect due to lightweight removable seats. CP has also been disregarded from the non-shoebox halls, because its main attenuation frequency is almost an octave higher than in the other non-shoebox halls due to its particularly short effective seat height.

The average frequency responses of the two hall types differ in the maximum seat-dip attenuation frequency and width, as well as the level of the frequency responses. The maximum seat-dip frequency f_{seat} depends on the seat height and the floor raking as established earlier. On the other hand, the attenuation width Δf at 20 ms seems to be related to the hall type at first sight. However, in most halls no considerable early reflections from the hall geometry will have arrived during the first 20 ms. Since the non-shoebox halls in this study accommodate closed seats and raked floor, while the shoebox-shaped halls mostly accommodate seats with underpass and flat floor, it follows that the bandwidth is in fact affected by the seat and floor type.

Concert halls with a raked floor and closed seats attain a deep narrowband initial attenuation, whereas halls with a flat floor and open seats have an asymmetric slowly-decreasing wideband initial attenuation. To quantify the attenuation bandwidth, the Q-values of f_{seat} are computed and grouped by hall type in Figure 10. The values differ significantly by seat type (open/closed) ($H(1) = 17.48$, $p < 0.001$), and by floor raking (raked/flat) ($H(1) =$

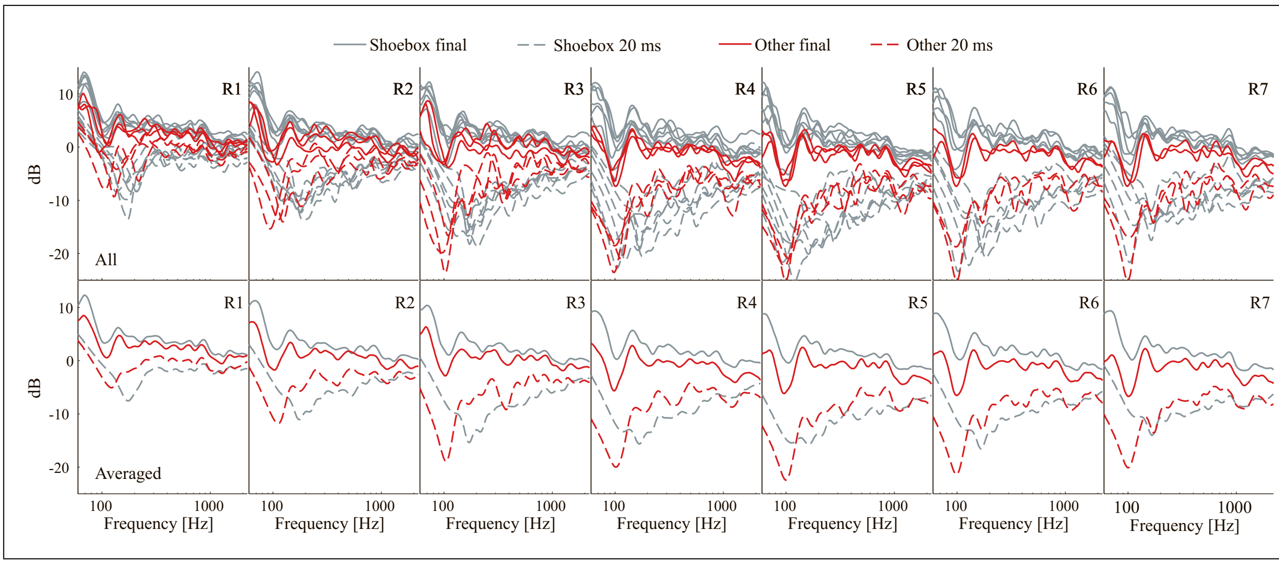

Figure 9. The 20-ms and final frequency responses of shoebox vs. non-shoebox halls at different receiver positions. The plots on the top row show all the responses, and the plots on the bottom row show the averages of the two categories. The included shoebox halls are: AC, MH, VM, BK, BB, SI, and non-shoe box halls: MG, MT, BP. The frequency responses were 1/3-octave smoothed.

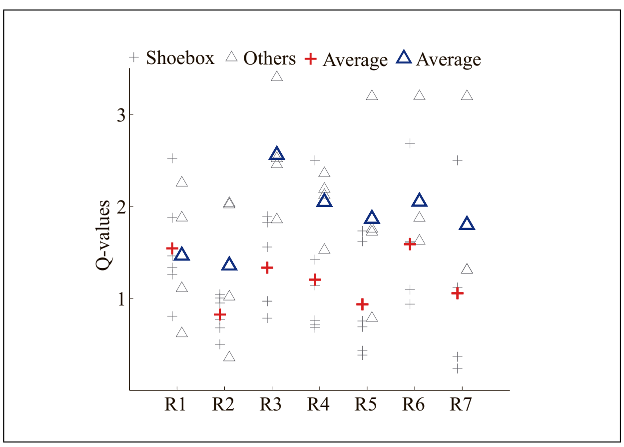

Figure 10. Q-values of the maximum seat-dip attenuation at 20 ms averaged per hall type. A higher Q-value corresponds to a narrower the attenuation bandwidth.

13.23, $p < 0.001$). However, the individual contribution of floor raking and seat type to the attenuation bandwidth cannot be fully resolved with this set of concert halls, because the receiver positions in the concert halls grouped either by floor raking or by seat type are nearly the same.

However, concert hall geometry affects the recovery of the seat-dip effect, as the two hall types have different final frequency responses. Both the level of the final frequency response and the difference between the 20-ms and the final response are greater in the shoebox halls than in the non-shoebox halls and the difference grows with distance. In addition, the level below 100 Hz of both frequency responses is considerably higher in the shoebox halls than in the other halls.

The magnitude of the seat-dip recovery can be estimated by the magnitude difference of the 20-ms and the final response at f_{seat}. The average difference is 19 dB for the shoebox-shaped halls and 15 dB for the non-shoebox shaped halls, and they differ significantly ($H(1) = 14.63$, $p < 0.005$). This indicates that the shoebox-shaped halls correct the seat-dip effect 4 dB more (on average) than the non-shoebox halls.

The development of the spectrum minimum and its frequency can also be analysed with respect to the hall type, and it is shown in Figure 11 until 80 ms after the direct sound. The analysis yields several observations. First, the shoebox halls seem to have a lower spectrum minimum, but it increases more rapidly in time than in the other halls. Second, the spectrum minima curves of the non-shoebox halls have a second dip, which is possibly associated with reflections from the seats behind the receiver. Third, the frequency of the spectrum minimum remains almost constant in time in the non-shoebox halls, while it varies in the shoebox-halls. This results most likely from the open seats in the shoebox halls that provide more paths of different lengths for the diffracted sound. Finally, depending on the receiver position, the frequency behaviour of the spectrum minimum during the first 5–7 ms is constant regardless of the hall type. Most probable reason for this behaviour is diffraction from the stage edge.

5.2. Spatiotemporal development

The recovery can be linked with the spatial energy distribution of the concert hall, which shows the direction of arrival for the reflections. The spatiotemporal analysis reveals that the shoebox-shaped halls possess a more omnidirectional energy distribution below 1 kHz than the non-shoebox halls. The cumulative spatial distribution of energy below 1 kHz is visualised in Figure 12a in BP (vineyard) and VM (shoebox) at receiver position R4. A second pair of halls is presented in Figure 12b with MG (fan) and MH (shoebox) at R4. The rows represent different time frames and the columns different planes. The first column

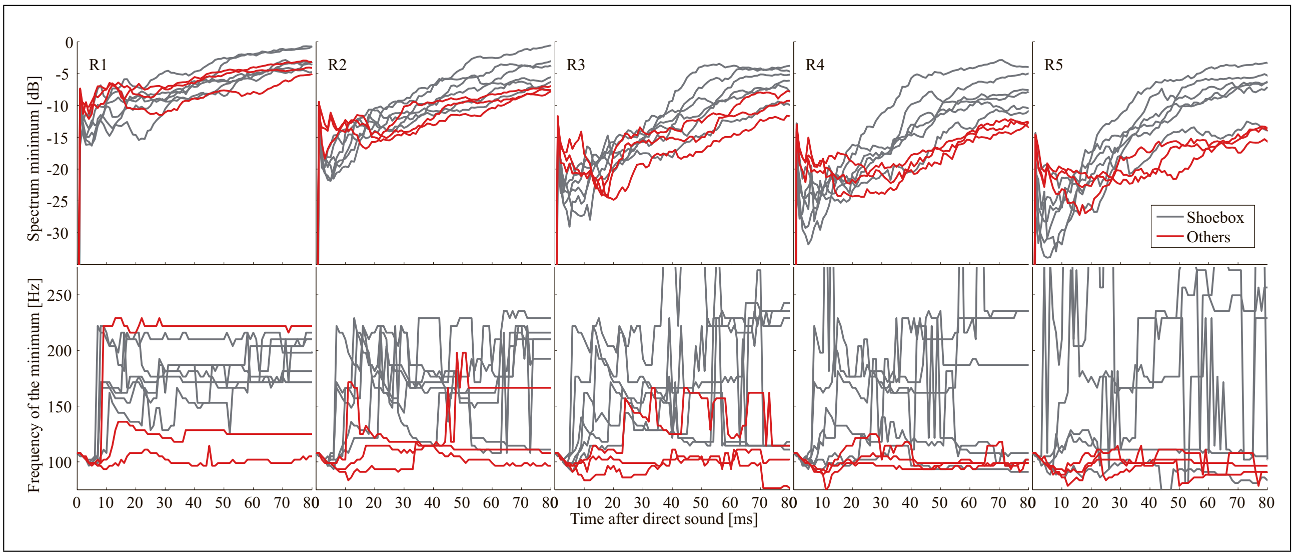

Figure 11. The spectrum minimum and its frequency at 1-ms time increments up to 80 ms after the direct sound in the shoebox vs. non-shoebox halls at different receiver positions. The plot on the top shows the magnitude of the spectrum minimum and the bottom plot shows the frequency at which the minimum occurs. The included shoebox halls are: AC, MH, VM, BK, BB, SI, and non-shoe box halls: MG, MT, BP. The frequency responses were 1/12-octave smoothed.

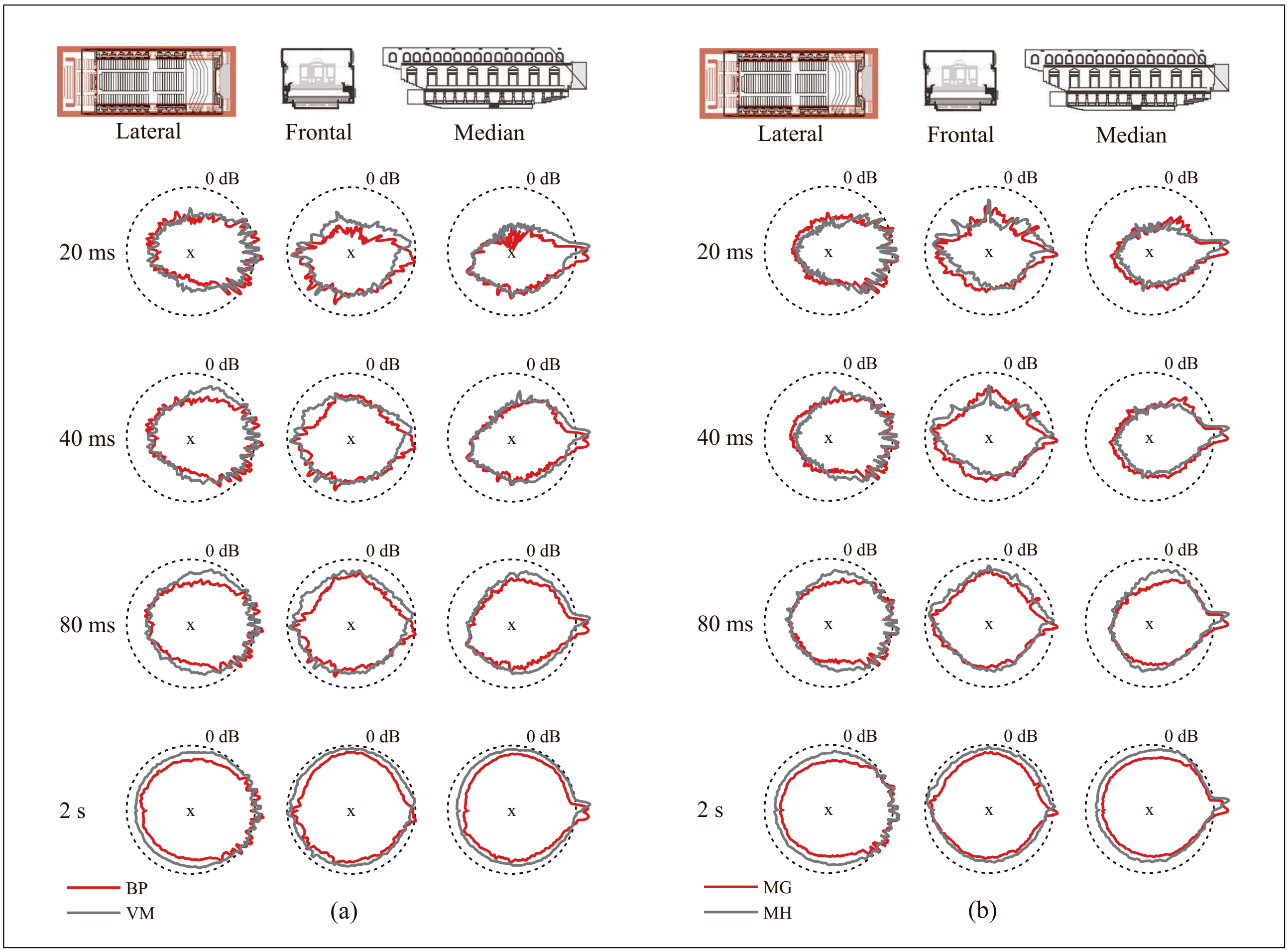

Figure 12. Spatial energy distribution at R4 is shown in four time frames: 20, 40, 80, and 2000 ms and three planes for hall pairs (a) BP-VM, and (b) MG-MH. The dashed line indicates the energy of a source in free field at 10-m distance. The impulse responses are low-pass filtered at 1 kHz, and the frequency responses of all sources on stage are averaged. A 3-deg sliding average is applied on the histograms. The concert hall sketch is indicative, and it is not in scale.

depicts the lateral (horizontal) plane, and the individual sources from the stage are clearly visible. On this plane, BP has a more narrow lateral energy distribution than VM, except during the first 20 ms. The second column displays the frontal plane, so the stage is located in the middle of the plot. On the frontal plane, the reflections from the upper section arrive earlier in VM than in BP. The third column shows the median plane with the stage on the right. Here the only major difference is that in BP, a reflection off the stage floor arrives at the receiver almost simultaneously with the direct sound. Although not shown in the figure, in both halls the spatial energy accumulates evenly from 80 ms onwards to the shape at 2 s. Finally, on all planes, the energy level of the final frequency response (2 s) is lower in BP than in VM. Similar observations can be made for the second hall pair MG-MH.

6. Discussion

Replacing a standard omnidirectional source with a loudspeaker orchestra on stage and using time-frequency visualisation techniques instead of room acoustical descriptors yield results well in-line with the literature discussing the seat-dip effect. Some features cannot be observed due to averaging many source positions, but some features are more visible by averaging.

Based on the results, the seat-dip effect forms at 5–7 ms after the direct sound in the analysed halls. During the first 20 ms after the direct sound the determining factors for the attenuation include the seat and floor type, and the source and receiver position, as these largely influence the path of the direct sound. The level of initial seat-dip attenuation depends on the source-receiver distance while the attenuation frequency depends mostly on the height of the seat backrest, seat underpass, and angle of incidence. The presence of the audience does not alter the seat-dip effect significantly. This can be understood by noting that the low-frequency absorption coefficients for the audience and for the empty seats are very similar [32]. In addition, the HRTF-measurements show that shoulders reflect sound at about 1 kHz [33], and below 1 kHz the shoulders can be assumed to diffract sound similarly to the tops of the seat backs.

The width of the seat-dip attenuation depends on the seat type and floor raking. Firstly, seats with underpasses yield numerous diffraction paths with different lengths, which generate a wide attenuation band in frequency. FDTD and boundary element simulations confirm that open seats create a wider attenuation band than closed seats [11, 19]. Secondly, a flat floor also contributes to the wide attenuation band, as the diffracted sound from preceding seat backrest arrives at a grazing angle to the consecutive seat backrests. This scattered sound energy increases attenuation at high frequencies up to about 1 kHz, as the differences between the paths travelled by the direct sound and the diffracted sound are small. On the contrary, with a raked floor the grazing angle increases and the attenuation bandwidth becomes narrower [14]. In this case, the seat diffraction is directed more upwards; thus the once-diffracted sound escapes the grazing angle. In addition, halls with flat floors have more diffraction paths as the stage is typically higher than the seat rows.

The seat-dip recovery depends on the hall geometry, i.e., the early reflections that arrive at non-grazing angles at the receiver position. Previously, both ceiling and lateral reflections have been separately suggested as the major contributors to the recovery. However, based on Figure 12, no clearly identified early reflections appear solely responsible for correcting the seat-dip effect. Instead, the recovery seems to benefit from omnidirectional cumulation of spatial energy between 30–80 ms after the direct sound. Shoebox-shaped halls provide more energy in this time frame, because the side walls are closer to the audience, and balcony overhangs provide reflections from above. In the non-shoebox halls, the ceiling may be closer, but the walls provide very little reflections to most parts of the audience within this time frame. To illustrate this, the recovery time in VM is 60 ms and the recovery seems successful; the seat-dip attenuation is diminished. Yet, the only difference between the spatial energy distribution at 40 ms and 80 ms is the increased level of spatial energy and no clear boost of energy in a certain direction can be seen. In BP, the recovery time is also 60 ms, although the attenuation never recovers properly. And indeed, the spatial energy distribution is less round in BP than in VM, and the level is lower in all analysed time windows. Interestingly, VM has been perceptually assessed to have a louder bass than BP [29].

The final frequency responses of all the halls studied feature an attenuation dip between 100–110 Hz. Among the 81 receiver positions, the dip is less prominent in two positions only: in BK where R5 is under the balcony, and in BP, where R3 is in front of a wall partitioning different audience segments. These receivers are obviously too close to a reflecting surface to yield valid measurement data.

The dip is most probably related to the receiver height, as the dip frequency increases when the receiver height is lowered. The receiver height corresponds to about one-third of the wavelength at the dip frequency. This suggests that destructively interfering sound must travel a path slightly longer than twice the receiver height. When the spectrum of a temporal window 100–2000 ms is computed, the prevailing presence of the dip suggests that it is generated by later reflections.

Figure 13 offers one plausible explanation to the dip; the ceiling reflections bounce between the seats at various approximately equal-length paths before reaching the receiver. Furthermore, the more rigid and fixed the seating, the more equidistant paths are gathered that deepen the dip. In particular in BK, SB, and WS where the seat underpasses are large and the seats are not tightly spaced, the dip in the final frequency response is very mild. The perceptual relevance of the dip is unknown.

In the fan- and vineyard-shaped halls, the frequency of the dip coincides with the maximum attenuation frequency f_{seat} whereas in the shoebox halls the dip is at a lower

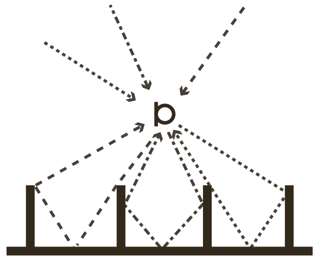

Figure 13. The cause of the dip in the final frequency response. The sound arriving from the upper hemisphere reflects between the seats before reaching the receiver. The path lengths of the reflections are nearly equal, which results in a noticeable dip in the final frequency response.

frequency than f_{seat}. This is one of the reasons why the shoebox halls have on average 4 dB larger level difference between the direct sound and the final frequency response than the fan-and vineyard-shaped halls. The large level difference indicates that shoebox halls may leave more space for the perception of early reflections and their low frequency content, since the direct sound would mask the early reflections less.

The orchestral instruments whose tuning range extend to the low-frequency region, such as the cello (tuning range 65–250 Hz), double bass (30–130 Hz), and tuba (35–350 Hz) are likely to be affected by the seat-dip effect. Bradley [14] showed that the seat-dip effect can attenuate the string bass as much as 6 dB in the 250-Hz octave band. The low-frequency instruments may also be masked by other instruments [34]. If the seat-dip effect is a deep dip at around 100 Hz, mostly the fundamentals of the low notes are missing from the direct sound. The bass might then be masked by other instruments with higher fundamentals and thus be perceived weaker. If the main attenuation dip is around 200 Hz with a wide bandwidth extending to higher frequencies, some harmonics of the low fundamentals are missing in the direct sound, but the fundamentals themselves arrive early on and are possibly masked less by other instruments.

7. Conclusions and future work

The seat-dip effect in twelve European concert halls were measured with a loudspeaker orchestra and analysed with recent time-frequency and spatiotemporal methods. The results confirmed the previous studies on the effect of distance, grazing angle, seat type, and presence of audience on the seat-dip attenuation. The main attenuation frequency was shown to depend on the effective seat height that comprises the seat backrest height compensated by possible blocking by the raked floor. Furthermore, it was shown that the width of the initial attenuation depends on seat and floor design. As for the recovery of the seat-dip effect, according to these measurements the attenuation is best corrected with spatially uniformly-distributed reflections during the first 30-80 ms after the direct sound. It was also discovered that the final frequency response has a dip at a fixed frequency that is most probably related to the receiver height.

The results raise further questions on the effect of the seat-dip attenuation on the perception of bass; in particular, the effect of the attenuation frequency range or width. In order to ultimately offer guidelines to seat design in concert halls, simulating the contribution of different elements to the wide- and narrowband attenuation as well as comparing the perceptual differences in the attenuation bandwidth in terms of bass are useful topics for future research. Similarly, the number of sources needed to measure the seat-dip effect in perceptually relevant way should be further investigated.

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