

Analysis and perception of the seat-dip effect in concert halls

Henna Tahvanainen



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A doctoral dissertation completed for the degree of Doctor of Science (Technology) to be defended, with the permission of the Aalto University School of Science, at a public examination held at the lecture hall T2 of the school on 15 October 2021 at 12:00.

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Abstract

One of the acoustic phenomena in concert halls is the so-called seat-dip effect, which is the selective low-frequency attenuation of the direct sound and reflections arriving at grazing angles to the audience. It has been considered detrimental to the concert hall's acoustics, and efforts to understand and model the effect have led to several design suggestions for its remedy. Perhaps somewhat surprisingly, the perceptual significance of the seat-dip effect has been very little studied. Most conclusions have been drawn from objective measurements with a few source-receiver positions in the concert halls, scale models, and simplified simulation models.

This work extends the analysis and study of the perception of the seat-dip effect with a relatively large database of measured room acoustic responses in concert halls and with a purpose-built scale model. The concert halls are measured with a loudspeaker orchestra that approximates an orchestra in layout and directivity. In addition to single-number room acoustic parameters, time-frequency and spatiotemporal analyses of the cumulative sound energy are used to characterise the seat-dip effect. This approach reveals that the initial seat-dip attenuation 20 ms after the direct sound in existing concert halls is typically either narrow-band attenuation centred around 100 Hz or asymmetric wide-band attenuation centred around 200 Hz depending on the seat and floor design. The initial attenuation then levels off to varying degrees depending on the concert hall geometry, and spatially even distribution of the reflected incident sound energy at the listener position appears to be beneficial. Furthermore, seats with underpass enhance the low frequencies below the main attenuation frequency.

Furthermore, listening tests with the auralised measurements in the concert halls were carried out to determine the audibility of the seat-dip effect and to study the perception of low frequencies. The results show that the single-number room acoustic parameters do not seem to capture the perception of low frequencies well. In addition, the results indicate that the seat-dip effect is not perceived in concert halls with sufficient reflected incident sound energy at the listener position. Consequently, to avoid hampering the low frequencies with the seat-dip effect, the main focus should be on designing adequate reflections, and the seating area design comes in second. Based on the results, it is recommended that seats with underpasses and flat or very moderately raked floors should be used.

Keywords room acoustics, concert halls, seat-dip effect, tone colouration

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Tiivistelmä

Yksi konserttisalin akustisista ilmiöistä on nimeltään katsomovaimennus. Nimensä mukaisesti katsomoon pienessä kulmassa saapuva ääni, yleensä suora ääni sekä osa varhaisista heijastuksista, vaimenee pienillä taajuuksilla. Vaimeneminen rajoittuu tietyille taajuuskaistoille riippuen katsomon ja penkkien rakenteesta. Katsomovaimennuksen on yleisesti ajateltu heikentävän konserttisalin akustisia olosuhteita, ja siihen liittyvä tutkimus on pääasiassa tähdännyt vaimennuksen poistamiseen. Katsomovaimennuksen havaittavuutta on tutkittu yllättävän vähän ja johtopäätöksiä vaimennuksesta on tehty analysoimalla muutamia lähde-vastaanottopisteitä saleissa ja pienoismalleissa sekä yksinkertaistetuilla tietokonemalleilla.

Tässä työssä laajennettiin katsomovaimennuksen analysointia ja havaittavuuden tutkimusta laaja-alaisin konserttisalimittauksin sekä pienoismallilla. Mittauksissa hyödynnettiin kaiutinorkesteria, jonka avulla saadaan kokonaiskuva katsomovaimennuksesta yksittäisten lähdepisteiden sijaan. Tutkimuksessa huomattiin, että katsomovaimennus on joko syvä ja kapea notko noin 100 Hz taajuudella tai laajakaistainen, epäsymmetrinen vaimennus, syvimmillään noin 200 Hz taajuudella. Vaimennustyyppi riippuu penkkien muodosta ja lattian kaltevuudesta. Alkuvasteen katsomovaimennuksen tasoittuminen ajan kanssa vaihtelee konserttisalin geometrian mukaan. Tasaisesti jakautunut äänienergia saleissa vaikuttaisi auttavan vasteen tasoittumisessa. Penkit, joiden alla on ilmatilaa, jossa ääni pääsee kulkemaan, vahvistavat myös pientaajuuksia katsomovaimennustaajuuksien alapuolella.

Saleista mitatuilla impulssivasteilla tutkittiin laboratorio-olosuhteissa katsomovaimennuksen havaittavuutta sekä yleisesti bassoisuuden havaitsemista. Tutkimukset osoittavat, että olemassaolevat yksilukuarvot eivät kuvaa bassojen havaittavuutta salissa kovinkaan hyvin. Lisäksi katsomovaimennusta ei havaita saleissa, joissa on riittävästi heijastuksia. Katsomovaimennuksen haittojen ehkäisyssä tulisi siis katsomoalueen suunnittelun sijaan ensisijaisesti keskittyä riittävien varhaisten heijastusten varmistamiseen. Tämän työn tulosten perusteella suositellaan tasaista tai hyvin loivasti kallistuvaa katsomoa ja riittävää ilmatilaa katsomon penkkien alle.

Avainsanat huoneakustiikka, konserttisalit, katsomovaimennus, äänen värittyminen

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"It's not the note you play that's the wrong note – it's the note you play afterwards that makes it right or wrong."

Miles Davis

"The only true voyage of discovery . . . would be not to visit strange lands but to possess other eyes, to behold the universe through the eyes of another, of a hundred others, to behold the hundred universes that each of them beholds, that each of them is"

Marchel Proust: Remembrance of Things Past

Preface

The research leading to the results presented in this thesis has received funding from the Academy of Finland [257099], the European Research Council under the European Community's Seventh Framework Programme (FP7/2007-2013) / ERC Grant Agreement No. [203636]. I would also like to acknowledge the personal grants given by Emil Aaltonen Foundation, Finnish Foundation for Technological Promotion, and Kaute Foundation. I would also like to thank the Antti-Jussi Kosonen fund in North Karelia for the Matti Puhakka scholarship. My conference trips and research visit have been supported by the Helsinki Doctoral Education Network in Information and Communications Technology, and Foundation for Aalto University Science and Technology.

I would like to acknowledge the significance of my supervisor Prof. Tapio Lokki in bringing ideas into this work, extending my work also outside the scope of the thesis, and helping to distil the results into something practical. Of course, this work could have not been possible without my thesis instructor DSc. Jukka Pätynen, and my other co-authors: DSc. Aki Haapaniemi, Prof. Jin Yong Jeon, and Dr. Hyung-Suk Jang. In the course of the thesis, I also received help from Ms Nathalie Lurin, Ms Nakyong Jang, and DSc. Antti Kuusinen. I sincerely thank each of you for your input. Likewise, I would like to thank the pre-examiners of this thesis, Prof. William Davies and Prof. Densil Cabrera, and the opponent PhD Eckhard Kahle for taking the time to discuss, support, and encourage this work.

During my research, I had the possibility to be a part of several teams and research settings. Firstly, I am thankful for the former Virtual Acoustics team and Akulab, the current Aalto Acoustics lab and its past and present members for the eight years spent there. In addition, I had the opportunity to complete a research visit at the Architectural Acoustics lab under the leadership of Prof. Jin Yong Jeon at Hanyang University in Seoul. I received a tremendous amount of help in building the scale model and experienced many interesting culinary adventures. 고맙습니다! During the thesis process, I also completed an internship at Facebook Reality Labs, which particularly inspired me to look out for practical solutions in research work.

I am also thankful to my colleagues at Yamaha Music Japan for a very aspiring

working environment and the opportunity to delve into my passion for musical instruments that ended up extending the submission of this thesis by a few years and at the same time allowed me to explore the Japanese research scene in acoustics. In particular, I ended up finding some interesting Japanese research related to my PhD topic in the archives of Mr Hideo Miyazaki. ヤマハの皆さん、大変お世話になりありがとうございました。

A great deal of gratitude goes to my current superiors and co-workers at the AINS Group under the guidance of DSc Mikko Kylliäinen for the flexibility in the process of finalising of this thesis, and for entrusting me with projects that put these research results in practical use as an acoustic consultant.

My family and friends. While my parents and my brothers have offered me a haven of continuity and tranquillity in the beautiful hills of Karelia, I have also been extremely lucky to make friends all over the world. Thank you for making the world a beautiful place. Finally, I would like to thank Archontis for jumping in at the deep end with me.

I would like to dedicate this work to my father whose unexpected adieu played a significant role in having me sit down to finalise it.

Tampere, Finland, September 14, 2021,

Henna Tahvanainen

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List of Publications

This thesis consists of an overview and of the following publications which are referred to in the text by their Roman numerals.

- I** H. Tahvanainen, J. Pätynen, T. Lokki. Analysis of the seat-dip effect in twelve concert halls. *Acta Acustica United with Acustica*, vol.101, no. 4, pp. 731–742, 2015.
- II** H. Tahvanainen, T. Lokki, H.S. Yang, J.Y. Jeon. Investigating the seat area design and enclosure on the seat-dip effect using scale model measurements. *Acta Acustica United with Acustica*, vol.4, article 15, 2020.
- III** H. Tahvanainen, J. Pätynen, T. Lokki. Studies on the perception of bass in four concert halls. *Psychomusicology: Music, Mind and Brain – Special Issue on Performance Spaces of Music*, vol. 25, no. 3, pp. 294–305, 2015.
- IV** H. Tahvanainen, A. Haapaniemi, and T. Lokki. Perceptual significance of seat-dip effect related direct sound colorations. *Journal of the Acoustical Society of America*, vol. 141, no. 3, pp. 1560–1570, 2017.

List of Publications

Author's Contribution

Publication I: “Analysis of the seat-dip effect in twelve concert halls”

The authors devised the idea together based on the measurements ran by JP and TL together with other team members. DC analysed the measurements and wrote about 90 % of the paper with input from the coauthors.

Publication II: “Investigating the seat area design and enclosure on the seat-dip effect using scale model measurements”

The idea for this paper was conceived by DC and TL. DC and HY designed and built the scale model. DC measured and analysed the results and wrote about 90% of the paper with input from the coauthors.

Publication III: “Studies on the perception of bass in four concert halls”

DC designed, ran, and analysed the experiments and wrote about 90% the paper with input from the coauthors.

Publication IV: “Perceptual significance of seat-dip effect related direct sound colorations”

The authors devised the idea together. AH and DC had equal contribution to this paper. AH prepared the signals, ran the analysis of measured room impulse responses, and wrote 50% of the paper. DC ran and analysed the perceptual study and wrote 50% of the paper while TL provided comments on the manuscript.

List of Abbreviations

| | |
|-------------|------------------------------------|
| BEM | Boundary Element Method |
| BI | Bass Index |
| EDT | Early Decay Time |
| FEM | Finite Element Method |
| FDTD | Finite Different Time Domain |
| GA | Geometrical Acoustics |
| JND | Just Noticeable Difference |
| RIR | Room Impulse Response |
| SDE | Seat-Dip Effect |
| SDM | Spatial Decomposition Method |
| SIRR | Spatial Impulse Response Rendering |

List of Abbreviations

1. Introduction

1.1 Motivation

The placement of the audience and the orchestra in performance spaces have varied and developed from era to era and from one musical function to another (Spitzer and Zaslav, 2004, pp.343-368). Depending on the nature of the performance venue, the orchestra might have been placed on a balcony, a pit, on the floor or on a stage. The audience, in turn, might have been standing or sitting; having everyone seated would guarantee a better visibility (Forsyth, 1985).

The changes in societal structures brought about by the industrial revolution created new clientele that would readily pay for concert tickets. This led to larger performance venues and more consideration for their visual and acoustical conditions (Thompson, 2002, pp.20). These considerations helped shape the current performance setting where the orchestra plays on the stage and the audience is quietly appreciating the performance while seated. Designing a hall with good acoustics and visibility in most (if not all) seats while also maximising the number of seats is still the task of architects and acousticians today.

The seats and the seated audience form a periodic structure. When sound travels at grazing angles across that periodic structure, it undergoes selective attenuation additional to spherical spreading. This phenomenon is called the seat-dip effect (SDE), and it leads to a lack of low frequencies between about 80-300 Hz in the direct sound and some of the early reflections in the concert hall. The SDE is present in every performance space with seats, but it was noticed relatively recently, given the time span of the history of concert halls (Sessler and West, 1964; Schultz and Watters, 1964). Namely, the SDE put a damper on the inauguration of the New York Philharmonic Hall in 1962. In particular, the parenthetical comments included the weakness of the double basses and cellos (Beranek et al., 1964). In the subsequent measurements, Sessler and West (1964) and Schultz and Watters (1964) noticed a selective attenuation at low frequencies in the early response of the concert hall.

More concretely, the SDE involves diffraction and reflection provided by the

seats, the floor and nearby surfaces. When sound travels at near-grazing angles to the audiences, it reflects between the seats and interferes destructively at some frequency with the direct sound depending on the path difference between the direct sound and the reflected sound, hence the selective attenuation band. Even before the first papers introducing the SDE, Békesy (1933) ran some experiments outdoors with listeners seated on rows of benches in the 1930's. He noticed that when sound was passing through the benches, it attenuated selectively at specific frequency bands. He recommended that the direct sound should not arrive at small angles to the audience based on his experiments.

The SDE is usually considered as an acoustic defect (Blessner and Salter, 2009; Gade, 2014; Long, 2005) and it has even earned the title of "the low frequency thief" (Greenberg, 1985). Particularly, concerns were raised for its effect on the auditory spaciousness of the concert halls (Barron and Marshall, 1981). The topic inspired a lot of research in the 1990's (Bradley, 1991; Davies and Lam, 1994; Cox and Davies, 1995; Davies et al., 1996; Davies and Cox, 2000; Ishida, 1995; Takahashi, 1997; LoVetri et al., 1996) and spawned a few PhD theses (Davies, 1992; Ishida, 1993; Mommertz, 1993; Cheene, 1995), and a body of abstracts (Greenberg, 1985; Chéenne et al., 1993; Bradley and Soulodre, 1997; O'Keefe, 1998; Morimoto et al., 2001; Shimizu, 2001; Cirillo and Martellotta, 2004). The topic of SDE was somewhat swept under the carpet in concert hall acoustic research after the establishment of a threshold of audibility for the effect (Davies et al., 1996), and the fact that a seemingly easy solution to remedy the effect would be raked audience areas and seats with no underpasses (Ishida, 1993).

Since the discovery of the SDE, the discussion has been evolving around the perceptibility of the lack of bass in the direct sound in the presence of sufficient late sound energy, as the SDE did not seem to present a perceptual problem in the early shoebox-shaped halls (Schultz, 1965). Some perceptual studies with simulated sounds have found the SDE hampering the bass (Barron and Marshall, 1981; Davies et al., 1996). In contrast, other studies have stressed the importance of the amount of late reflected energy that compensates for the SDE (Schultz, 1965). The discussion boils down to three possible scenarios for directing the efforts in concert hall design: 1) designing adequate reflections in the concert hall to hide the effect, 2) designing the seating area to eradicate the effect, and 3) a combination of the two. The question became topical again with the recent advances in concert hall measurements (Pätynen and Lokki, 2010), modelling (Lokki et al., 2011b), and perceptual studies (Lokki et al., 2016). Today, a relevant topic is to what extent the SDE should be taken into account in modelling when designing a concert hall.

When evaluating the perceptual relevance of the SDE, the discussion should not only concern the characteristics of the concert halls but also the aspects of the listeners and the musical instruments involved. The room impulse responses in concert halls are considered linear while hearing and musical instruments exhibit level-dependent properties. For example, the equal loudness contours

show that hearing is more sensitive to the level at low frequencies. Musical instruments playing louder tend to contain more high partials. Furthermore, the number of instruments playing at each passage depends on the orchestration. A case in point would be loud passages, where almost all instruments play. Composers may also compose pieces with a specific performance space and its acoustics in mind (Meyer and Hansen, 2009). Thus, the SDE needs to be approached holistically. The analysis of measurements in a variety of halls together with accurate modelling of wave-based phenomena can verify and explain the birth mechanism of the SDE and provide means to objectively modify the effect. Perceptual studies with plausible concert hall auralisations and relevant musical repertoire and passages yield the extent of the perceptual significance of the SDE and its effect on the sound quality.

1.2 Main contributions

The publications included in this thesis tackle the analysis and perception of the SDE with detailed measurements in 15 concert halls and a scale model of a chamber music hall. In contrast to the previous research analysed by single source–receiver pairs, the results in this thesis are analysed as an average of multiple sources to expose the characteristics of the SDE more clearly. Subsequently, it is possible to connect the SDE characteristics to seating area design and concert hall geometry. Furthermore, listening tests with several concert halls and modern reproduction methods suggest that designing sufficient reflections in concert halls is the number one concern related to the SDE.

The main results of this thesis are related to the SDE attenuation properties in existing halls and the role of reflections provided by the concert hall geometry (Publication I), the effect of seating area design on these attenuation properties (Publication II), and the perceptual significance of these attenuation properties (Publication IV) and more generally the perception of low frequencies and low-fundamental-frequency musical instruments, such as double bass and tuba, in different concert halls (Publication III).

1.3 Structure

Chapter 2 sets the stage with a brief overview of methods in research on concert hall acoustics. Chapter 3 summarises the objective analysis of the SDE, including experimental observations from the measurements and research on its mechanism and modelling. Chapter 4 presents the subjective aspects related to the SDE and its perceptual relevance. It also extends the discussion to the effects of musical instruments and hearing properties on the SDE. Chapter 5 presents a tie-up between the objective and subjective aspects of the SDE to provide implications to the design of seating areas and concert hall geometry

in general. Chapter 6 concludes the work and presents some future research directions.

2. Methods for studying concert hall acoustics

The SDE influences the acoustics of all spaces with a seated audience, and the effect has been chiefly studied in concert halls and auditoria. Some research also exists about opera houses (O’Keefe, 1997, 1998; Tahvanainen et al., 2015b) and movie theatres (Holman, 2007). Similar low-frequency attenuation is also observed with church pews (Martellotta and Cirillo, 2009). Since the SDE is a part of the acoustic phenomena in concert halls, this chapter introduces the most common methods for studying the acoustics of the concert halls and the methods used in this thesis.

The problems in acoustics are typically divided into three categories: 1) production, 2) propagation and 3) reception of sound (Lindsay, 1966). In the context of concert halls and performance spaces, these correspond to 1) the orchestra comprising the musicians, singers, and musical instruments, 2) the concert hall, 3) the audience, i.e., the individual listeners (Lokki and Pätynen, 2020a). While the medium, i.e., the concert hall, is considered to have a linear response, the source and the listener are not, meaning their responses are level-dependent. This is discussed in more detail in Chapter 4.

Sound propagation in concert halls can be studied with various methods, such as direct measurements, the building of a scale model, and computer simulations, and often these methods are used in parallel in concert hall design (Knudsen, 1970; Rindel, 2002; Jeon et al., 2009). Furthermore, perceptual studies and auditory models are conducted to understand the effect on the listener (Zacharov, 2018). Understanding how musical instruments produce and radiate sound is also an integral part of understanding the acoustic experience in a concert hall. It is touched upon in later chapters with the context of the SDE.

2.1 Concert halls and performance spaces

Concert halls can be roughly classified based on their geometry, and some of the classes are presented and labelled in Fig. 2.1. Based on the geometry, the concert halls provide different reflections, and thus the sound field generated in each hall is different. Figure 2.2 shows the sound energy distribution (normalised to

10 m) of a shoebox-shaped (Vienna Musikverein, VM) and a vineyard-shaped hall (Berlin Philharmonie, BP) below 1 kHz at different time windows after the direct sound.

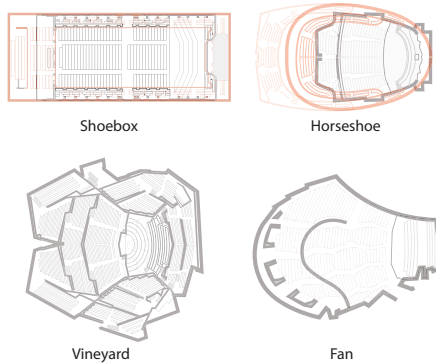


Figure 2.1. Plans of some the most common performance space geometries.

2.2 Measurements

The information about the acoustics of a room is contained in the room impulse response (RIR), i.e., the transfer function between a source and a receiver in the room. Conceptually, the RIR can be divided into three different parts: direct sound, early reflections, and late reverberation. The early reflections typically consist of sparse distinct reflections, while the late energy often resembles exponentially decaying noise.

The RIRs are commonly measured with the sine-sweep technique (Farina, 2000). The ISO 3382-1 (2009) standard describes the measurement procedure for the RIRs, including averaging measurements over several source–receiver positions to obtain a set of single-number room acoustic parameters. These parameters are used to estimate the perception of the acoustics of the concert halls, and they act as guidelines for concert hall design. As the standard parameters are defined at 125 Hz octave bands and above, other parameters computed from the RIRs have also been proposed to quantify the perceived level of low frequencies in a concert hall (Bradley, 1991; Barron, 1995; Soulodre and Bradley, 1995; Bradley and Soulodre, 1997; Beranek, 2011).

In the acoustic measurements of concert halls, it is typical to use a single omnidirectional source and multiple receiver positions, as recommended by the ISO 3382-1 (2009). Similarly, many of the measurements made to study the SDE focus on analysing a single source–receiver pair. While this approach may reveal how individual instruments might be influenced by the SDE, its effect on the section or orchestra sound is bypassed as the instrument sections are

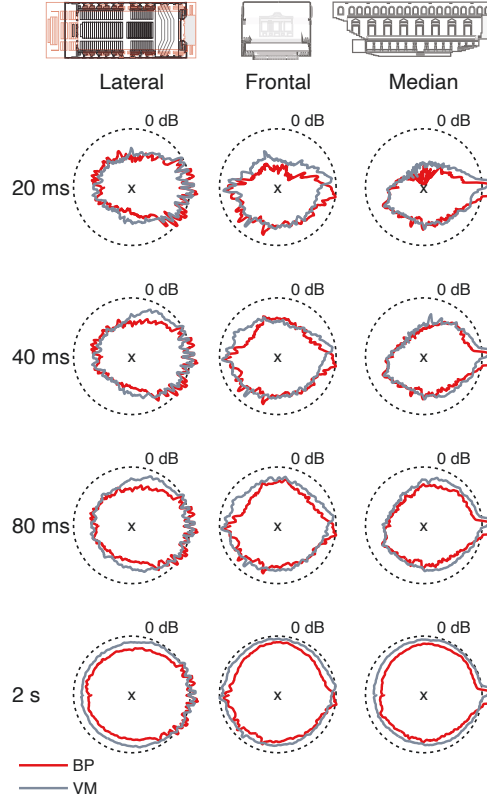


Figure 2.2. The sound energy distribution (normalised to 10 m) of a shoebox-shaped (Vienna Musikverein, VM) and a vineyard-shaped hall (Berlin Philharmonie, BP) below 1 kHz at different time windows after the direct sound.

actually spread around the stage. Moreover, in concert halls with low clarity, the listener may not even be able to focus on the individual instruments but rather on sections or the orchestra as a whole. Therefore, to understand what kind of spectral changes the SDE introduces on the whole orchestra, this thesis uses the approach of averaging multiple sources at each receiver, as presented by Pätynen et al. (2013). The multiple sources are obtained from the loudspeaker orchestra measurements run in various concert halls in Europe (Pätynen, 2011; Lokki et al., 2016). The orchestra was set up on the stage to resemble the layout and directivity of the symphonic orchestra, as shown in Fig. 2.3. As musical instruments tend to radiate omnidirectionally at low frequencies, approximating the instruments with loudspeakers is considered sufficient (Pätynen, 2011). More varied source directivities of the musical instruments can be produced by replacing the loudspeakers with a low-order spherical loudspeaker array with radiation control (Neal and Vigeant, 2020).

Furthermore, the frequency responses of the averaged loudspeaker orchestra

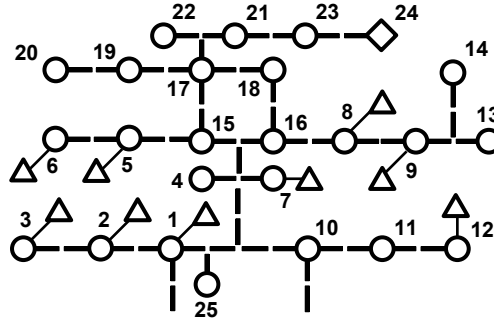


Figure 2.3. The layout of the loudspeaker orchestra used in the concert hall measurements (Pätynen, 2011). The circles indicate the main loudspeakers and the triangle a secondary loudspeaker placed horizontally on the floor. The loudspeakers 1-14 represent different string sections, 15-18 woodwinds, 19-20 French horns, 21-22, trumpets, 23 trombone, 24 tuba and timpani.

measurements are also visualised in a way that communicates the standard parameters and yields more detailed information about the time-frequency development of the RIR, as shown in Fig. 3.2. The analysis is based on the method presented by Pätynen et al. (2013) whereby the frequency response is analysed in 10-ms incremental time windows and scaled with the frequency response at 10 m to obtain a frequency response that is comparable to the strength parameter G .

Parallel to the spectral changes, the directions of arrival (DoA) of the reflections need to be captured with an array of microphones to understand where the reflections in the concert hall are coming from and whether there are some anomalies. The arrays can be planar, circular, or spherical, such as the first-order ambisonic microphone array or the open array with omnidirectional sensors (Tervo et al., 2013).

The earliest method for analysis and synthesis of sound fields in concert halls was Ambisonics (Gerzon, 1975; Farina and Ayalon, 2003). Other commonly used methods for analysing and rendering the direction of arrival of reflections in concert halls with a low number of microphones are the spatial decomposition method (SDM) (Tervo et al., 2013), and Spatial Room Impulse Rendering (SIRR) (Merimaa and Pulkki, 2005). For the discussion on the theoretical and perceptual differences of these methods, the reader is referred to (McCormack et al., 2020). Extensions of these methods in the Ambisonic domain also exist (Zaunschirm et al., 2020).

In this thesis, the RIRs are measured with a six-channel open microphone array, and the analysis and resynthesis of the sound field are carried out by SDM (Tervo et al., 2013). The method estimates a single direction of arrival for each sampling instant. An example of the results of the DoA analysis in the measured concert halls is plotted in Fig. 2.2. For the listening tests, the directional estimates are quantised to the direction of the nearest loudspeaker. To this end, panning can also be used.

2.3 Scale models

Concert halls are expensive to build, and alterations for studying the changes in acoustics are impractical. Therefore, scale models of 1:8 to 1:50 are typically employed in design projects and research work (Knudsen, 1970).

The use of scale models in acoustics is based on the assumption that dimensions, absorption properties of the materials, and air attenuation can be scaled with frequency. In other words, the behaviour of sound depends on the relationship of its wavelength and the size of the object it encounters. It is straightforward to show that frequencies and dimensions have a direct scalable relationship. At the same time, some additional assumptions about material porosity must be made to scale air viscosity (Emori and Schuring, 1977). Air absorption generally presents a problem for acoustic scaling because it is more prominent at high frequencies than at low frequencies (Barron, 2009), and below 5 kHz, other attenuation mechanisms are more pronounced at typical humidity levels in concert halls (Emori and Schuring, 1977). Typically, scale model measurements are run with low-humidity air (2% or so), or the air is replaced by nitrogen in order to improve the accuracy at the high frequencies (Emori and Schuring, 1977; Barron, 1995; Jeon et al., 2009; Baruch et al., 2018). Alternatively, filtering can be applied for correcting the air absorption, but it may introduce artefacts (see for example Polack et al. (1989)).

The absorption materials of the scale model need to be verified in a scale model reverberation room. Choosing the materials is often based on trial and error and ease of building. Wood is often used, and for example, varnishing can help to reduce its ultrasonic frequency absorption (Jeon et al., 2009). Particular attention is paid to the absorption of the seats and the audience, as it is often the major contributor to the overall absorption. Typically, the scale model audience is without legs, but for accurate seat-dip effect studies, it would seem that legs are essential in the case of open seats (Tahvanainen and Lokki, 2018).

The source and the receiver need to be scaled, as well, and the source needs to produce ultrasonic frequencies. To this end, spark sources (Picaut and Simon, 2001; Ayrault et al., 2012), and laser beams (Gómez Bolaños et al., 2013) are often employed. As for the scale model receiver, miniature microphones and scale model heads (Xiang and Blauert, 1993; Robinson and Xiang, 2013) have been used.

For research purposes, the scale models have been used to study the seat-dip effect and ceiling diffusion (Baruch et al., 2018) to mention a few. For the seat-dip effect, the scale models have often been simplified to vertical slat or honeycomb structures (Schultz and Watters, 1964), although to obtain an accurate picture of the scattering and diffraction, a more realistic model is recommended (Barron, 2009). Figure 2.4 shows a scale model designed to study the seating area in Publication II.



Figure 2.4. 1:10 scale model of a chamber music hall seating area with 335 seats.

2.4 Room acoustic simulation

Room acoustic simulations are both a complementary and competing method to scale models when designing and researching concert hall acoustics. Other application domains include virtual reality and game audio, hearing aid research, architectural history and music research (Brinkmann et al., 2019).

Sound is essentially propagating as waves, but it can also be approximated as rays under certain assumptions, mainly at high frequencies. The simulation methods that apply the former approach are called wave-based methods, while the methods using the latter approach are referred to as geometrical acoustics (GA) methods. Wave-based methods include boundary element (BE), finite element (FE), finite difference time domain (FDTD), discontinuous Galerkin and spectral methods, and they can describe diffraction, interference and standing waves (Aretz, 2012; Bilbao, 2013; Hamilton, 2016; Wang et al., 2019). The GA methods include ray tracing, image source method and acoustical radiosity (Savioja and Svensson, 2015), to mention a few, and they can be employed when the mode density and modal overlap in the room are high enough.

Most commercial room acoustics modelling software available is based on the GA methods, which cannot directly model the SDE. However, a recent GA approach exists that takes into account wave phenomena, thus reproducing the SDE (Charalampous, 2020). Many other attempts exist to embed diffraction into GA methods (Calamia, 2009; Pohl, 2014). While commercial FEM and BEM solvers exist, their use has a high computational cost in concert hall acoustics, where the required air volume is large. To tackle this issue, some FDTD-based solvers for room acoustics exist that make use of graphical processing units to speed up the computations (Southern et al., 2013; Saarelma, 2013; Hamilton, 2016). Saarelma and Savioja (2019) have also presented a way to visualise

the spatiotemporal distribution of sound energy at the desired frequency range using FDTD-simulations in room acoustics. All in all, a hybrid approach in room acoustic modelling is often considered due to the strengths and weaknesses of each method (Aretz, 2012; Southern et al., 2013).

2.5 Perceptual evaluation

Perceptual evaluation of concert halls aims to measure how the listeners perceive the acoustics. On the one hand, the listeners are asked to rank the concert halls by preference or some other aspect, such as bass or clarity. On the other hand, there is a general attempt to establish a relationship between perceptual attributes and objective parameters to design purposeful acoustics.

It is physically impossible to compare the acoustics of two or more concert halls simultaneously. To evade the issue, two solutions exist: first, to evaluate concert halls consecutively with questionnaires either in situ (Hawkes and Douglas, 1971; Barron, 1988; Sotiropoulou et al., 1995; Kahle, 1995) or via mail (Hidaka and Beranek, 2000). Evaluating concert halls in situ provides the most authentic experience while being also susceptible to bias and limited by the auditory memory (Sams et al., 1993; Moore, 2012). Specifically, no orchestra would be able to play the same way one concert after the other. In fact, many musicians and conductors tune in to the acoustics of the concert hall they are performing in (Spitzer and Zaslav, 2004).

The second approach to compare the acoustics of concert halls is to reproduce the acoustics in laboratory conditions (Soulodre and Bradley, 1995; Lokki et al., 2016; Pätynen and Lokki, 2016). Sound recordings in concert halls can be used, but the recordings are still dependent on the orchestra. The use of measured (and simulated) RIRs convolved with anechoic symphony orchestra recordings enables direct comparisons between the halls and removes the effect of the orchestra (Schroeder et al., 1974; Pätynen et al., 2008; Weinzierl et al., 2018; Böhm et al., 2021). Depending on the research objective, only the early part of the RIRs can be used (Marshall, 1967; Bradley and Soulodre, 1997; Haapaniemi and Lokki, 2014). In the simulated RIRs, the SDE has been modelled as a filter (Barron, 1974; Barron and Marshall, 1981; Davies et al., 1996).

In this thesis, the convolution approach is used, with the room impulses responses captured from a loudspeaker setup on stage that resembles the layout and directivity of a symphony orchestra. However, this approach is limited by how well it can reproduce the authenticity of the experience with loudspeakers and recordings. In the best-case scenario, not only auditory but also visual, olfaction, and tactile cues would be reproduced accurately. Especially, the seat vibrations may be a part of the low-frequency sensation in concert halls (Merchel and Altinsoy, 2018).

The process of reproducing the acoustics of the concert hall for the listener is referred to as auralisation (Kleiner et al., 1993). It can be either headphone-

based (or binaural) or loudspeaker-based. In this thesis, the concert halls are auralised with two different loudspeaker systems in two different spaces: a listening room with a 24-speaker setup and an anechoic room with a 39-speaker setup.

Apart from the evaluation system, it is important to consider what is being evaluated and how it is carried out. There are three main classes of the perceptual evaluation test methods (Lawless and Heymann, 2010, pp. 5-8). The first class consists of the discrimination tests that measure whether there are any perceivable differences between the acoustic conditions, for example, the audibility of the different SDE types in Publication IV. When the differences are subtle, forced-choice methods, such as paired comparisons and ABX tests, are often employed. If a difference between conditions is apparent, different scales or rankings can be used.

The second class comprises descriptive tests that produce objective or subjective descriptions of the concert halls regarding perceived sensory attributes. A recent example in concert hall acoustics is the individual vocabulary profile tests run by Lokki et al. (2016). The study concluded that the main perceptual attributes for concert halls are clarity/definition, timbre, and reverberance, and it leads to a concert hall acoustics wheel similar to that of wine aroma wheel (Kuusinen and Lokki, 2017).

The third class, referred to as affective or preference tests, employ ranking of choice tests. For example, Lokki et al. (2016) found two preference groups for the concert hall acoustics: those who prefer clarity and those who preferred a high degree of reverberance. In another study, the asynchronous note onset of symphony orchestra instrument groups was preferred (Tahvanainen et al., 2015a). More reviews of sensory evaluation methods in sound are provided by Zacharov (2018).

An axiom of perceptual psychology is that humans are good at comparisons (Lawless and Heymann, 2010, pp. 204). Thus, in this thesis, the perceptual evaluations were carried out as triangle and paired comparison tests to provide a simple and flowing listening test experience. As for the statistical analysis, a Matlab toolbox developed by Wickelmaier and Schmid (2004) was used throughout the thesis.

3. Analysis of the seat-dip effect

This chapter covers the terminology related to the SDE, experimental observations, various explanations of the SDE mechanism and modelling efforts. The research aims to understand the mechanism of the SDE and subsequently to control the attenuation. However, the modelling of the SDE has not been able to satisfactorily explain all the experimental observations. Thus to this day, the mechanism of the SDE is not fully understood. In general, the measurements for the SDE have been made with unoccupied seats since summoning an audience of more than a thousand people can be a daunting task. At the same time, partially occupied concert halls may not give the complete picture of the effect of the audience on the SDE (Tahvanainen and Lokki, 2018).

In this thesis work, Publication I continues the analysis of the SDE with a large number of existing concert hall measurement responses, as preceded by Bradley (1991) and Pätynen et al. (2011). Publication II falls into the continuum of studying the SDE with a scale model but with the approach of averaging multiple sources.

3.1 Definitions and terminology

The SDE in a concert hall occurs when sound from the stage arrives at small angles to the seating area, reflects, and interferes with the direct sound at the receiver position. In some literature, the angle of arrival is measured from the line perpendicular to the incident plane, the virtual plane formed by the top of the seat backrests (incidence angle). However, in this thesis, the angle of arrival is defined as its complement, the grazing angle, i.e., the angle between the incident ray and the incident plane. It means that the angle is measured from the plane formed by the top of the seat backrests, as shown in Fig. 3.1. This is in order to ascribe to the common notion of the SDE occurring at small angles.

Some reflections from the seating area (floor, between the seats, and tops of the seat backrests) arrive at the receiver in-phase and some out-of-phase with the direct sound; they create a pattern of dips and peaks in the frequency response. This pattern changes over time, and it is visualised, for example, in

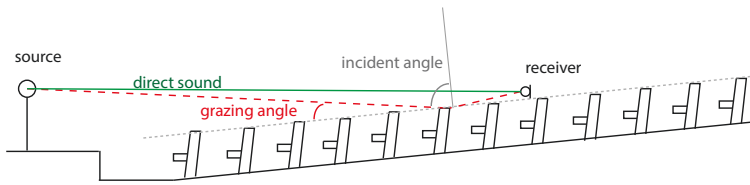


Figure 3.1. The definition of the grazing angle in the seating area.

the large-scale array measurements of an auditorium by Witew et al. (2017). This pattern, the SDE, has the most substantial presence in the early part of the impulse response, with typically one attenuation dip observed at 5-7 ms and reaching its maximum about 15-20 ms after the arrival of the direct sound. The attenuation reached within this time window ideally contains no reflections from the concert hall enclosure, and hence it is called the initial SDE. However, the stage reflection and diffraction from the stage edge can also arrive within the first 20 ms and undergo the SDE (Ishida, 1993, pp. 44-49).

As the non-grazing-angle reflections start to arrive, the impact of the seat-dip attenuation on the later part of the impulse response is much smaller. Figure 3.2 shows an example of the time-frequency development of the impulse response of the two measured concert halls averaged over 24 sources on the stage at different time windows. Figure 3.2 also illustrates the main characteristic variables of the SDE: the main attenuation frequency, attenuation bandwidth, and recovery time. The recovery of the SDE refers to the development of the main attenuation dip in time so that it eventually levels with the rest of the frequency response. Moreover, the level of the low frequencies below the main attenuation dip depends on the seating area design and the build of the walls and ceiling.

3.2 Experimental observations

Based on the earlier research and the results of this thesis, the determining factors for the main attenuation dip appear to be the grazing angle, both in azimuth and elevation, the height of the seat backrest, and the underpass size. Other seat parameters include row spacing and the degree of seat upholstery. Furthermore, the audience's presence seems to affect the SDE in some cases. In addition, the diffraction from the floor in front of the stage seems to play a role. All these aspects are discussed in detail next.

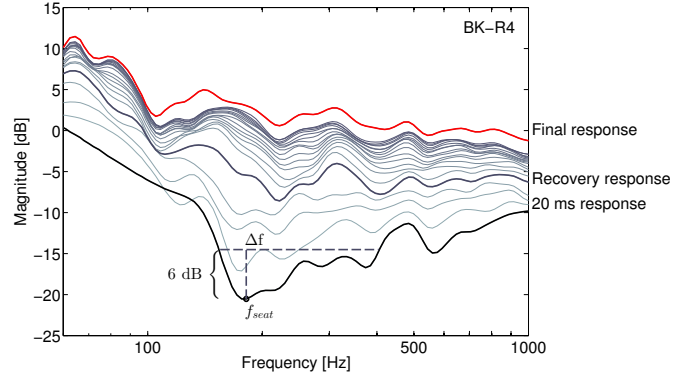


Figure 3.2. Illustration of the time-frequency visualisation and the characteristics of the SDE. The bold line represents the initial SDE, the 20 -ms response. The main attenuation frequency is marked as f_{seat} , and the attenuation width as Δf . Recovery time can be calculated from the recovery response, as each thin grey line represents a 10-ms increase in the analysed time window. In this case, the recovery time is 60 ms.

3.2.1 Seat properties

The seat consists of a backrest and a base. The seat base may be tipped-up; in such a case, the bottom of the base is typically padded with absorbent material. The backrest may extend to the floor, or there may be an underpass, in which case the base may rest on pedestal support. In this thesis, the former case is called a closed seat and the latter an open seat. Often the underpass of an open seat may be obstructed by a step-wise raking floor. Such a seat is called a blocked seat. These different types of seats are illustrated in Fig. 3.3.

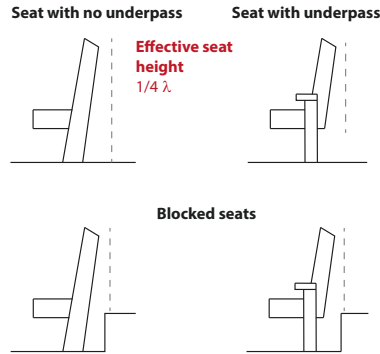


Figure 3.3. Seat with no underpass (Closed seat), Seat with underpass (Open seat), and versions of both where the step-wise raking floor is obstructing the underpass (Blocked seat). The effective seat height corresponds to the height of the seat backrest that is not blocked.

The height of the unobstructed seat backrest (labelled as effective seat height in Publication I) dictates the main attenuation frequency, which is close to a quarter-wavelength of the effective seat backrest height (Ishida, 1995; Bradley,

1991). In the concert hall measurements in Publication I, the main attenuation frequency appears to follow relatively well the effective seat height. However, in the scale model measurements in Publication II, the measured main attenuation frequency is lower than postulated for the closed seats and higher than postulated for the open seats. In addition, the seat underpass seems to affect the level below the main attenuation frequency as postulated by Davies (1992) and Ishida (1993) and shown in measurements in Publication II.

In typical concert halls, the seat height and the row-to-row spacing have similar dimensions (Appleton and Fischer, 2015). The row spacing appears to affect, in particular, the number of dips observed in the initial SDE (Bradley, 1991). In addition, the SDE requires a minimum number of seats per row (Davies and Lam, 1994) and a minimum number of rows to form.

The degree of the upholstery of the seats appears to have minimal effect on the SDE (Sakurai et al., 1993). However, some simulations suggest that seat absorption could reduce the SDE (Davies, 1992; Liao and Min, 2019). In practice, the seat absorption coefficients are obtained by measuring seating blocks rather than individual seats in the reverberation room (Bradley, 1992; Nishihara et al., 2001). The absorption coefficients are also affected by the seat geometry, layout, and possibly by some vertical resonances between the seats (Choi et al., 2015).

On a final note, lightweight removable seats with large underpasses, such as those in the Beethovensaal in Stuttgart, Germany, seem to move the main attenuation frequency SDE to about 350 Hz and the dip levels off within 30-40 ms after the direct sound as shown by the measurements in Publication I.

3.2.2 Grazing angle

The grazing angle in elevation is determined by floor raking, the height of the stage and the receiver, and the distance between the source and the receiver. In azimuth, the angle is determined by the relative horizontal location of the source and the receiver. The effects of azimuth and elevation grazing angle on the SDE can be seen in many ways. One of the first notable observations is that the main attenuation dip appears after the sound has travelled through several seat rows, and the attenuation worsens with distance as the angle of incidence decreases (Schultz and Watters, 1964; Sessler and West, 1964). The SDE cannot be observed on the balconies, as they generally contain a few rows of seats. In addition, the attenuation is worse at the height of the seated listeners' ears but reduces with increasing receiver height until the attenuation dip disappears. Consequently, more bass may be heard in concert halls when standing up from the seats (Bradley, 1991).

There are several ways to increase the grazing angle and thus reduce the seat-dip attenuation. Apart from raising the source itself, the source height can be increased by making the stage higher. It should be noted that the reflection from the stage floor and the diffraction from the stage edge will be different between raising the source and raising the stage. In addition, the angle of incidence can

be increased by floor raking. A steeper raking leads to a steeper attenuation dip and lower main attenuation frequency than the flat floor (Davies, 1992; Ishida, 1993).

3.2.3 Averaged seat-dip attenuation

Much of the previous research has focused on analysing the SDE from the perspective of a single source. However, the approach adopted in this thesis to replace the standard omnidirectional source with a loudspeaker orchestra on stage brings out more distinct average properties of the SDE.

The average response of multiple source positions exposes the SDE and its main characteristics more clearly than individual measurements. The peak-dip pattern for individual source–receiver pair varies drastically, and it is hard to find any trends. This is perhaps best illustrated when observing the time–frequency development of the main attenuation dip. Following the approach by Davies and Lam (1994), the spectral minimum and its frequency, i.e., the main attenuation frequency, are plotted at a cumulative time window of 1 ms in Fig. 3.4. It shows for one receiver location the results of each source–receiver pair and the source-averaged response.

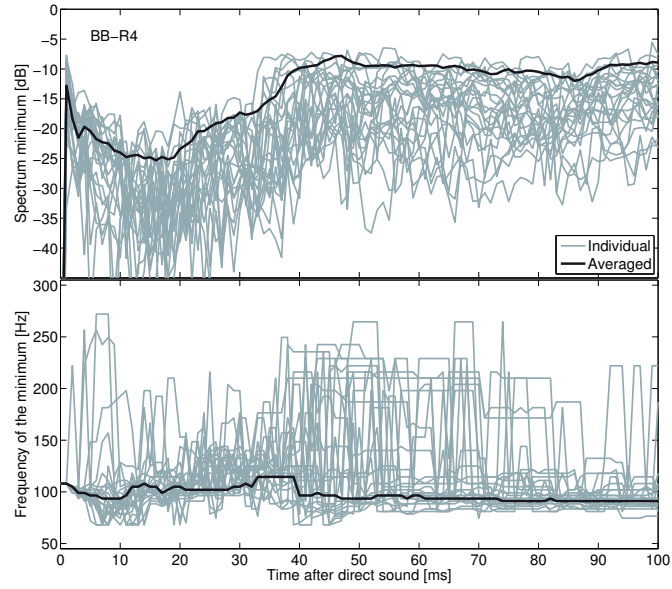


Figure 3.4. The attenuation minimum in dB (top) and the main attenuation frequency (bottom) at a cumulative 1 ms time windows for single source–receiver pair (grey lines) and the source-average (bold black line) at one receiver location.

It can be seen that the main attenuation frequency of the single source–receiver pairs varies with time, indicating that the peak-dip pattern is quite complicated. However, the main attenuation frequency of the source-averaged response stays much more constant, showing that the main dip persists almost at a constant

frequency. Similarly, the spectrum minimum takes a clearer shape with the source-averaged response. When the source averages are plotted for several concert halls, an interesting pattern emerges, as shown in Publication I. The shoebox-shaped concert halls with open seats and flat floors experience a deeper spectrum minimum than the vineyard-shaped halls with closed seats and raked floors, and the spectrum minimum also recovers faster.

Another result of Publication I is that the majority of concert halls fall into one of the two types of averaged initial SDE spectra: those that have a relatively shallow main attenuation dip at around 200 Hz that extends to 1 kHz, and those that have a deep dip around 100 Hz or below. The spectra of the two profiles are shown in Fig. 3.5 for Berlin Konzerthaus (shoe-box) and Berlin Philharmonie (vineyard). The former was observed in shoebox-shaped halls with a flat floor and open seats in the measured concert halls. The latter was observed in fan/vineyard-shaped halls with raking floor and closed seat. The scale model measurements in Publication II verified that the main attenuation frequency is related to the effective seat backrest height, albeit not precisely by $1/4$ of the wavelength. In contrast, the attenuation width was associated with the floor raking and its effect on the grazing angle. The attenuation bandwidth also becomes narrower because floor raking increases the positive diffraction from the tops of the seat backrests in front and behind the receiver, especially above 500 Hz.

The recovery is also different between the two average spectrum types, as can be seen in Fig. 3.5. This depends on the geometry of the concert hall enclosure and is discussed later on. The perceptual differences between these two SDE types were studied in Publication IV.

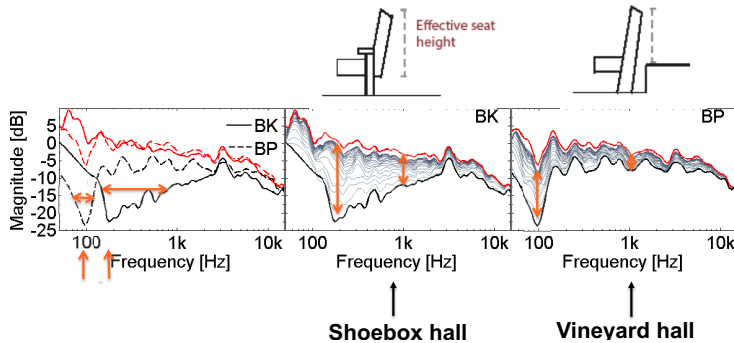


Figure 3.5. The main two types of the average SDE spectra illustrated with Berlin Konzerthaus (BK, shoe-box) and Berlin Philharmonie (BP, vineyard). In the left-hand plot, the black lines depict the initial SDE at 20 ms, and the red lines the final frequency response at 2 s.

3.2.4 Presence of audience

The audience becomes a part of the periodic structure formed by the seats. The human tissue itself is not known to absorb low frequencies very well, but the seated audience changes the geometry of the seating area in at least two ways that affect the low frequencies. First, the legs of the seated listener may obstruct or irregularise the seat underpass. Thus, the effective seat height becomes more extended, and the main attenuation frequency could be lower than in the unoccupied case. However, depending on the size of the underpass, the obstruction may only be partial, in which case some sound can pass through the underpass.

Second, the shoulders and the head occlude the distinct diffracting edge - the top of the seat backrest. Consequently, if the original seat backrest remains below the shoulders of the seated listener, the effective seat height increases with the seated audience, and the main attenuation frequency could be lower. However, it is not clear whether the main diffracting surface is the head or the shoulders. Mommertz (1993) measured sound propagation over the audience and showed the shoulders indeed reflect sound. In addition, he found evidence of the so-called head-dip effect at 1-2 kHz.

Consequently, seats that are closed or obstructed, and have a seat backrest higher than the listener's head, or at least higher than the shoulders, should generate an SDE that does not depend on the audience. Otherwise, the SDE should be different in the occupied and unoccupied case.

Indeed, some of the previous work on the SDE report a change in the effect with the presence of audience (Ishida, 1993; Mommertz, 1993), while others report no effect (Schultz and Watters, 1964; Sessler and West, 1964). A more detailed review of the previous results that report no effect reveals that many measurements were made with a large number of empty seats (occupancy around 10%) (Tahvanainen and Lokki, 2018). This means that the audience most likely did not cover a significant part of the seating area to considerably alter the SDE. Furthermore, the audience's presence was not expected to alter the essential seat features defining the SDE, such as seat underpass and seat backrest height.

For example, the measurements conducted in Publication I in a partially occupied concert hall (9%, occupants around and in front of the microphone) showed no change in the SDE in the presence of an audience. The seats in that concert hall had no underpasses, but the seat backrest height was lower than the height of the shoulders of an average seated listener. Thus, a change in the main attenuation frequency could have been observed. However, it is possible that the number of audience members was insufficient.

Similarly, the measurements conducted by Sessler and West (1964) at the Philharmonie Hall at Lincoln Center in New York showed no change in the SDE in the 20-ms response with and without an audience. The hall features open seats on a slightly inclined floor. However, only the first six rows of seats were occupied, which may not have been sufficient, considering that the SDE reaches

its maximum at a much larger distance. In addition, the seat underpasses were small and could have been blocked by the step-wise raking floor even without the presence of the listeners' legs. Likewise, Schultz and Watters (1964) measured La Grand Salle in Montreal partially occupied (10 %) by 100 people: 8 rows in front and behind the receiver. No influence of the audience on the SDE was observed. The concert hall features a raked floor, so presumably, the seats are blocked. Based on the photos of the concert hall, it also seems likely that the seat backrest was higher than the shoulder height of the seated listener. Finally, it may also be that 100 people may not be enough to bring out the effect of the fully occupied seats.

Previous research that has shown some effect on the audience includes the work of Ishida (1993, pp. 70-79). The results show a reduction of low frequencies in the fully occupied Snape Maltings concert hall in Snape, UK, installed with very lightweight seats with underpasses. He found that the ratio of the main attenuation frequencies in the occupied and unoccupied case is the ratio between the seat backrest height and the height of the seated audience, as postulated above.

A part of the SDE is the broad peak at the low frequencies below the main attenuation dip, occasionally referred to as bass boost. Ishida (1993) and Davies (1992) touch the issue in their theses, but no further investigations appear to have been made on the matter. Ishida postulated that the bass boost occurs due to the multiple reflections between the low part of the seats and the floor (Ishida, 1993, pp. 60-62). In the measurements in Publication II, it was noticed that the bass boost was reduced with obstructed underpasses. Based on the observations of Ishida (1993) and Tahvanainen and Lokki (2018), the bass boost may be reduced when the legs of the seated listener substantially obstruct the underpass. Tahvanainen and Lokki (2018) noticed that the presence of the audience reduced the level below the main attenuation frequency in many different hall settings. Thus the bass boost may also be related to the geometry of the spacing between the seat rows.

It is worth noting that in some concert halls, the reflection-diffraction pattern of the SDE may change due to tip-up seats. In that case, when occupied, changing the spacing between the seats becomes smaller, and the lap acts as an additional reflecting surface compared to the unoccupied case. These changes are typically seen at frequencies higher than the main attenuation frequency.

At high frequencies, the audience adds absorption, and the audience's presence tends to alter other acoustical parameters of the concert hall, such as reverberation time. It is estimated that the audience accounts for 60-80 % of the absorption in concert halls, and the absorption depends on the angle of arrival (Nishihara et al., 2001). A typical design strategy for seat materials is to match the absorption of the empty seat to that of the seated audience so that the changes between empty and occupied halls would be as small as possible.

To conclude, the audience seems to affect when the essential seat parameters change due to the audience's presence, especially in the case of seats with

underpasses.

3.2.5 Recovery

The seat-dip attenuation recovers or levels off as more and more reflections arrive at the listener. The recovery depends on the reflections provided by the concert hall geometry (Bradley, 1991; Pätynen et al., 2013). The recovery rate is not constant because each reflection arriving at the listener contributes differently to the accumulating energy. It is in part because the SDE is angle-dependent. As shown by Pätynen et al. (2013) and in Publication I, concert halls that provide more early reflections tend to recover better from the initial SDE than concert halls with fewer early reflections.

When the SDE was first discovered, it was considered that perhaps it is not perceivable in most halls because the non-grazing reflections will cover it up (Schultz and Watters, 1964). Based on the results in Publication I, it appears indeed that shoebox-shaped concert halls that have strong early reflections can level off the initial SDE well. Furthermore, concert halls that have a relatively low level of reverberation, such as the vineyard- and fan-shaped halls with raking floor and closed seats, tend to have an attenuation dip in the full RIR as shown in Publication I.

It was suggested that ceiling reflections (Bradley, 1991) and the lateral reflections (Pätynen et al., 2013) might level off the initial SDE. However, especially ceiling reflections may colour the sound and should not be used on their own as a remedy for the seat-dip attenuation (Davies et al., 1996). Based on the analysis of measurements in twelve concert halls in Publication I, it appears that generally, the SDE is well-corrected in the later part of the frequency response in concert halls where the spatial sound energy between 30-120 ms is more or less omnidirectional.

The recovery time can be estimated in many ways by using the narrow frequency range affected by the initial SDE (Pätynen et al., 2013). For example, the centre time of the main attenuation frequency can be calculated, which indicates the overall energy increase. Another way to estimate the recovery time is to measure the flatness of the frequency response by comparing the accumulating energies of the main attenuation frequency and a reference frequency, say at 1 kHz. As a simple observation for the accumulating time-frequency response, one could also estimate when the magnitude of the main attenuation has increased by a certain amount. From this approach, one can also find the time window during which the seat-dip attenuation is maximally recovered. Based on measurements in twelve European concert halls, the time window of maximal recovery is between 30-80 ms after the direct sound (Publication I).

3.3 Mechanism

The experimental observations have led to several explanations and theories about the mechanism of the SDE. The mechanism can be viewed both in the time and frequency domain. At its simplest, a seat-dip-like effect can be generated by a signal and its delayed copies. Their combination results in an inverse comb filter, as the signal and its copies would be out-of-phase at the listener's position at particular frequencies corresponding to their time delay and would interfere destructively. In a concert hall, multiple surfaces can generate delayed copies of the original signal; therefore, the comb-filter effect varies with time.

The destructive interference occurs due to a phase change. Ishida (1995) showed with a simple model of two parallel barriers that since the source and the receiver are both above the seats, the direct sound interferes with various diffracted and reflected sound paths between the seats. Each reflected path interferes destructively with the direct sound at some low frequency. The main attenuation dip occurs when the diffracted sound wave reflects off the floor between the seats (Ishida, 1995; Economou and Charalampous, 2015). Combining these paths for several sources on stage is considered to explain the two seat-dip attenuation profiles observed in Publication I. It is considered that seats with underpass allow for more varied pathways than the closed seats, and thus the attenuation of the open seats is more broadband.

One reason why the sound waves bend between the seats can be found in the change in absorption brought about by the seating area. Sound travelling at grazing angles in the vicinity of an absorptive surface bends towards that surface. This effect occurs outdoors for sound travelling close to the ground, albeit at much larger scales than in a concert hall (beyond a distance of 100 m) (Attenborough and van Renterghem, 2021). In concert halls, the sound bends between the seats as the seating area introduces an absorptive surface at low frequencies in the concert hall. Notably, the absorption appears to be non-local, i.e., angle-dependent (Sakurai et al., 1993; Takahashi, 1997).

In addition to the bending, the tops of the seat backrests act as secondary sources, and these secondary spherical reflections can be seen in the FDTD-simulations (Lokki et al., 2011b) and measurements (Witew et al., 2017) of the audience seating area. This phenomenon is referred to as diffraction. According to Ishida (1995), the diffraction from the tops of the seat backrests causes positive interference at high frequencies.

The seating area forms a periodic structure that allows for multiple ways of sound scattering. Sound travelling at grazing angles over rough surfaces, either periodic or non-periodic, undergoes low-frequency attenuation (Biot, 1968; Twersky, 1957; Tolstoy, 1982). It happens when the roughness is small compared to the acoustic wavelength. The periodic roughness introduces surface waves (Tolstoy, 1982). Indeed, Schultz and Watters (1964) postulated that the boost of low frequencies below the main attenuation frequency is created at least partially due to acoustic surface waves. The supporting measurements were done with a

scale model of a honeycomb structure. Mommertz (1993) continued experiments with parallel barriers and explained that at low frequencies, the seating area could support guided surface waves whose cut-off frequency corresponds to about a quarter wavelength of the barrier height. Surface waves emerge as the air particles form elliptical motion by moving parallel and perpendicular to the floor. Indeed, directly on top of the seats, the sound intensity vectors shows vortices at some low frequencies in the FE-simulations (Liao and Min, 2019). It means that some of the sound energy is trapped near the seated ear level.

Proving the existence of surface waves in actual concert halls may be difficult because other reflections are also present (Schultz and Watters, 1964). Mommertz (1993) attempted to quantify the surface waves with measurements in a multipurpose hall by placing the loudspeaker and microphone close to the floor to evade direct sound. The level of low frequencies was higher at seated ear level than closer to the floor. He then attributed the increased level of mid-and high frequencies at the ear level to the scattering from the top of the seat backrests. According to Mommertz (1993), the attenuation gap between the low frequency boost by the surface waves and the mid-and high frequency scattering would then be the observed main attenuation dip of the SDE. In the measurements in Publication I and Publication II, the boost of low frequencies at seated ear level is primarily seen with open seats. It is suspected that the open seats allow for more air space and thus particle motion parallel to the floor, and this may increase the surface wave component at the seated ear level. Ishida (1993) noticed that the low frequencies below 50 Hz were actually reduced with the absence of a rigid floor. In sum, the role of surface waves on the SDE requires further research.

In the frequency domain, the SDE has been explained with the cavity between the two consecutive seats acting as a vertical resonator (Sessler and West, 1964). The resonance frequency depends on the seat backrest height and whether the seats are open with an underpass, thus forming a cavity open at both ends (half-wave resonator) or closed at one end (quarter-wave resonator). Also, a horizontal resonance could be formed between the two seating rows. Bradley (1991) proposed the horizontal resonance to account for the secondary dip at a higher frequency in certain seat backrest height and row spacing combinations.

The resonator theory has received some critique for not explaining the time-varying effect of the SDE. The resonance theory is also not supported by the fact that the main attenuation frequency seems to correspond more or less to a quarter wavelength of the effective seat backrest height as shown in the extensive measurements in Publication I and by Ishida (1995) and Bradley (1991). Furthermore, the resonance theory does not directly explain the dependence of the main attenuation frequency on the angle of incidence, as the frequency does vary about an octave with the grazing angle (Ishida, 1995). However, it is possible that the horizontal spacing becomes significant at larger angles of incidence (Bradley, 1991), since occasionally two apparent attenuation dips are present, especially in the case of closed seats and raked floor. However, the fact

that the main attenuation frequency is more affected by row height than row spacing can also be explained by the path difference created by each change. By simple two-dimensional geometrical analysis, it can be seen that doubling the row height will increase the path between the seats more than doubling the row spacing.

To summarise, the SDE appears to be a sum of multiple phenomena: destructive interference, diffraction over periodic roughness, and bending towards an absorptive surface. In addition, surface waves could explain the boost of the level below the main attenuation frequency. Finally, some resonances between the vertical and horizontal spacing between the seats may also be involved, although the mechanisms mentioned above appear to be sufficient to explain the effect.

3.4 Modelling

Two purposes for modelling the SDE have emerged. On the one hand, modelling can contribute to the understanding of the effect, and on the other hand, the SDE needs to be taken into account in the simulations used for concert hall design.

The simplest analytical model of the sound travelling over the seating area can be constructed analytically in 2D. The geometry can consist of slats placed at regular intervals or a number of uniform absorptive layers on a semi-infinite plane or a combination of these. Such analytical models tend to reproduce some of the experimental observations regarding the SDE, but not all. These analytical models were convenient before it was computationally feasible to use wave-based methods for concert hall modelling.

Ando et al. (1982) modelled the SDE as a single reflection from a periodic boundary, and his results matched the overall frequency response of a seating area scale model. With the help of the model, he showed that the SDE could be reduced by making the floor absorptive. Takahashi (1997) studied the SDE with scattering from a periodic boundary and a single reflection from a layered boundary surface. He showed that an absorptive surface will always yield low-frequency attenuation at grazing angles. However, even the addition of the periodic boundary by approximating the seats as slats could not improve the analytical model enough to capture the correct effect of incidence angle on the SDE. However, a layered admittance model used as a boundary condition in BEM simulations by Osa et al. (2007) yielded similar results as periodic seating row model (Tomiku et al., 2014, pp.154-163). Furthermore, Kawai and Terai (1991) used two- and three-dimensional BEM models to study the SDE, but their results did not agree well with measurements. Davies and Cox (2000) used a 2D BEM model to study pits under the seats as a remedy to the SDE and verified the results with a scale model. The use of BEM has also been reported by Cheene (1995) in the study of sound transmission over theatre seats. To model the seating area as a part of the concert hall requires elaborate and

computationally heavy room acoustic modelling. The implementation of multiple diffractions is required to model the SDE, and that can readily be provided by wave-based simulation methods such as the FDTD and BEM. LoVetri et al. (1996) and Lokki et al. (2011b) have shown FDTD-simulations of the SDE that yield informative visualisations of the reflected waves. Saarelma and Savioja (2019) have shown visualisations of FDTD-simulations of slatted structures in rooms. These modelling methods, however, are not yet available for full audio bandwidth.

On the contrary, the round-robin simulations of a concert hall reveal that most room acoustic algorithms that are available for full audio bandwidth cannot accurately predict the low frequencies as they are based on GA methods (Brinkmann et al., 2019). Some techniques exist to attempt to take into account the SDE in the GA models (Savioja and Svensson, 2015; Cirillo and Martellotta, 2004; Economou and Charalampous, 2015; Charalampous, 2020). For example, Cirillo and Martellotta (2004) used commercial room acoustic simulation software and added acoustically semitransparent planes for church pews to simulate the selective absorption of the SDE, and they reported an improvement in the prediction model. Furthermore, a geometrical wave-based method has been reported to simulate the effect well due to incorporating spherical reflection coefficients (Economou and Charalampous, 2015; Charalampous, 2020).

An alternative approach considering the SDE in the GA models would be to detect and filter the early reflections arriving at grazing angles using, for example, a filter constructed from the averaged measured RIRs in Publication I. Barron and Marshall (1981) and Davies et al. (1996) have also used SDE filters in their simulated concert hall RIRs. With a filter approach, it has been shown that spectral colouration due to source directivity can be sufficiently modelled with an average filter for the first early reflections in a perceptually-motivated room acoustic simulation (Steffens et al., 2021).

4. Perception of the seat-dip effect

This chapter explores the detection of the SDE and other perceptual aspects related to the low frequencies in concert halls. As the SDE is a low-frequency phenomenon, it is assumed to hamper the perception of low frequencies in performance spaces. Since the discovery, the considerations for the perceptual significance of the SDE have been twofold. Schultz and Watters (1964) suggested that the perceptual effect of the SDE is not drastic if the reverberant field is sufficiently strong. Similarly, Kuttruff (2001, pp.179) did not consider the SDE an acoustic fault since it occurs in all concert halls. Sessler and West (1964), on the other hand, were concerned that the sound quality in the stalls would be inferior to that in the balconies and suggested that a steeply raking floor would minimise the adverse effects of the SDE. Continuing on this line, Barron and Marshall (1981) noticed that seat-dip-filtered lateral reflections reduce spatial impression. Following the idea of the detrimental effect of the SDE on the acoustics of the concert halls, many different solutions were proposed to reduce or eliminate the effect (Ando et al., 1982; Bradley, 1991; Davies and Lam, 1994; Davies and Cox, 2000). Echoes of this are still carried to today, with a recent book on the topic targeted to a wider audience classifying the SDE as an acoustical defect (Blessner and Salter, 2009). In this thesis work, the result of Publication IV underlines that the perceptual effects of the SDE may not be as serious as previously thought.

Several metrics calculated from the RIRs have been proposed to capture the perception of low frequencies in concert halls. However, these parameters consistently exclude the octave bands below 125 Hz and, in some cases, even 250 Hz (Kirkegaard and Gulsrud, 2011), meaning that the parameters do not cover the SDE. In this thesis work, Publication III shows that the existing parameters cannot adequately capture the low-frequency perception in concert halls.

As the overall musical experience in a concert hall also depends on musical instruments, repertoire, and properties of human hearing, simply considering the effect of SDE on the RIR and its derivative parameters does not provide a complete picture of the perceivability of the SDE. While the RIR is linear (although frequency-dependent), musical instruments and human hearing possess level-dependent features (Lokki and Pätynen, 2020b). For example, the

perceived reverberance seems to depend on the level (Lee and Cabrera, 2010). At least hearing sensitivity, auditory masking, and temporal integration time may be relevant for the perceptual effects of the SDE. Musical instruments have direction- and level-dependent frequency responses, and occasionally they interact with other structures, such as the stage floor.

4.1 Detection of the seat-dip effect

The design for eliminating the SDE starts from the premise that the SDE is detrimental to the acoustics of the performance venues. Some authors have concluded that having a flat early frequency response in concert halls is unnecessary, for if it were, the effect would have been noticed much earlier than in the 1960s. Nonetheless, there appear to be only two articles directly addressing the question of perceptibility of the SDE, Davies et al. (1996) and Publication IV of this thesis.

Davies et al. (1996) obtained a perceptual threshold for the SDE with respect to changes at the 200 Hz octave band at 80 ms using simulated concert halls. The just noticeable difference (JND) was found to be -3.8 ± 0.2 dB. Moreover, from these results, a JND at 18 ms was extrapolated (Davies and Cox, 2000). There are, however, a few limiting factors to this result. First, the SDE typically extends beyond the 200 Hz octave band. Second, the same SDE spectrum was applied to the direct sound and early reflections, although the SDE depends on the incident angle of each reflection. Third, the range of the parameters of the simulated concert halls used in the study was limited to fairly dry halls, as clarity C_{80} varied between 0.2–3 dB.

In Publication IV, the perceptibility of the initial SDE was studied with RIRs of real concert halls with more ratios between early and late reflections (C_{80} -2.5–2.2 dB). The direct sound 0–15 ms was manipulated to correspond to one of the two averaged SDE types: narrowband SDE centred at 100 Hz or asymmetric wideband SDE dipping at 250 Hz, as shown in Fig. 3.5. As a third category, the direct sound was uncoloured, meaning that its spectrum was modified to be flat. Otherwise, the RIRs were kept unmodified. The listening test results were not in line with the threshold obtained by Davies et al. (1996). The direct sound colouration due to the initial SDE is not significantly audible in the presence of sufficient reflected energy, even if the threshold was exceeded. When the colouration was audible, the preference was towards the uncoloured sound, indicating that strong low frequencies in the concert hall are preferred. Based on the listeners' comments, the low-frequency dip in the direct sound affects the strength of low frequencies and timbre.

4.2 Perceptual aspects

4.2.1 Low-frequency room acoustic parameters

The attempt to quantify the perception of room acoustics with parameters has lead to the ISO 3382-1 (2009) standard that describes the measurement procedures of the room acoustic parameters in performance spaces. The parameters come with just noticeable differences that can help evaluate whether the changes in the room acoustics are perceptually significant.

In addition, several parameters exist outside the standard, and several authors have identified the need for extending the ISO parameters (Kirkegaard and Gulsrud, 2011; Bradley, 2011; Nishihara and Hidaka, 2012). In particular, since the ISO parameters do not cover the low frequencies, additional parameters have been introduced to evaluate the perception of bass and to quantify the SDE (Davies and Lam, 1994; Bradley, 1991; Bradley and Soulodre, 1997; Barron, 1995; Beranek, 2011), albeit with varying degrees of success. This is exemplified by the results in Publication III; the proposed parameters do not indisputably correlate with the perception of bass in concert halls.

Perceived level

The most frequently cited room acoustic parameter, strength G , is correlated with the subjective level of sound (ISO 3382-1, 2009). It is defined as the ratio of the sound energy between the omnidirectional source measured at a receiver, $p(t)$ and at 10 m in the free field ($p_{10}(t)$) over the entire room impulse response

$$G = 10 \log \frac{\int_0^\infty p^2(t) dt}{\int_0^\infty p_{10}^2(t) dt}. \quad (4.1)$$

With different integration time windows and bandwidth covered, some derivatives of this parameter have been studied as possible indicators for the perceived level of bass in concert halls. To this end, the strength G is redefined as a function of both time window tw in milliseconds and the centre frequency of the octave band f_c ,

$$G(tw, f_c) = 10 \log \frac{\int_0^{tw} p^2(t, f_c) dt}{\int_0^\infty p_{10}^2(t, f_c) dt}. \quad (4.2)$$

For example, Bradley (1991) considered the early strength of the first 40 ms, $G(40)$, to indicate the subjective perception of bass. In a binaural listening test involving ten assessors, Soulodre and Bradley (1995) found a correlation between the perceived level of bass and the early strength $G(50, 125 - 500)$, i.e., G measured at 50 ms after the direct sound at the 125 to 500 Hz octave bands. Later, Bradley and Soulodre (1997) found a linear relationship between $G(80, 125)$ and the perceived level of bass in a listening test with ten assessors.

Some additional results can be found in a conference abstract by Morimoto et al. (2001), where the listening tests based on scale model measurements

showed that the SDE influences the perception of both bass and loudness and that the bass perception should be evaluated within the first 100 ms after the direct sound.

Apart from the direct strength parameters, their ratios at different octave bands have been proposed to describe the perceived level of bass. For example, Beranek (2011), based on an earlier suggestion of bass level balance by Barron (1995), proposed a strength-based criterion for the perception of bass in concert halls called the Bass Index (BI),

$$BI = G(\infty, 125) - [G(\infty, 500) + (G(\infty, 1000))] \quad (4.3)$$

A serious shortcoming of these parameters is that they do not extend to the 63 Hz frequency band, as pointed out by Kirkegaard and Gulsrud (2011) and that they do not seem to explain the perceptual results in concert halls in every case. For example, in Publication III, the perceived level of bass was studied in concert halls only with the musical instruments with low-frequency fundamentals and notes played between approximately 60–180 Hz. The results show that the concert halls with lower seat-dip frequency and less reflected sound energy were perceived to have the lowest level of perceived bass. The perceived level of bass correlated best with the aforementioned strength-based parameters when the 63 Hz octave band was included. Still, none of the considered parameters would rank the concert halls in the same order as the perceived level of bass. Indeed, Lokki and Pätynen (2020b) showed that the level-independent strength parameter could not accurately reflect the perception of the low frequencies as the growth rate of hearing sensitivity increases with the level at low frequencies.

Previously, increasing the low-frequency reverberation time was suggested to compensate for the missing low frequencies due to the SDE (Beranek, 2004). However, listening tests by Bradley and Soulodre (1997) showed that the perceived level of bass correlated with early and late levels in concert halls rather than reverberation time at the 125 Hz octave band. Kahle (1995) found the Early Decay Time (EDT) to somewhat correlate with the perception of the level of bass.

Clarity

The low frequencies are often described with adjectives related to sound quality, such as "boomy" or "muddy". Sound quality is often equated with clarity which refers to the degree to which sounds can be distinguished in music (Beranek, 2004) or the ability to hear musical detail (Barron, 2009). According to Reichardt et al. (1975), subjective clarity has at least two aspects: 1) how well notes are separated in time and 2) how well simultaneously playing instruments can be distinguished. High clarity in a concert hall is often associated with low perceived reverberation (Barron, 2009).

The clarity index C_{80} (Reichardt et al., 1975) is defined as the ratio between

the early and late sound energy with a cross-over time of 80 ms,

$$C_{80} = 10 \log \frac{\int_0^{80ms} p^2(t) dt}{\int_{80ms}^{\infty} p^2(t) dt}. \quad (4.4)$$

Other parameters to describe clarity include centre time and definition (ISO 3382-1, 2009). Some time-varying clarity parameters based on binaural responses also exist (Lee et al., 2018).

Clarity depends on the musical excerpt and the musical instruments. The parenthetical comments of the assessors in the listening tests in Publication III raise the point that that clarity seems to correlate with the perceived level of bass and that the presence of more bass improves the articulation of the instruments. Likewise, Soulodre and Bradley (1995) have also concluded that the assessment of clarity should include a loudness component.

Timbre

The low frequencies are often attributed to "warmness", which is considered a timbral description (Schultz, 1965). Timbre, or tone colour, is a property that can be used to characterise the quality of sounds in addition to pitch, loudness, duration, and spatial position, and even room reverberation (McAdams, 2013). It is one of the primary cues for musical instrument recognition and can be, albeit crudely, approximated by looking at the distribution of overall spectral energy (Moore, 2012). Changes in the timbre of musical instruments may also help identify the dynamic strength, i.e., whether the instrument is played pianissimo or fortissimo (Weinzierl et al., 2018). Timbre encompasses time-varying aspects (such as the attack, brightness, richness) and more discrete features such as interaction sound between the player and the instrument.

Timbre is one of the key perceptual characteristics of concert halls, along with loudness and clarity. In perceptual studies of concert hall acoustics, it has been found to consist of perceptual attributes related to bass, brightness and proximity (Kuusinen and Lokki, 2018). Similarly, the comments by the listening test participants in Publication III and Publication IV indicate that alterations to the main attenuation frequency of the SDE and its bandwidth within the first 15 ms change the perceived timbre. The timbral aspects have not been widely discussed in the context of the SDE and may provide a fruitful topic for future research.

Auditory spaciousness

Auditory spaciousness is a multidimensional perceptual attribute, describing the sensation of being surrounded by music, and it is predominantly caused by the level of early lateral reflections (Blauert and Lindemann, 1986). With simulated concert halls, Barron and Marshall (1981) found that the SDE can affect auditory spaciousness, with seat-dip filtered lateral reflections resulting in a reduced spatial impression. Furthermore, when low frequencies were removed from the lateral reflections, it resulted in a smaller sound spread and thinner

sound. In other words, the low frequencies below 400 Hz are an essential part of auditory spaciousness (Barron, 1974, pp.73). However, the effect of SDE on auditory spaciousness could be more carefully studied in the presence of ample reflections and actual concert hall responses.

4.2.2 Hearing properties

Some properties of human hearing particularly contribute to the perception of the low frequencies in concert halls. These provide some answers as to when and from where should the low frequencies arrive at the listener.

The first property is auditory masking - a process by which the threshold of audibility for a sound is increased by the presence of a masking sound (Moore, 2012). Masking can occur in frequency, space, and forwards and backwards in time. A particular consequence of masking is the precedence effect that determines the perceived location of a sound source based on the first arriving sound with an echo threshold (Moore, 2012, pp.253–256). In the context of concert halls, it implies the direct sound and the early reflections arriving within the threshold time window are perceptually fused to give an impression of a single localised event. This is the basis for the concern of a perceived lack of bass in the direct sound due to the SDE, as the grazing angle incident sound arrives already within 5-7 ms after the direct sound is likely to be perceptually fused with the direct sound (Davies and Lam, 1994). In the context of musical instruments, low tones can be masked by the high tones, thus rendering the low-fundamental-frequency instruments dull (Meyer and Hansen, 2009, p. 367-368).

Regarding the early reflections masking the SDE, Marshall (1967) suggested that ceiling reflections can mask lateral energy, and Barron (1974) considered that the bass sounds in the lateral reflections may be masked by the total sound level. Lateral reflections are more favourable to binaural loudness than ceiling reflections and assumingly cover better the lack of bass (Lokki and Pätynen, 2011). Furthermore, Lokki et al. (2011a) found that early lateral reflections preserving the temporal envelope of the direct sound contribute to the perceived amount of bass. Davies (1992) noticed that during training for their listening tests, most listening test participants found it hard to detect any attenuation as soon as the first non-seat-dip filtered reflections arrived. Results of Walther et al. (2013) indicate that the perception of bass may be enhanced if the low frequencies are missing in the direct sound and arrive at the listener with the early reflections instead. In some cases, the perception of bass may also depend on the phase relationship of the frequency components of the signal (Laitinen et al., 2013; Pulkki and Karjalainen, 2015).

The second property is the perceptual integration time which is the cross-over time between the early and late response of the concert hall, typically taken to be 80 ms. In other words, the concert hall sound field is assumed to be diffuse after 80 ms, and it is considered the limit between early and late sound in the standard room acoustic parameters, for example. However, Souloudre et al.

(2003) have suggested that this cross-over time is actually frequency-dependent and that at low frequencies, it would be considerably longer, about 160 ms. In a correlation study based on in-situ questionnaires, Kahle (1995) concluded that the energy of the direct sound up to 20 ms and the energy of at about 80-100 ms influence positively the perception of bass. Morimoto et al. (2001) also suggested that bass perception should be evaluated at 100 ms after the direct sound. By this time window, the SDE has recovered in most concert halls meaning that the SDE would constitute a relatively small part of the early response at low frequencies. It could help explain why in most concert halls, the SDE is not perceived. The longer perceptual integration time at low frequencies also highlights the importance of designing a sufficient amount of the reflections containing low frequencies, rather than merely remedying the SDE by seating design.

The third property of the human hearing to be taken into account in assessing the loudness in concert halls involves the equal loudness contours. The contours indicate how intense a 1000 Hz sound has to be to sound equally loud to the given tone. The rate of loudness growth differs for tones of different frequencies, and for low frequencies, it is higher than for mid-frequencies.

Figure 4.1 shows the frequency responses at the listener's eardrums with different dynamics overlaid on the equal loudness contours at two different seats in two different concert halls (Lokki and Pätynen, 2020b). Each equal loudness contour corresponds to a 10 dB increase in the perceived loudness, measured in sones. It can be seen that the most significant differences between the two concert halls lie in the low frequencies below 300 Hz and that these differences correspond to substantial changes in the equal loudness contours at low frequencies. This highlights the importance of a good overall low-frequency response in concert halls. The lack of low frequencies in the direct sound and early reflections combined with inadequate late sound energy brings about a concert hall with a weak low frequency response. This fact, combined with the high growth rate of loudness at the low frequencies, may accentuate the differences in the perceived level of bass and reduce the perceived dynamics in concert halls (Lokki and Pätynen, 2020b).

4.2.3 Musical instruments and repertoire

The SDE may be problematic for the audibility of some musical instruments as the frequency range of the SDE covers the fundamental and some of the first harmonics of the instruments. When the effect was first discovered in the Philharmonic Hall in New York, the parenthetical comments brought about the weakness of the cellos and the double basses in particular (Beranek et al., 1964; Barron, 2009). Later, it has been estimated that the SDE could cut out as much as 6 dB of the double bass sound at the 125 Hz octave band (Bradley, 1991).

Figure 4.2 shows the frequency ranges of the most common orchestral instruments and singing voices along with the typical SDE frequencies associated with

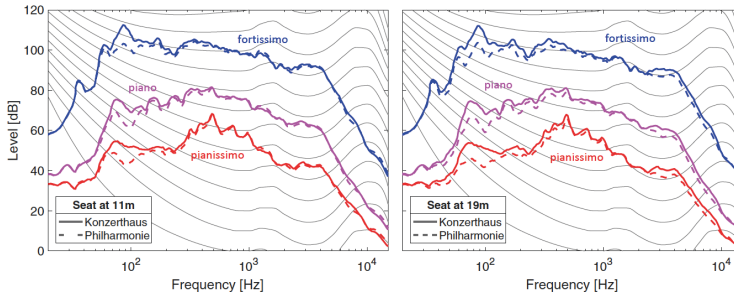


Figure 4.1. Equal loudness contours overlaid with the frequency responses of the two concert halls as measured in at the listener's eardrum at different dynamics of the orchestra. Adopted from Lokki and Pätynen (2020b).

seat type. Large instruments such as the double bass, cello, bassoon, and tuba, are mostly affected due to their low-frequency fundamentals. There are two perceptual effects in place. Firstly, since the SDE reaches maximum attenuation within the first 20 ms after the direct sound, it is likely to be perceptually integrated with the direct sound, as mentioned above. Thus, some fundamentals and harmonics of the musical instruments are missing in the direct sound due to the SDE. One could link the perceptual effect of this with the missing fundamental phenomenon, or the so-called "virtual pitch", which suggests that if the lowest partials of a complex harmonic tone are missing, the perceived pitch of the sound will still correspond to the fundamental frequency of that complex tone (Pulkki and Karjalainen, 2015). In that case, the timbre of the direct sound from this instrument may be thinner and the pitch weaker.

Secondly, the lowest partials of these instruments arrive slightly delayed at the listener with the non-grazing-angle reflections, given that the reflections are sufficient. Walther et al. (2013) suggested that the perceptual effect of such a delay may be an enhancement of bass. To speculate even further, this could be the basis for some conductors using intended asynchrony between the low-fundamental-frequency instruments and the other instruments in the symphony orchestra to enhance bass (Tahvanainen et al., 2014).

The perception of these low-fundamental-frequency musical instruments (double bass, cello, tuba, trombone) was studied in concert halls with different seating area designs and geometries in Publication III. According to the results, these instruments are perceived louder in concert halls with higher main attenuation frequency of the SDE and ample lateral reflections than concert halls with a lower main attenuation frequency and less lateral reflections. On the contrary, the effect on clarity seems to vary across the instruments. For example, the clarity of the cellos and double basses seem to benefit from more perceived loudness in the bass frequencies, while this is not the case for the tuba and the trombone.

As the SDE varies with the angle of arrival, both the position of the source

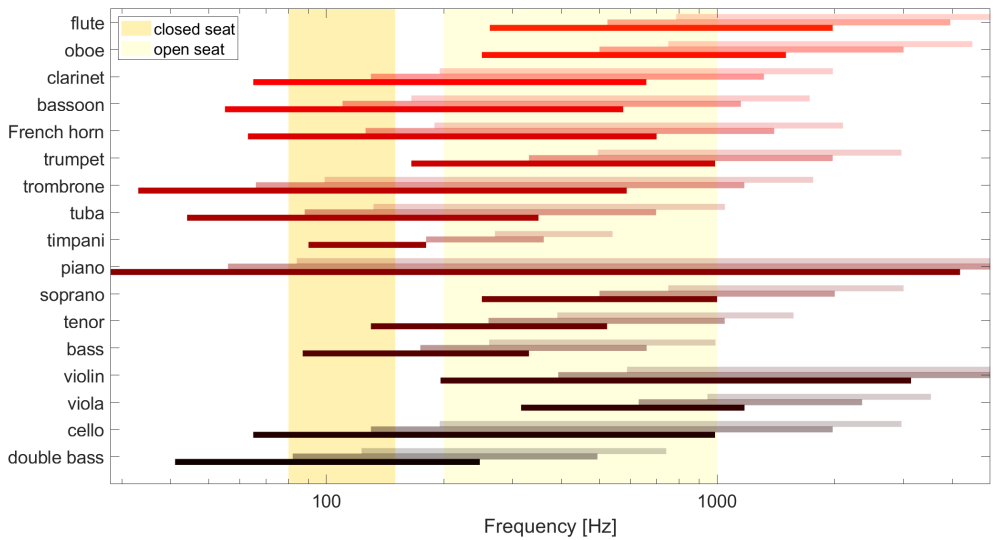


Figure 4.2. The fundamental and the first and second harmonics of the orchestra instruments and singing voice. The darkest colour represents the fundamental, and the lighter shades the harmonics. The frequency range of the SDE associated with the seat type is presented in yellow shades.

and its directivity pattern at the SDE frequency range will affect the seat-dip attenuation experienced by the musical instrument. At low frequencies, however, musical instruments tend to have monopole or dipole radiation patterns (Meyer and Hansen, 2009), so the positioning of the instruments on stage will play a more significant role than the instrument directivity on the SDE. For example, in the customary American seating of the orchestra, the double basses and the cellos are arranged on the opposite side of the stage than in the German seating (Meyer and Hansen, 2009). Thus it would be expected that the frequency balance between the two arrangements in the same hall is different.

The seat-dip attenuation is objectively at its worst at about 20 ms after the direct sound. However, with musical instruments and hearing, the perceptual time windows may be up to ten times longer. Firstly, as mentioned, the perceptual integration time at low frequencies may be as long as 160 ms (Moore, 2012), meaning the direct sound influenced by the SDE as well as the non-grazing-angle reflections may be perceptually integrated. Secondly, there exist the concepts of the perceptual onset time (Vos and Rasch, 1981), and perceptual attack time (Gordon, 1987) for musical instrument sounds, which differentiate between when the sound is first heard and when the most salient rhythmic element is heard, respectively. Depending on the musical instrument in question, these perceptual times are typically between 20 - 200 ms after the physical onset of the sound (Bechtold and Senn, 2018). It suggests a complicated relationship between the attack of the instruments, the low-frequency perception, and the

lack of bass in the direct sound.

Apart from the SDE, the construction of the concert hall can influence the low-frequency sounds of the musical instruments. For example, the sound radiation of the double bass at the low frequencies is influenced by the distance from the wall, type of wall, and stage risers (Meyer and Hansen, 2009). Generally, building materials of walls, ceiling, and floor have an influence on whether the low frequencies are reflected rather than absorbed or transmitted. Additional strengthening of the sound power at low frequencies occurs when the source is less than a wavelength away from the wall, and the strengthening is also dependent on the wall construction. Whether or not this phenomenon is beneficial for perception seems to depend on the instrument. A particular example is shown by Meyer and Hansen (2009, pp.288) with a cello placed at a distance of 75 cm from a wall. Compared to wood wall panelling, a hard wall will increase the radiated sound power of the cello below 100 Hz, while in the region of 150 Hz, the radiated sound power is higher with wood panelling.

As to the floor, the stage floor may be amplifying the double bass sounds via the floor pin (Guettler et al., 2012). In addition, the floor on the stalls may transmit vibrations to the seated listener, and these tactile vibrations are integrated into the auditory experience (Abercrombie and Braasch, 2010; Merchel and Altinsoy, 2018).

Finally, when talking about the sound source in the concert hall, an essential factor in evaluating the perceptual effect of the SDE is the actual musical content. The orchestration of at least some of the classical Western music can be explained by the fact that the respective composer would compose a piece of music with a specific performance space in mind (Meyer and Hansen, 2009). Generally, the frequency content of the classical music composition is not evenly distributed. For example, the analysis of anechoic classical music recordings by Lee and Cabrera (2009) shows that the main content falls within the 100 - 2000 Hz third-octave bands. Particularly low-frequency content is typically present at powerful passages with fortissimo. In such passages, the double basses often double the cellos, and their harmonic content will coincide in frequency (Meyer and Hansen, 2009). Of course, in some cases, the low-frequency instruments are the only sounding instruments, and they may have problems standing out in the concert hall (Meyer and Hansen, 2009, pp.290). This both explains why the lack of bass due to SDE is not often perceived and highlights that for the exceptional cases of low-frequency passages in music, paying attention to the low frequency response of the concert hall is essential.

5. Concert hall design and the seat-dip effect

From the acoustic point of view, concert hall design starts with ensuring an adequate reverberation time for symphonic music, which translates to choosing an adequate volume per seat and adjusting the amount and placement of absorption materials. Apart from this, the major geometrical factors of importance in concert hall design are the shape of the hall and the sight lines, which set the boundary conditions for the seating area design (Gade, 2014).

There are two primary needs that the concert hall seating area has to meet: everyone should both see and hear the orchestra on the stage (Appleton and Fischer, 2015). Ensuring audience comfort and proper emergency routes are also significant concerns. Seat density, floor rake, and seating layout, among others, submit to these needs. For example, the emergency regulations restrict the number of seats per row between gangways. At the same time, the overall width of the seating area is limited by the maximum comfortable angle that the head can turn from the centre line, which is about 30°. Similarly, ensuring an adequate line of visibility typically results in a high floor rake, high stage, and installation of balconies. Ultimately, the goal is to maximise the number of seats (and thus profit) within the aural, visual, comfort, and safety limitations.

The seating design, together with the stage design, also affects vertical and horizontal relationships between the audience and the performers. The sight lines from the performers' perspective also influence the dominance of the audience-performer relationship, especially in theatres (Mackintosh, 2003). Ideally, half of the audience is below the eye line of the performer and half above.

As for the aural quality in concert halls, the related architectural features were recently tackled and reviewed by Lokki and Pätynen (2019). The SDE is seen as an element that affects the aural quality of concert halls. As noted previously, the SDE is often discussed as an acoustic defect that should be mitigated. Consequently, several studies have been dedicated to designing structures that would eliminate it (Ando et al., 1982; Bradley, 1991; Davies and Lam, 1994; Davies and Cox, 2000). The very first proposal to minimise the SDE was to steeply rake the floor of the concert hall, as this would lead to a larger angle of incidence and thus move the main attenuation dip to a low frequency and diminish the bandwidth of the attenuation (Schultz and Watters,

1964). Later, Ishida (1993) proposed that the optimal floor raking would be about 20% or 11.5° , while keeping the angle of incidence larger than 7° . This recommendation was based on considering the energy differences at 20 ms after the direct sound at the main attenuation frequency with a single source-receiver pair.

Bradley (1991) was the first to analyse the relationship between early sound energy and the SDE grouped by hall geometry. His suggestion was to hang ceiling reflectors to provide overhead reflections that would not undergo seat-dip attenuation because of the large angle of incidence. The ceiling reflectors have, however, been argued to produce unwanted colouration to the sound (Davies and Lam, 1994). Bradley (1991) also suggested using stage risers as these would increase the angle of incidence and thus reduce the SDE. Ishida (1993, pp.186-187) sketches a few solutions that combine some of the suggested remedies.

Many solutions aim to change the seating area absorption to eliminate the reflections between the seats and floor that cause the SDE. Ando et al. (1982) concluded that the floor between the seats should be absorptive to avoid the seat-dip attenuation, and to this end, he proposed slit resonators under the floor. Economou and Charalampous (2015) also showed that making the floor absorptive reduces the attenuation dip compared to a hard floor. Ishida (1993) experimented with perforated panels with air space underneath the seats and noticed the placement of these resonators is very critical for a successful reduction of the SDE: the resonators should be in front of the seats. Later replications of these results showed that the absorption material might be more efficiently placed under the seat squabs (Davies and Cox, 2000).

Davies and Lam (1994) proposed to reduce the SDE by placing floor absorbers between the seat rows, such as vents, Helmholtz resonators, and absorbent panels. While these absorbers had some reductive effect, they also increased absorption across the whole frequency range. Cox and Davies (1995) suggested putting a large pit under the seats spanning many seat rows. The pit could be covered by a grill and a carpet and could include a ventilation system. Filling the pit with foam would not significantly improve the results. On average, the SDE was reduced by about 3 dB, which seems relatively modest considering the extent of the construction. Finally, Davies and Cox (2000) compared various combinations of the aforementioned remedies and concluded that the most effective solution was indeed the pit, especially for seat rows further back. However, such floor absorber construction may downgrade the enhancement of the low frequencies generated by the guided surface waves.

Although not suggested directly as a remedy to the SDE, orchestra shells placed at the back of the stage sometimes improve the early low-frequency levels due to reflections from the shell structure at different grazing angles of incidence to the audience (Bradley, 1996). Similarly, the rail in front of the orchestra pit in an opera house increases the angle of incidence (Tahvanainen et al., 2015b).

In the scientific textbooks, the research on eliminating the SDE has been distilled into a few feasible recommended measures in the acoustic design of

concert halls. Long (2005, pp.663) lists the following measures to reduce the SDE: installing overhead reflectors, breaking the seating arrangement to smaller clusters like in the vineyard-shaped halls, and elevating the orchestra platform. In addition, the thorough instructions by Gade (2014) recommend sloping of the audience area to avoid the SDE.

The studies for elimination measures have been made with little attempt to prove the perceptual importance of the SDE before Davies et al. (1996) condensed its subjective significance to a single-number parameter: a threshold of -3.8 ± 0.2 dB at the 200 Hz octave band in the early energy from 0 to 80 ms. Since then, the threshold has been used to evaluate the perceptual significance of some elimination measures (Cox and Davies, 1995; Davies and Cox, 2000). However, in this thesis work, the perceptibility studies of Publication IV show that the abovementioned threshold value does not always indicate perceptual significance. This is especially true if the threshold is extrapolated to shorter time windows or if the main attenuation frequency falls in the lower octave bands than 200 Hz.

Instead, the perceptual studies completed in Publication III and Publication IV provide evidence that in shoebox-shaped halls, the SDE does not cause perceptual problems. Still, it may be perceptually significant in concert halls with less reflective energy. In other words, if the low frequencies are not present in the direct sound due to the SDE, and there is not much additional sound energy either, then a lack of low frequencies may be perceived.

Consequently, the first matter to take care of in a concert hall with respect to the SDE would be to design sufficient reflections: it means focusing on the hall's geometry. There has been a recent tendency in concert hall design to divert from the traditional shoebox-shaped halls, which further emphasises designing for adequate early reflections. Thus, it is easy to understand why the SDE was first noticed in 1964 in a concert hall whose geometry drifted away from the traditional shoebox-shaped hall (Schultz, 1965).

The analysis of the spatiotemporal sound energy distribution of concert halls in Publication I shows that the shoebox-shaped halls possess a more omnidirectional spatial distribution of incident sound energy below 1 kHz, and the overall level is higher than that of the non-shoebox-shaped halls (see Fig. 2.2). By the time window of 30-80 ms, the seat-dip attenuation has recovered in the shoebox-shaped halls, and the evenly distributed energy from the upper hemisphere has arrived at the listener. On the contrary, in the non-shoebox-shaped halls, some individual reflections may be seen within this time window, but the attenuation dip persists. This concurs with the idea of Barron (1974, pp.239) that a significant portion of reflections should arrive within the first 100 ms of the direct sound on paths remote from the audience seating.

Nevertheless, after the hall geometry has been decided upon, can something be done to improve the situation with seat design? If the number of reflections remains small, the listeners preferred the direct sound with no seat-dip filtering present, as in the vineyard halls in Publication IV. Hence, some elimination

measures for the SDE might be useful. An interesting approach would be to install very lightweight seats on a flat floor, as in Beethovensaal in Stuttgart, to obtain a fairly flat frequency response at 30-40 ms after the direct sound. However, such seats may lack grandeur and require extra attention on audience comfort.

If a flat frequency response in the direct sound is not feasible and some SDE remains, the preference tends towards the narrow attenuation bandwidth associated with closed seats. Ishida (1993, pp.180) also suggested that blocking the seat underpasses would ameliorate the SDE. Such an approach, however, only concerns the main attenuation frequency and its bandwidth, and one of the shortcomings of the results in Publication IV is not considering the level below the main attenuation frequency. As shown with real concert halls with averaged sources in Publication I, the level below the main attenuation frequency appears far worse with blocked underpasses. Furthermore, other perceptual benefits have been identified in Chapter 4 that would support the introduction of underpasses. Firstly, ensuring seat underpasses is a good way to enhance the level of low frequencies, especially below 100 Hz, as shown by the concert hall measurements in Publication I and the scale model measurements in Publication II. In particular, enhancing these low frequencies may be beneficial for the perceived dynamics and generally increase the perceived loudness (Lokki and Pätynen, 2020b). Secondly, with the underpasses, the SDE lies between about 200 - 1000 Hz. Removing frequency content at this range from the direct sound and having it arrive with early reflections may benefit both clarity and level of the low frequencies (Walther et al., 2013).

Ensuring an underpass on inclining floors typically means that the inclination must be continuous, not step-wise raking unless the steps are relatively small. Nonetheless, this limits the raking to very moderate degrees. Such solutions exist, for example, in the Sage Gateshead Hall, the UK and the Sibelius Hall in Lahti, Finland; where at least the latter has also documented to have a good level of low frequencies (Lokki et al., 2012).

Several ideas for seat design need further investigations to verify their effect on the SDE. For example, regarding the arrangement of seats, it would be possible to make, e.g., irregularly placed booths of seats or have seats more randomly positioned in the room to break the regular structure causing the SDE. It appears that smaller seat row width reduces the SDE (Davies, 1992; Ishida, 1993). However, such seating arrangement modifications may not always comply with other requirements on comfort and safety. Another suggestion provided by James Heddle (personal communication, March 8, 2016) is to design ample row spacing between the seats and less steep inclination, as exemplified by the St. Peter's Lutheran College Performing Arts Center in Queensland Australia.

Furthermore, many hydraulic and retractable seating solutions have been installed in recent years, especially in multipurpose halls. Such systems allow for easy variation of row spacing and floor inclination tuned to the concert hall geometry. Such systems could also serve as ways to study the SDE further via

measurements. Generally, the effect of such solutions on the low frequencies in performance spaces should be investigated, as they may introduce coupled air spaces. Finally, the SDE is a phenomenon additional to absorption. While it appears that the seat absorption itself would not have a significant influence on the SDE, there is some indication based on the modelling by Davies (1992, pp. 188-189) and Liao and Min (2019) that highly absorbent tops of the seat backrests could reduce the SDE.

6. Conclusions and future work

The SDE is the term given to the low-frequency attenuation of the direct sound and early reflections arriving at grazing angles to the seating area. It results from several acoustic phenomena over periodic structure formed by the seating area in a concert hall, such as reflection, diffraction, layered absorption boundaries, and possibly guided surface waves.

Whether the SDE is perceived in the concert hall or not depends essentially on the seating area design, the spatiotemporal distribution of the incident sound energy, and the repertoire being played. The attenuation frequency range (the SDE spectrum) can be modified with several construction elements. Depending on the SDE spectrum, it may present a perceptual problem by reducing the perceived level of bass and spatial impression, render the sound of large musical instruments such as the double bass and the cello weaker and thinner, especially in concert halls with dry acoustics. On the other extreme, if tuned to the correct frequency range, the seat-dip attenuation may help enhance the perceived level of bass and clarity when the bass frequencies are sufficiently present in other reflections that do not undergo the SDE. The SDE appears to alter the timbre to some degree as well. At the moment, no room acoustic parameters exist to indisputably capture the perceptual effects of the SDE.

In this thesis, the SDE was studied by applying methods beyond the ISO 3382-1 (2009) standard, in particular by investigating the time-frequency and spatiotemporal development of the source-averaged SDE with a large data set of measured RIRs in concert halls and by listening tests on the auralised measurements. The main findings of this thesis are:

- The SDE can be defined by the main attenuation frequency, amplitude and bandwidth, and recovery time. In addition, the SDE influences the low frequencies below the main attenuation frequency.
- The averaged initial SDE spectrum in existing concert halls can be divided into two types that depend on the seat design and floor raking. Open seats on a flat floor render a wide attenuation bandwidth centred asymmetrically around 200 Hz. Closed seats on a raked floor render a narrow attenuation dip centred at around 100 Hz. In addition, the level below the main

attenuation frequency is higher in the former than in the latter.

- The main attenuation frequency depends strongly on the seat design, especially the seat backrest height and the size of the unobstructed underpass. Seats with unobstructed underpasses increase the level below the main attenuation frequency compared to obstructed seats.
- Floor raking contributes to the attenuation bandwidth due to increased angle of incidence of the direct sound and positive diffraction from the tops of the seat backrests preceding and following the receiver.
- The recovery time depends on the concert hall geometry. The main attenuation dip levels off with reflections from all over the upper hemisphere, rather than distinct lateral or ceiling reflections. Shoebox-shaped halls provide an even spatiotemporal distribution of sound energy more readily than vineyard- or fan-shaped halls.
- When sufficient reflections are provided by the concert hall, the SDE is perceptually insignificant. The initial SDE is likely to be concern at only specific range of distances in the concert hall stalls.
- The current room acoustic parameters aimed at describing the low-frequency perception cannot capture the perceptual significance of the SDE. The SDE appears to influence the perceived level and clarity of low frequencies and timbre.
- To ensure adequate low-frequency response in the concert hall, the open seats on the flat or mildly raking floor should be installed, with ample reflections from the upper hemisphere.

Several future research ideas emerged during the thesis. Firstly, it appears that seat underpasses are relevant for the increased level of the low frequencies below the main attenuation frequency. It would be interesting to define a sufficient size for the underpass, especially with a seated audience. Furthermore, the role of surface waves in this phenomenon remains unclear. Other changes in the seating area for future consideration are the lightweight removable seats, large row spacing, and hydraulic seating. Concurrently, it would be necessary to ensure that current room acoustic simulation software used in performance space design accurately models the effect. To this end, filters based on measurements or simulations could be used.

Secondly, perceptual studies on the detection of the SDE could be extended with a setup where the early reflections would be filtered according to the average SDE type. Equally important, the filter response could be modified to take into account the increased level below the main attenuation frequency for the seats with underpasses. Furthermore, the effect of the SDE on the perceived dynamics, timbre and auditory spaciousness could be studied, especially with a variety of musical passages.

Thirdly, more perceptual studies could be aimed at studying the quality of bass in concert halls, especially in an attempt to provide some room acoustic parameters that correlate with the perception of bass. Concert halls differ in the perceived level of low frequencies, timbre, and clarity with low-fundamental frequency musical instruments. It appears to be possible to have varying quality of bass with similar perceived loudness.

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