# The Influence of Room Acoustics on Solo Music Performances.

## An Empirical Investigation

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# The Influence of Room Acoustics on Solo Music Performances. An Empirical Investigation

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von der Fakultät I - Geisteswissenschaften
der Technischen Universität Berlin
zur Erlangung des akademischen Grades

Doktorin der Philosophie
- Dr. phil. -

genehmigte Dissertation

**Promotionsausschuss**
Vorsitzende: Prof. Dr. Bénédicte Savoy
Gutachter: Prof. Dr. Stefan Weinzierl
Gutachter: Prof. Dr. Heinz von Loesch

**Tag der wissenschaftlichen Aussprache**
05.10.2015

Berlin 2015

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# Abstract

During the performance of music the surrounding space is a factor essentially affecting the sound of what is played. An adjustment of the performance to the concert hall acoustics as described by many musicians is therefore intuitive and comprehensible but it has rarely been the subject of research. In this thesis, the relationship between room acoustics and solo music performance was empirically investigated.

Music performances of the same pieces were recorded in different room acoustical environments by conducting one study with a cellist in real-world concert halls and another study with musicians of standard orchestral instruments in virtual rooms simulated with dynamic binaural synthesis. By means of a software-based analysis and perceptually motivated regression models the performance characteristics tempo, agogic, dynamic strength, dynamic bandwidth and timbre aspects were subsequently determined from the recordings. Furthermore, the room acoustical properties of the real and simulated concert halls were characterised by measuring impulse responses and calculating room acoustical parameters. Here, computer models were utilised, in particular to take the directivity of the played instruments into account when exciting the rooms. In this way, the room acoustical conditions that musicians are typically confronted with on concert hall stages were determined as accurately as possible and their impact on the performance was examined in detail. Moreover, the influence of the played instrument and the musical content was taken into account.

More than half of the variance in the performance characteristics that were determined in the real-world concert spaces could be explained by four room acoustical parameters. This is a remarkable result considering the presence of many other factors possibly influencing a concert situation such as audience, personal form of the performer and environmental factors other than the room acoustics. One fifth of the variance in the performance characteristics obtained in the simulated environments was explained by five room acoustical measures. A fundamental result of this experiment furthermore was that the musicians reacted very individually to the room acoustical conditions. In both investigations, sig-

nificant effects of the studied room acoustical parameters on the performance characteristics were revealed. The investigated timbre aspect describing soft and hard playing was affected most strongly be the room acoustical conditions, while the adjustment of the performers' tonal rendition in the laboratory experiment was at the same time particularly individual. From the room acoustical parameters measured in the real concert halls, it was the duration and the amount of reverberant energy that had the strongest influence on the investigated performance characteristics. The acoustical enhancement and amount of reverberant energy were the parameters with the strongest effect in the study with virtual concert halls.

The musicians' descriptions of their performative adjustments given in guided interviews that were conducted in both studies provided information on the strategies behind some of the significant relations between room acoustical parameters and performance characteristics found in the statistical analysis. In the investigation carried out in real-world concert situations, the influence of contextual variables was furthermore enquired from the performer in the interviews, which revealed a distinct network of influences among the factors for each concert situation.

# Zusammenfassung

Bei musikalischen Darbietungen ist der umgebende Raum ein den Klang entscheidend beeinflussender Faktor. Die von vielen Musikern beschriebene Anpassung ihrer Aufführung an die Konzertsaalakustik ist daher intuitiv nachzuvollziehen, war bisher aber kaum Gegenstand der Forschung. In dieser Arbeit wurde der Zusammenhang zwischen Raumakustik und der Spielweise von Soloinstrumentalisten empirisch untersucht.
Musikalische Aufführungen derselben Stücke wurden in verschiedenen akustischen Umgebungen aufgenommen, indem zum einem ein Cellist auf einer Konzertreise begleitet und zum anderen Spieler von Standard-Orchesterinstrumenten mit Hilfe der dynamischen Binauralsynthese in simulierte Raume versetzt wurden. Mittels einer software-basierten Analyse und perzeptiv motivierter Regressionsmodelle erfolgte anschließend die Bestimmung der Aufführungsmerkmale Tempo, Agogik, Lautstärke, Dynamikumfang sowie mehrerer Klangfarbenaspekte aus den Aufnahmen. Ferner wurde die Akustik der realen und simulierten Konzertsäle durch Messung von Impulsantworten und Berechnung raumakustischer Kriterien charakterisiert. Dabei wurden Computermodelle zu Hilfe genommen, um insbesondere der Richtwirkung der gespielten Instrumente bei der Anregung der Räume Rechnung zu tragen. So konnten die raumakustischen Bedingungen, mit denen Musiker typischerweise auf Konzertsaalbühnen konfrontiert sind, möglichst exakt bestimmt und ihre Auswirkung auf die Spielweise im Detail untersucht werden. Hierbei wurde auch der Einfluss des gespielten Instruments und des musikalischen Inhalts berücksichtigt.
Über die Hälfte der Varianz der Aufführungsmerkmale, die in realen Konzertumgebungen bestimmt wurden, konnte durch vier raumakustische Parameter erklärt werden. Dies ist ein beachtliches Ergebnis, wenn man die zahlreichen anderen Faktoren wie die Tagesform des Musikers, das Publikum oder andere Umgebungsvariablen außer der Raumakustik bedenkt, die eine Konzertsituation potentiell beeinflussen können. Die Varianz der in virtuellen Sälen ermittelten Aufführungsmerkmale wurde zu einem Fünftel durch fünf raumakustische Kriterien erklärt. Ein wesentliches Ergebnis dieser Untersuchung war zudem, dass

die Musiker sehr individuell auf die raumakustischen Bedingungen reagierten. In beiden Teilstudien wurden signifikante Zusammenhänge zwischen den untersuchten raumakustischen Parametern und Aufführungsmerkmalen nachgewiesen. Der untersuchte Klangfarbenaspekt, der hartes bzw. weiches Spielen beschreibt, wurde am stärksten von den raumakustischen Bedingungen beeinflusst, wobei die Anpassung der klangfarblichen Gestaltung durch die Musiker im Laborversuch gleichzeitig sehr individuell war. Von den raumakustischen Parametern, die in den realen Konzertsälen gemessen wurden, waren es die Dauer und die Stärke des Nachhalls, die den deutlichsten Einfluss auf die untersuchten Aufführungsmerkmale hatten. Die akustische Verstärkung und die Stärke des Nachhalls waren die Parameter mit dem größten Einfluss in der Studie mit virtuellen Konzertsälen.

Die von den Musikern selbst in Leitfadeninterviews beschriebenen spieltechnischen Anpassungen gaben Aufschluss über die Strategien hinter einigen der signifikanten Zusammenhänge zwischen raumakustischen Parametern und Aufführungsmerkmalen aus der statistischen Analyse. In der in realen Konzertsituationen durchgeführten Untersuchung wurde der Musiker außerdem nach dem Einfluss kontextueller Variablen gefragt, was für jede Konzertsituation ein spezifisches Geflecht von Einflüssen zwischen den Faktoren erkennen ließ.

# Acknowledgements

This PhD thesis was written at the Audio Communication Group TU Berlin.

I would like to express my appreciation and thank you to Prof. Dr. Stefan Weinzierl for supporting me at all points on the way of this doctoral journey and always enabling a free, productive and enjoyable working environment. I am also grateful to Prof. Dr. Heinz von Loesch for his great interest in my project and his highly appreciated comments on my various presentations of intermediate results.

I am indebted to Jean-Guihen Queyras for agreeing to take part in my field study in such a cooperative and friendly way. This collaboration was a great benefit for my project and it gave me the opportunity to gather much more than my recordings and impulse response measurements. My thanks also go to the musicians who participated in the laboratory study, enduring the experimental setup and the never-ending performance of the same musical excerpts with such interest and enthusiasm. It was a great pleasure and benefit to work with them.

The recordings and measurements made for the field study would not have been possible without the help and courtesy of the agents of Jean-Guihen Queyras, the concert promoters and the management of the concert halls: Catherine Le Bris, CLB Management; Jean-Marc Peysson, Agence de Concerts Caecilia; Jeroen Tersteeg, Nymus Artists; Inés Fernandéz Arias, Fondación Caja Madrid; Gabriel Veiga Nicole, Auditorio Nacional de Música Madrid; Jerôme Guigou, Mairie de Forcalquier; Vera Dumon and Erwin Grommen, Cultuurcentrum Hasselt; Nicole Renevey, Festival International de Musiques Sacrées Fribourg; Axel Loup, Collège St-Michel Fribourg; Otelo Lapa, Caroline Mascarenhas and Helena Simões, Fundação Calouste Gulbenkian Lisbon; Darius Weinberg, Wigmore Hall London; Marlène Amiot and Dominique Eble, Théâtre Jean Vilar Vitry-Sur-Seine.

I am grateful to Frank Schultz and Stefanie Otto for the indispensable help with the measurements in Europe's concert halls that entailed such long journeys and I want to thank Thanos Lykartsis for his greatly appreciated assistance during the laboratory experiment. My thanks further go to the sound engineering department of the UdK Berlin and the Quality and Usability Lab TU Berlin for lending me technical equipment that was essential for my studies.

This thesis would certainly not have been possible without the exchange with people from the same and related academic disciplines. I want to thank my colleagues at the Audio Communication Group, especially Dr. Steffen Lepa for introducing me to the mysteries of hierarchical linear models as well as Fabian Brinkmann, Vera Erbes, Dr. Alexander Lindau and Frank Schultz for the office fun. I am thankful to Dr. Alexander Lerch for patiently answering all my questions on performance analysis and having a critical look at my project in its initial phase. Being able to work at the Centre for Music and Science at the University of Cambridge as a visiting student was an immense opportunity that broadened my horizon in many ways. Thank you to Prof. Dr. Ian Cross for hosting me and for the valuable comments on my work. I further want to thank my former colleagues at the Experimentalstudio des SWR, Freiburg, for their interest in my research and their critical questions.

This work was mainly funded by the German National Academic Foundation that made it possible for me to encounter people, places and ideas that I would otherwise not have known of. I gratefully acknowledge this scholarship and would like to thank the team for postgraduate promotion, especially Dr. Pascal Pilgram, for all the assistance and organisation. This research has further partially been funded by a Promotionsabschlussstipendium of the women's representative of the TU Berlin and by the German Research Foundation (DFG WE 4057/9-1).

I want to express my thanks to my parents Vreni and Ruedi who have always encouraged and supported me. Thank you to my husband Kiril and to my daughter Anelia for the unlimited support, the patience and the fun times.

# Glossary

## Terms and definitions

| | |
|---|---|
| *Agogic* | Performance characteristic quantitatively determined in this thesis related to tempo modulations. |
| Auralisation | Making the impulse response of a system (in the context of this thesis: room) audible to listeners. |
| Binaural room impulse response | Response of a room to a single pulse captured with microphones in the two ears of a dummy head or human listener. In contrast to a room impulse response, the BRIR contains directional information because it includes the HRTF of the dummy head/human listener. |
| Convolution | Multiplication of two impulse responses in the frequency domain. If, for example, an anechoic music signal is convolved with a room impulse response, the audible outcome is the music sounding in the respective room. |
| *Dynamic bandwidth* | Performance characteristic quantitatively determined in this thesis related to the range between quiet and loud tones. |
| Dynamic binaural synthesis | Method for the auralisation of rooms on the basis of BRIRs for different head orientations that are convolved with an anechoic signal depending on the head orientation of the listener, which is registered with a tracking system. |
| *Dynamic strength* | Performance characteristic quantitatively determined in this thesis related to how quiet or loud music is played. |
| *Forte* | Term used in music notation and performance relating to loud playing. |
| Head related transfer function | Filter containing the entire time-frequency information of the outer ear, the head and the torso that is crucial for the localisation of sound sources. |

| | |
|---|---|
| Hierarchical linear model | Multilevel regression model accounting for a grouping structure within collected data. |
| Impulse response | Response of a system to a single impulse containing the entire time-frequency information of this system. In the context of this thesis, the system is usually a room. |
| Intercept-only model | Special case of an HLM containing no explanatory variables and used to decompose the total variance on the different levels of the data. |
| *Legato* | Term used in music notation and performance relating to a smooth connection of consecutive tones. |
| *Piano* | Term used in music notation and performance relating to quiet playing. |
| *Staccato* | Term used in music notation and performance relating to detached and short playing of consecutive tones. |
| *Tempo* | Performance characteristic quantitatively determined in this thesis related to how slow or fast music is played. |
| *Timbral bandwidth* | Performance characteristic quantitatively determined in this thesis related to the variability of the tonal rendition. |
| *Timbre (dark – bright)* | Performance characteristic quantitatively determined in this thesis related to the tonal rendition in the range from dark to bright. |
| *Timbre (lean – full)* | Performance characteristic quantitatively determined in this thesis related to the tonal rendition in the range from lean to full. |
| *Timbre (soft – hard)* | Performance characteristic quantitatively determined in this thesis related to the tonal rendition in the range from soft to hard. |

**Abbreviations, subscripts and variables**

| | |
|---|---|
| AIC | Akaike's information criterion |
| ANC | Auditorio Nacional Sala de Cámara |
| BIC | Bayesian information criterion |
| $BR$ | Bass ratio |
| BRIR | Binaural room impulse response |
| BPM | Beats per minute |
| CCC | Cloître du Couvent des Cordeliers |
| CCG | Cultuurcentrum |
| CHA1 | Chamber hall 1, prototype room model used in the laboratory study |
| CHA2 | Chamber hall 2, prototype room model used in the laboratory study |
| CHU | Church, prototype room model used in the laboratory study |
| CI | Confidence interval |
| CON1 | Concert hall 1, prototype room model used in the laboratory study |
| CON2 | Concert hall 2, prototype room model used in the laboratory study |
| comp | Subscript for HLMs with PCA components as predictors |
| $C_{80}$ | Clarity |
| dBA | A-weighted decibel |
| $EDT$ | Early decay time |
| ESM | Église du Collège St. Michel |
| $G$ | Sound strength |
| $G_{\mathrm{e}}$ | Early sound strength |
| GGA | Gulbenkian Grande Auditorio |
| $G_{\mathrm{l}}$ | Late sound strength |
| $G_{125}$ | Bass strength |
| HLM | Hierarchical linear model |
| HRTF | Head related transfer function |
| IBI | Inter-bar-interval |
| ICC | Intraclass correlation coefficient |

| | |
|---|---|
| ins | Subscript for room acoustical parameters determined on stage with a single measurement position using a source with instrument directivity at an instrument-typical height and at an instrument-typical distance to a receiver at 1.2 m height |
| IOI | Inter-onset-interval |
| JND | Just-noticeable difference |
| LTAS | Long-time average spectrum |
| MIDI | Musical instrument digital interface |
| OPR | Opera, prototype room model used in the laboratory study |
| RMS | Root mean square |
| $RT$ | Reverberation time |
| par | Subscript for HLMs with room acoustical parameters as predictors |
| PCA | Principle component analysis |
| PLE | Palais Lobkowitz Eroicasaal |
| solo | Subscript for room acoustical parameters determined on stage with a single measurement position with 1 m between the omni-directional source and the receiver, both at 1 m height |
| SPL | Sound pressure level |
| $ST_{\mathrm{early}}$ | Early support |
| $ST_{\mathrm{late}}$ | Late support |
| TJV | Théâtre Jean Vilar |
| vlc | Subscript for room acoustical parameters determined on stage with a single measurement position using a source with cello directivity at 0.6 m height in 0.4 m distance to a receiver at 1.2 m height |
| WMH | Wigmore hall |

# 1 INTRODUCTION

During the performance of music the surrounding environment acts as an acoustical transformer, modifying the sound of the notes and chords that are played. Room acoustics thus presumably play a vital role for this art form that is tied to a sounding enactment. In the Western concert tradition, music performance is normally determined by the triad of composer, performer and listener (Dunsby, 2001). Accordingly, the question of the effect of the room acoustical surrounding on a music performance can be regarded from three points of view. Firstly, it is possible that a composer had a particular hall in mind when he wrote a piece or even a group of works. Meyer (1978) suggested that certain elements in Haydn's symphonies such as dynamic and rhythmical structures as well as the use of pauses are related to the halls which they were performed in. Blaukopf (1960) quoted several sources touching the issue of compositions being influenced by specific performance spaces and he furthermore established a connection between the speed of harmonic modulations in a composition and the reverberation time of a room (Blaukopf, 1954). According to Blaukopf, the modulation speed should decrease with increasing reverberation time in order to avoid the blurring of harmonies. He thereby referred to Forkel (1802), who wrote about the speed of changing harmonies being dependent on the characteristics of the designated performance space in the context of Johann Sebastian Bach's compositions.

However, many performance spaces of previous centuries no longer exist or have ceased to serve their original purpose and in any case the contemporary concert culture does not involve tying the performance of certain compositions to individual halls. Hence, the perspective can be shifted towards the listener and the question whether certain rooms are particularly suitable for the enjoyment of certain musical styles. In this context, two early studies shall be mentioned: Kuhl (1954) aimed to determine the optimal reverberation time of music studios for different musical styles (classical, romantic, modern) on the basis of expert listeners' judgements, concluding an optimal 2.1 s for Johannes Brahms' Fourth symphony on the one hand, and around 1.5 s for Wolfgang Amadeus Mozart's Jupiter symphony and Le Sacre du Printemps by Igor Strawinsky on the other hand. Reichardt et al. (1955) came to similar conclusions by asking listeners to rate the suitability of different reverberation curves of music studios for several music pieces. Along similar lines but with no empirical evidence, Dart (1959) suggested categorising music into three classes: resonance-, room- and street-music. A more recent study extended the question to rock and pop music, deriving frequency independent reverberation times of 0.6 s to 1.2 s as an optimum (Adelman-Larsen et al., 2010).

In practice, at most the suitability of the room size for the performing orchestra or ensemble might be considered in the schedule of concert halls but generally musicians are confronted with a large variety of room acoustical conditions when performing all kinds of musical styles and compositions. This now eventually brings into focus the perspective of the performers and the main interest of this research project. Since a musician's perception of the sound that is transformed by the room acoustical environment can be assumed to influence the way he plays, a complex interaction evolves between acoustical production and perception. One can furthermore assume that players have an inner representation of the intended sound to be conveyed to the audience, so it is likely that they consciously adapt their way of playing to achieve the sound they have in mind for the listeners. The interrelation between room acoustics and the way musicians play is frequently addressed by performers themselves but it has not been thoroughly investigated. Can the influence of the room acoustical surrounding on music performance be empirically verified? Which aspects of performance are adjusted and in what way? Is the influence of the surrounding room dependent on the played instrument or even the musical content? Which room acoustical properties are relevant for the presumed performative adjustments? These questions were addressed in this research project with respect to solo music performances by conducting two empirical investigations: a field study with one cellist playing in real concert situations and a laboratory study with 12 musicians of different instruments playing in simulated room acoustical environments.

**Chapter 2** of this thesis is dedicated to theoretical considerations related to music performance: the terms performance and interpretation of music are elucidated, a model of solo music performance is proposed and recommendations of music scholars and performers regarding the adjustment of performances with respect to certain room acoustical conditions are presented. **Chapter 3** gives a revision of previous studies concerning the main research question (influence of room acoustics on music performance) as well as the closely related field of stage acoustics. In **chapter 4**, the methods of the investigations carried out in this thesis are presented by describing the research design, the measurement methods employed for quantifying room acoustical properties and performance characteristics as well as the analysis methods used for the quantitative and qualitative data obtained in the investigations. **Chapter 5** and **6** are dedicated to the field and laboratory study, respectively. Both chapters have a similar structure: the descriptions of the performances and the room acoustics involved in the studies are followed by the statistical analysis of the quantitative data and the evaluation of guided interviews, while the chapters are closed by conclusions drawn from the results. A discussion of all findings and the conclusions that follow from them is given in the final **chapter 7**.

# 2

# THEORY

## 2.1 Performance and interpretation of music

The terms performance and interpretation of music are frequently used as synonyms (especially the German equivalents *Aufführung* and *Interpretation*) but they are also often clearly distinguished. In the following section, both terms are examined more closely in order to define their use for the further course of this thesis.

The performance of music was paraphrased with „music-making“ by Dunsby (2001, p. 346), which literally means the music comes into existence in the moment of sound production. Danuser (1998, p. 1817), on the other hand, described music performance as the act of rendering music into sound, implying the independent existence of music before its manifestation as sound. This raises the question whether music *is* in the instance of its sounding or before. The answer partly depends on the question if the music is improvised or performed from a score, even though even in the former case it probably exists in the mind of the artist in some form. Moreover, this question is associated with the notion of musical pieces as independent art works and their fixation in scores (Dahlhaus & de la Motte-Haber, 1982, p. 94 ff.). However, this matter shall not be elaborated here, because irrespective of the answer both of the above cited authors evidently agree on the production of musical sound as the determining aspect of music performance, which shall be taken as starting point for a definition of the term here. After all, a characteristic inherent to the musical art is the fact that it is received and perceived only in the moment of sound production. Given the existence of a written representation of the music, experts may be able to imagine the sound of what they read in the score. The violinist and Schoenberg pupil Rudolf Kolisch even propagated the reception of music through score reading and declared performance as useless (Kolisch & Türcke, 1983, p. 9 ff.). However, most people do enjoy music while its sound is presented to them by a performer. Stressing this dependence of music reception on performance, Clarke (2003, p. 185) raised the question if listening to music and listening to performance could be distinguished at all. Considering the repeated performances of the same musical works by various artists, which constitutes a major part of the contemporary concert culture of Western classical music, it seems, though, that the audience is made clearly aware of the dualism of musical work and performance. So, the focus nowadays lies on the performer as intermediary between the creator of a musical work and its recipient, particularly because every performer presents the music in a distinct way. This diversity illustrates that there is an additional aspect to the performance of music as mere production of musical sound: the interpretation of music as recreating realisation of a musical composition (Eggebrecht, 1967), which involves both understanding a piece of music and rendering it into sound (Budde, 1980, p. 13). Referring to the multiple meaning of the term interpreter, Walls (2003, p. 17) compared the task of musical interpretation to the one of translating a foreign-language text to an audience. This appears appropriate, since in both cases the originator and the translator are not the same person and both comprehension as well as ability of expression of the original ideas are required from the latter. The concept of translation was also implied by Georgiades (1977, 45 f.) who remarked that the reversed act of transforming sound into notation could be called interpretation, as well, since it also demanded an understanding of the music. From these observations it becomes apparent that in the interpretation of music there is a strong emphasis on the apprehension of the musical work and the intent of the composer (Danuser, 1996; Davies & Sadie, 2001).

The intermediary role of the performer and his above described tasks as interpreter have been viewed critically by many (20$^{th}$ century) composers. Concerning the artistic role of both actors, Arnold Schoenberg, for instance, clearly distinguished between the creating composer as genius and the reproducing performer as servant and, similarly to his pupil Kolisch, he challenged the balance in the triad composer - performer - audience by stating that „not the author, but the audience only needs it [the performance]" (cited in Danuser, 1986, p. 253). Also assigning an inferior artistic importance to performers, Paul Hindemith denoted them as re-creators (*Nachschaffende*) or executors (*Ausführende*) and regarded the necessity of their intermediary position as „inevitable disadvantage" (Hindemith, 1959, p. 166). Characteristically, in Hindemith's opinion the technical expertise of a performer was his most important asset. For Igor Strawinsky, the interpreter's faithfulness to the composition was of major concern: „The secret of perfection, above all, lies in respecting the law that the work imposes upon the executor." (Strawinsky, 1949, p. 77) Certainly, not all composers shared the above views. Franz Liszt, for example, even attributed the completion of his work to the performer, since important aspects of his intentions could not be written down in the score (Liszt, 1910, p. XII). It was also him who, as early as 1855, spoke of Clara Schumann as *interpreter* and attributed the same importance to her role as to the one of her composing husband since he regarded the music to be useless if it was not brought to life by performance (Liszt, 1978, p. 192 f.). The non-composed cadences in Mozart's piano concertos may serve as just one further example for artistic freedom given to performers by a composer. As it was suggested in the first statement of Liszt, there is an additional level in the relationship between composer and performer: In most cases there is no direct interaction between the two, but the composition is rather written down in a score, which serves as an intermediary for the interpreter. However, it has been frequently noted that it is impossible to define every aspect of music in writing. Schoenberg even saw the „imperfection of notation" as the actual problem that made interpretation necessary in the first place (cited in Danuser, 1986, p. 255). So ultimately, the unnotable aspects of a score inevitably result in a certain subjectivity on the part of the performer.

The above observations accentuate the challenge of the interpreter: finding a way to grasp a compositional idea and the means of expressing it in sound with a possibly imperfect score as primary source of information. In this context, René Leibowitz, a further member of the Second Viennese School, postulated the idea of „*une lecture radicale*“ of a score, that is studying the music to its roots in order to reveal its meaning (Leibowitz, 1986, p. 61) . Similarly, in Heinrich Schenker's philosophy of performance, as it was summarised by Rothstein (1984, p. 5 ff.), the answer lies in the structure of the music. According to him, there is no need for interpretation, as the right way of sound rendition is given by the musical context. Both authors apparently considered the problem of notation as superable by putting great emphasis on what Danuser (1992, p. 4) called the structural function of a score (*Struktursinn*). According to him, it is expressed in pitch and tone duration and can be revealed by musical analysis. The performance function (*Aufführungssinn*), on the other hand, denotes those markings in a score that refer to tempo, dynamics, pedalling etc. Regarding the performance level, Schenker interestingly made a clear distinction between the effects desired by a composer and the ways of realising these on the part of the performer. In fact, he regarded an alteration of the performance instructions as legitimate and necessary if a certain situation demanded it as long as the desired effects were achieved (Rothstein, 1984, p. 10). Returning to the twofold task of a performer, one could conclude that the structural level of a score provides the basis for understanding the musical composition while its performance level contains clues regarding the adequate expression of this meaning, whereby both levels and tasks are surely permeable.

An aspect that has not been mentioned so far is the historical perspective of interpretation: In the majority of cases there is not only the score between performer and composer but also a considerable time span. Before the 19$^{th}$ century, composer and performer were often the same person or worked together very closely and predominantly contemporary music was performed, so the tonal rendition of a score was rather unambiguous (Danuser, 1980, p. 33). At the same time, the „imperfection of notation“ and the involved necessity to grasp the intention of a composer was already recognised in the mid 18$^{th}$, for example by Carl Philipp Emanuel Bach (Wagner, 2000, pp. 58). In the course of the 19$^{th}$ century the concept of interpretation became more pronounced when con-

cert programmes increasingly featured non-contemporary pieces (Kopiez, 1994, p. 9; Danuser, 1980, p. 33 f.). As Danuser pointed out, this entailed a certain ambiguity in notation due to differences between composers, styles or eras and musical pieces had moreover began to be viewed as individual works that were composed for posterity and demanded a faithful rendition. Furthermore, a shift from the theory of the affects towards the notion of conveying (subjective) sentiments in music had taken place in the second half of the 18th century (Kopiez, 1994, p. 9). After the emergence of the historically informed performance practice in the course of the 20th century, the distinction between the presentation of affects by means of clearly defined performance techniques and the expression of emotions through individual art works was simplified towards the idea that Early Music could be correctly re-enacted through historically informed performance practice while music since the Classical period required interpretation (Dahlhaus, 1978). Both Dahlhaus and Danuser (1992, p. 1) reasoned that this opposition was not tenable since all music demanded informed reconstruction *as well as* interpretation, a view that was also shared by other authors (Hill, 1994). With the above opinions of different composers in mind, it must therefore be part of musical interpretation today to reconstruct the historical context of any musical piece in order to understand what the composer meant and what he expected from the performer regarding extensions or absolute faithfulness to the score (Danuser, 1980, p. 34).
Taking all the above points into account, the summary of the tasks of an interpreter given by Georgiades (1977, p. 47) seems to be applicable: studying source material, conducting structural and stylistic analysis, considering the history of thought and acting as a practising musician.

Returning to the starting point, where music performance was outlined as the production of musical sound, it can be specified now that – assuming a musically meaningful performance beyond mechanical reproduction – it is the sounding element of a comprehensive process, the musical interpretation. In other words, the performance of music is a unique event in which the actual realisation of an interpretation manifests itself to an audience (Davies & Sadie, 2001). While

„the exact reproduction of all elements of a performance is impossible except through a recording, an interpretation can be repeated." (White, 2003, p. 612) Even though an interpretation by a single performer is not invariable, it has a rather stable character. The factors that determine the uniqueness of a performance shall be examined in the next section.

## 2.2 Model of a solo music performance

Danuser (1996, p. 1060) remarked, that the best performer was not the one who presented the same version of his interpretation of a musical work evening by evening, but the one who adapted his performance by communicating with the audience and taking into account the environing conditions such as room acoustics and atmosphere. The reasoning behind this is that a performance is embedded in the context of its occurrence. Thus, performed music cannot be seen detached from the environment it takes place in, since this environment has the potential to influence and become part of the specific sonic realisation of an interpretation. As Leman (2008, p. 51) stated, „there is a complex relationship between [human] action and perception on the one hand, and the natural and cultural environments on the other hand." In this section, a model of a solo music performance focussed on the musician's perspective is proposed, accounting for the elements of the performance itself, involving action and perception, and the context it takes place in, that is the natural and cultural environments.
Figure 2.1 shows the proposed performance model.[1] The grey and green boxes represent the core elements of a performance while the white boxes illustrate the contextual variables potentially influencing the performance.

Preceding the performance itself, a concept of how to play the music is formed by the musician (Sloboda, 1982; Gabrielsson, 1999; shown in grey in figure 2.1). In sight-reeding and improvisation only certain aspects of a performance con-

[1]In ensembles or orchestras there may be more or other elements. Since this thesis only deals with solo performances, these cases are not addressed here.

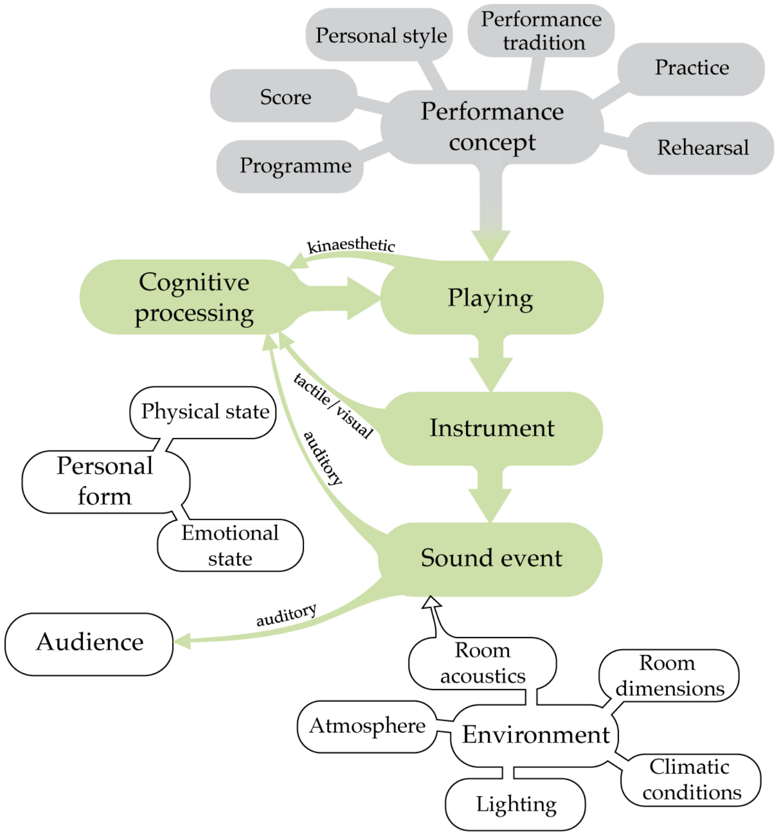



**Figure 2.1.** – Model of a solo music performance situation. Grey and green boxes stand for the main elements of a music performance, white boxes represent contextual variables.

cept may be developed beforehand, but these special cases of performance are not considered here. According to Gabrielsson (1999, p. 502), two main steps can be distinguished in the process of planning a performance: the acquisition of a mental representation of the music with an idea of its transformation into sound on the one hand, and the practice aimed at attaining the required technical proficiency on the other hand. These two steps are not necessarily accomplished consecutively but rather simultaneously, since they are strongly interrelated, as Gabrielsson stressed. He stated that one important part of the mental representation was the structural understanding of the music, on which the musical material to be performed, that is the programme, has a very elementary influence. The music is notated in the score with its structural and performance function made out by Danuser (1992, p. 4; see section 2.1). The former denotes the entire meaning of a musical work that is accessible through music analysis, so this concept is very closely related to the structural understanding described by

Gabrielsson. The performance function refers to the expressive markings in the score which determine the idea of how to transform the score into sound to a certain extent and can vary in different editions. Gabrielsson (1999, p. 503) pointed out that the mental representation of a piece does not only involve structural features but also attributes such as emotions, associations, body movements or sound patterns, a notion that will be returned to below. All these aspects eventually lead to specific decisions about how to transfer the musical score into sound. On the one hand these decisions are formed by factors like the musician's personality, background and experience with performance in general, which can be summarised as personal style. Furthermore, there are certain performance traditions and schools that a performer might follow and on which the decisions on the way to perform in terms of playing technique greatly depend. With regard to the second major step in the acquisition of a performance concept, the practice, a distinction is made in the model in figure 2.1 between the practising for the preparation of a performance and the rehearsal in the actual concert settings. The practice can evolve over an extended period of time and involves several stages (Chaffin et al., 2010). During the rehearsal, the performance concept might be changed to accommodate situational demands. It becomes clear that the performance concept is very similar to what was described as interpretation in the above section. In fact, forming a performance concept is an important part of the interpretation of a piece.

During the actual performance (shown in green in figure 2.1), the motor action of playing that is governed by the performance concept is directed towards the instrument that in turn produces a sound event. The sensory (kinaesthetic, tactile, visual, auditory) feedback from the body movements, the instrument and the sound is cognitively processed by the performer and also guides his playing. It should be noted that the cognition may be mental or embodied. „While involved with music, the human body interacts with physical energy and the human mind deals with interpretations that are built on top of that corporeal interaction.“ (Leman, 2008, p. 51) As Leman pointed out, the focus in research on music cognition was on the processing by the human mind, while recently there has been a shift towards corporeal aspects. Both mental and embodied cognitive processing help to activate and control the motor action of playing the instrument. There are different theories on how the planning and execution of movement is controlled by sensory feedback and two principles of motor action appear to be interesting in this context: the ideomotor and the closed-loop mechanisms, which were reviewed by Greenwald (1970). Before explaining these principles, the modalities of sensory feedback shall be briefly looked at.

The visual feedback probably plays a minor role in music performance, as Repp (1999) pointed out, at least for solo musicians. After all, there are many musicians who close their eyes while playing, possibly internally experiencing the musical movement (see Leman, 2008, p. 98) Kinaesthetic receptors enable the control of body movements and tactile information is necessary for the nuanced control of the instrument. Since music performance is about sound production, it is perhaps not surprising that numerous studies have investigated the role of auditory feedback. Most of them thereby concentrated on the effect of altered, that is usually delayed, or suppressed auditory feedback on music performance (e.g. Pfordersher, 2006) and it was generally found that the latter causes almost no disruptions. Repp (1999) showed that the presence of auditory feedback is well important for the control of expressive performance but a recent study by Bishop et al. (2013) implies that even expressive dynamics and articulation can be achieved with suppressed auditory feedback.

The ideomotor theory states that the anticipation of a sensory feedback triggers the action that causes it (see Stock & Stock 2004; Shin et al. 2010 for reviews and Koch et al. 2004; Keller & Koch 2008 for empirical evidence). For music performance, this implies that at least parts of the performance concept are represented as sensory stimuli in the mind of a player. This is in line with what Gabrielsson viewed to be part of the mental representation of a piece of music, as was explained above, and indeed there is empirical evidence that sound and motor patterns are planned and exist in the memory of performers (Palmer & Pfordersher 2003; Palmer 2006; Leman 2008, p. 95 f.). This is taken a step further by the notion of musical imagery. It entails the sensing of music that is not actually played at that instance, that is the anticipation of movements, sounds or even musical expression during the performance itself (Leman 2008, p. 85 ff.; Bishop et al. 2013). In ideomotor theory this is what causes the activation of the motor action, which eventually leads to the real sensory feedback that was anticipated.

According to the closed-loop theory (Adams, 1971), the sensory response of a specific motor action is compared to an image of this response and an error correction takes place if necessary. Over the course of rehearsal time, erroneous responses automatically evoke their corresponding corrections. In terms of music performance, this mechanism can be viewed on the simple level of acquiring technical proficiency to play a certain piece. When looking at the performance in connection with the environment it takes place in, the closed-loop theory could explain the adjustment of musicians' way of playing to the room acoustical conditions. Obviously, the closed-loop theory also assumes the occurrence of musical imagery. The anticipated auditory stimuli then represent the ideal sound of the performance that was developed as part of the performance concept. The actually perceived sound during performance is transformed by the room acoustical surrounding, so the comparison with the auditory image will lead to an adjustment of the way of playing if the perceived sound does not correspond to the ideal. This mechanism may be complicated by the fact that the ideal sound of the performance concept might not refer to what the player perceives but what the listeners hear, since the performance is directed towards them, after all. Consequently, the comparison process might involve an intermediate stage, in which the sound in the audience area is deduced from what the musician perceives on stage and the comparison then takes place between the deduced and the ideal imagined sound. It is by no means certain, though, that all musicians adhere to the practise of this intermediate deduction (see section 2.3).

We now return to the performance model in figure 2.1: The aspects determining the performance concept that were described above may be subject to changes, but they can be considered as quasi-constant in a set of performances of the same musical pieces within a limited time span. By contrast, there are a number of influences concerning the performance that change in each concert and that are often mentioned in passing in literature: audience, room, occasion and instrument (e.g. Clarke, 1991; Danuser, 1996; Gutknecht, 1997). In the model proposed here, the instrument is a core element of the performance rather than an influencing factor. Furthermore, the occasion of a performance might be characterised by several aspects which are shown separately in the model: audience, programme and atmosphere. The physical and emotional state of the performer certainly have to be taken into account as situational variables, as well. The room, in turn, is constituted of several aspects like the dimensions of the concert hall, its climatic conditions, the lighting and the room acoustics. All of these variables were summarised in three main categories in the model: audience, environment and personal form.

The contextual variables shown as white boxes in the proposed model are to be understood as potential influence factors in a given performance situation. They may or may not have an effect on the elements of a music performance in a certain situation, which is why no specific connections are shown in figure 2.1. Only the influence of the room acoustical surrounding on the sound event is assumed as given in the proposed model – in light of the idea that music performance is mainly about sound production. Once a composition is realised as a sounding event in a space, the room acoustical surrounding always modifies this sound, acting as an acoustical transformer between the instrument on the one hand and the performer and the audience on the other hand. The interrelation of the other situational variables and their consciously perceived influence on certain aspects of the performance was investigated in the field study of this thesis in guided interviews. The results showing the network of relationships in several individual performance situations are reported in section 5.4.

## 2.3 Performative adjustments recommended by scholars and musicians

As early as the 17th century, the German scholar Athanasius Kircher listed different room properties that he considered as disadvantageous for the adequate transmission of affects: too small and narrow; too full of people, carpets or books; too big (cited in Risi, 2003, p. 155). These characteristics may well contribute to what can very generally be denoted as unfavourable room acoustics and it is not surprising that scholars concerned with the performance and reception of music were aware of such properties. Similarly, Johann Joachim Quantz wrote in his famous book of 1752, *Versuch einer Anweisung die Flöte traversière zu spielen*:

„Ein Stück, das uns in der Kammer fast bezaubert hätte; kann uns hingegen, wenn man es auf dem Theater hören sollte, kaum mehr kenntlich seyn.“ (Quantz, 1752, p. 280)

„A piece that almost enchanted us in the chamber might, on the other hand, be barely recognisable when we hear it in the theatre.“

Both statements assume the transformation of performed music through room acoustics but they are rather concerned with the impact this has on the listener instead of establishing a relation to the performance itself. On the contrary, in several of the famous music treatises of the 18th and 19th century as well as in more modern works there are explicit recommendations for performers on how to react to specific room acoustical conditions. Below, these views and instructions are elaborated on.
Quantz did refer to the performer's perspective when he explained the advantages and disadvantages of certain rooms for certain kinds of music:

„An einem Orte, wo es stark schallet, und wo das Accompagnement sehr zahlreich ist, machet eine große Geschwindigkeit mehr Verwir-

„In a location that resounds loudly and where the accompaniment is very large, great speed causes more confusion than pleasure. [...] The rung als Vergnügen. [...] Der an großen Orten allzeit entstehende Wiederschall verlieret sich nicht so geschwind; sondern verwickelt die Töne, wenn sie gar zu geschwinde miteinander abwechseln [...]. In einem kleinen Zimmer, wo wenig Instrumente zur Begleitung da sind, kann man hingegen Concerte nehmen, die eine galante und lustige Melodie haben, und worinnen die Harmonie sich geschwinder ändert, als zu halben und ganzen Tacten. Diese lassen sich geschwinder spielen, als jene." (Quantz, 1752, p. 166)

reverberation always arising in large spaces does not disappear quickly but entangles the notes if they alternate too quickly. [...] On the other hand, in a small room where there are few accompanying instruments, one can take concerts that have a gallant and merry melody and in which the harmony changes faster than at half and full bars. These can be played more quickly than the former."

As a consequence, he recommended to carefully choose the right pieces of music for the rooms that were used as performance spaces. In a technical chapter of his book, he also directly referred to adapting the playing technique:

„Nicht alle Triller dürfen in einerley Geschwindigkeit geschlagen werden. [...] Spielet man an einem großen Orte, wo es sehr schallet; so wird ein etwas langsamer Triller beßere Wirkung thun, als ein geschwinder. Denn durch den Wiederschall geräth die allzugeschwinde Bewegung der Töne in eine Verwirrung, und folglich wird der geschwinde Triller undeutlich. Spielet man hingegen in einem kleinen oder tapezierten Zimmer, wo die Zuhörer nahe dabey ste-

„Not all trills should be played in the same tempo. [...] If one plays in a big place that resounds strongly, a slightly slow trill will have a better effect than a fast one. Because an all too quick movement of the tones is confused by the reverberation and hence the fast trill is blurred. If, on the contrary, one plays in a small or wallpapered room where the listeners stand close by, a fast trill will be better than a slow one."

hen: so wird ein geschwinder Triller besser seyn, als ein langsamer.“ (Quantz, 1752, p. 83 f.)

Obviously, Quantz was well aware of the impact of reverberation on certain temporal aspects of music performance and this relation is still frequently mentioned by musicians to date.
Interestingly, none of the other important treatises on instrumental techniques of the second half of the 18$^{th}$ century – *Versuch über die wahre Art das Clavier zu spielen* (Carl Philipp Emanuel Bach, 1753), *Versuch einer gründlichen Violinschule* (Leopold Mozart, 1756), *Klavierschule* (Daniel Gottlob Türk, 1789) – mentioned the influence of the room acoustical surrounding on music performance. However, Louis Spohr later gave a clear recommendation concerning the performance of solo violin pieces accompanied by a chamber music formation in his *Violinschule*:

„[...] dass hier, in kleinem Raume und mit schwacher Besetzung, der Ton des Instruments nicht bis zur grössesten Stärke gesteigert werden darf und alles Rauhe im Spiel, was sich im Concertsaal bey der Entfernung der Zuhörer verliert, sorgfältig vermieden werden muss.“ (Spohr, 1833, p. 246)

„[...] that here, in a small room and with weak instrumentation, the tone of the instrument must not be risen to its greatest strength and every roughness in playing, which is lost in the concert hall at the distance of the listeners, has to be avoided carefully.“

So, just like Quantz, Spohr referred to the size of the accompanying ensemble and of the room but instead of temporal aspects, he associated an adaptation of the played dynamic strength and roughness with these characteristics. A similar remark concerning room size and strength can be found in Carl Czerny’s *Vollständige theoretisch-practische Pianoforte-Schule*, although the author did not elaborate on the exact manner of loudness adjustment:

„Die Kraft des Anschlags muss überhaupt auch nach der Grösse des Locals bemessen werden.“ (Czerny, 1839, p. 63)

„Also, the strength of the attack has to be chosen according to the size of the location.“

In his book *Kunst des Violinspiels*, Carl Flesch outlined the ideal of a favourable disposition needed by a musician to achieve a successful performance. According to him, this disposition does not only entail an ideal technical, physical and mental constitution of the player but also an adequate room, since:

„Günstige akustische Verhältnisse erhöhen das Vergnügen an der eigenen Klangproduktion und rufen rückwirkend gesteigerte Sensibilität hervor. [...] In einer solchen ungemein günstigen seelischen Verfassung ist er [der Musiker] imstande, alles zu empfinden, was in dem Werk an Gefühlswerten vorhanden ist, und alles auszudrücken, was er selbst hierbei empfindet.“ (Flesch, 1928, p. 80)

„Beneficial acoustical conditions enhance the enjoyment of the own sound production and retrospectively evoke increased sensitivity. [...] In such an immensely favourable mental constitution he [the musician] is capable of feeling every single emotion in the musical work and of expressing everything that he himself feels at this.“

It is noteworthy that in his view the acoustical environment has an impact on the sensitivity of the performer and thus influences the musical expression in particular. Basically, this is in line with Kircher and Quantz, except that Flesch considered the emotional effect on the player and not the listener. Furthermore, he aptly described the interaction of room acoustics and the musical sound production by stating:

„Ein akustisch richtig gebauter Saal muß ein ebenso resonanzfähiger Körper sein wie das Instrument selbst, auf dem gespielt wird. Der Künstler spielt nicht nur im sondern gewissermaßen auch auf dem Saale.“ (Flesch, 1928, p. 91)

„An acoustically properly built hall needs to be an equally resonant body as the instrument that is played. The artist does not only play inside the hall but he virtually plays the hall itself. “

As he explained, this insight should help prevent musicians from too much self-criticism after a performance with unsatisfactory sound since the latter could not be improved by changing the own way of playing:

„An eine Besserung durch Anpassung an die Saalverhältnisse glaube ich übrigens nicht. Wenngleich der Spieler versuchen kann, seine Tongebung durch Abdämpfung oder Verstärkung der Akustik des Saales in primitiver Weise anzupassen, so ist er im allgemeinen einem akustisch ungünstigen Raum doch auf Gnade und Ungnade ausgeliefert.“ (Flesch, 1928, p. 91)

„By the way, I do not believe in an improvement by adjusting to the hall conditions. Even though the player can try to primitively adjust his sound production to the acoustics of the hall with attenuation or enhancement, he is, in general, utterly at the mercy of an acoustically unfavourable room.“

So, even if he did not approve of adapting to the room acoustics while performing, Flesch did mention changing the dynamic strength as a basic means available to musicians. Furthermore, it must be remarked that in this context he only spoke of good or bad rooms and thus attached the adjustment of the playing technique only to the perceived room acoustical quality and not to specific room acoustical properties.

In more recent treatises, both the violinists Ivan Galamian and Paolo Borciani, like Spohr and Czerny, gave specific instructions concerning the performance in different acoustical spaces. With chamber music in mind, Borciani pointed out that the musical works nowadays played in large halls had originally been composed for a performance practice involving much smaller rooms.

„Daher ist es nötig, daß die Ausführenden ihren Ton den gesteigerten Raumdimensionen anpassen, ausnahmsweise auch dazu übergehen, in besonders großen Sälen allzu lange Bindungen zu trennen und gewisse

„Therefore it is necessary that the performers adjust their sound to the increased room dimensions, as exception also proceed to separate overly long ligatures and change certain bow strokes in especially large halls. [...]

Bogenstriche zu ändern. [...] Den Klang dem Raum anzupassen, ist wesentlich, die Unterschiede der Klangebenen nicht zu respektieren, ist aber geradezu ein Verrat am Geist der Musik. [...] Man muß darauf achten, die Dynamik der Ausführung nicht zu mindern, vielmehr die Kontraste zu beachten und statt einer gedankenlosen Klangsteigerung lieber ein breiteres Vibrato vorzuziehen.“ (Borciani, 1973, p. 67 f.)

Adjusting the sound to the room is crucial, but not respecting the differences of the sound layers is simply a betrayal of the music's spirit. [...] One must take care not to reduce the dynamics of the performance but rather to beware of the contrasts and to prefer a wider vibrato over a mindless sound enhancement.“

Borciani was very much concerned with the correct relationship of the dynamic layers, but with articulation, bowing and vibrato he also mentioned aspects of musical interpretation that have not appeared in the previous citations. He repeated this recommendation on the use of vibrato in a later section:

„Zuletzt, wir wiederholen es, muß man in einem großen und wenig klingenden Saal häufig ein weiteres Vibrato anwenden als in einem kleinen, gut klingenden.“ (Borciani, 1973, p. 117)

„Finally, we repeat it, in a large hall with weak sound it is often necessary to use a wider vibrato than in a small hall with good sound.“

Galamian compared the performance of music to giving a speech and advocated a clear and understandable playing that should be adjusted to the room acoustical surrounding:

> „If the auditorium is small and the acoustics are good, not too much adjustment will have to be made. The larger the hall, the more must consideration be given to the acoustical factors. If the resonance in the auditorium is dead, then all dynamics have to be upgraded. This is easy enough in soft passages, but when the forte and fortissimo are called for the player has to have flexibility, has to know how to change

> his bowing when needed, dividing strokes more often, in order to get the necessary amount of sound without forcing the tone. [...] Speed will also be an important factor which must now be considered a variable. Extreme speeds should better be avoided in large halls, and this is mandatory where any kind of echo is present in the acoustics. In such a case, too great a speed will have a tendency to blur the clarity. To fill a hall with sound is, however, not just a matter of loudness but rather largely one of carrying power. [...] The more correctly the tone is produced, the farther it will carry. On the violin the tone must not be forced.“ (Galamian, 1962, p. 9 f.)

Apart from the recurrent reference to the size of a hall, the author also mentioned its resonance and the presence of echoes as room acoustical aspects influencing a performance. In addition to his recommendation to adjust the dynamics in acoustically dry rooms, he stressed the necessity to avoid forcing the tone of the instrument, which is in line with Spohr. His remarks concerning bowing and tempo support the suggestions of the previous authors, as well.
With regard to the disapproval of adjusting to the room acoustical surrounding, an argumentation similar to Flesch's was brought up by the Guarneri quartet. They noted that rehearsals in concert halls were useless to them, at least in terms of exploring the acoustics, since it was barely possible to judge the sound of a hall from the position on stage, the more so as rehearsals take place in empty halls.

> „In a dry hall we may tend, almost unconsciously, to hold notes a shade longer, and in a resonant hall, to articulate with extra care. But that's a subtle, instinctive process, not a planned happening. Basically speaking, if a hall is good, it's good and if it's bad, it's bad. You can't make it better by playing softer, louder, slower or faster.“ (Blum, 1987, p. 18)

So, just like Flesch, they emphasised that room acoustical quality could not be improved by adapting the way of playing, but they also named several performance aspects that might nevertheless be changed: articulation, dynamics and tempo. Furthermore, they addressed the very important fact that these adjustments may happen unconsciously.

The above review illustrates which aspects of room acoustics were considered by musicians and scholars to possibly have an influence in the context of music performance and for which aspects of playing they saw the necessity of adjustment under certain circumstances. The room properties named were size, acoustical quality, resonance/reverberation and presence of echoes, while the size of the accompanying orchestra or ensemble was also taken into account. As to performance characteristics that might be adjusted depending on the hall, many different aspects were specified: tempo, dynamic strength, carrying power, articulation, vibrato and, for string instruments, bowing. Interestingly, timbre aspects of performance were not addressed in any of the statements. It is remarkable that the description of room acoustical properties is rather general, especially compared to the wide range of performance features that were named. This must not necessarily be an indication for a lacking richness of detail in the perception of room acoustics, but could be due to a less elaborate vocabulary for room acoustical properties.
Summarising the various statements leads to a quite coherent overall picture:

- Fast tempi should be avoided in large halls with reverberation.
- The size of the hall determines the strength of attack.
- Forcing the tone of the instrument should be avoided in large and dry halls while the same holds for small rooms, which presumably also lack reverberation.
- Instead of achieving pure loudness by forcing the tone in large halls, performers should use carrying power and string players can concentrate on a wider vibrato, separated ligatures and more divided bow strokes. Dry halls, on the other hand, might evoke a prolongation of tones.
- In large and dry halls, dynamics should not be reduced but rather upgraded while the contrasts and dynamic layers are maintained.

Of course, the question arises whether these or other playing strategies are actually put into practice and can be empirically accounted for. Furthermore, different musicians apparently have different views on adjusting their way of playing and these adaptations might also happen unconsciously. Also, a rather obvious aspect implied in the above citations is that different strategies exist for different instruments. These issues will be addressed in the course of the following chapters.

3

# RELATED WORK

## 3.1 Room acoustics and the performance of music

The importance of room acoustics for the performance of music has not only been recognized by music scholars but also by room acoustic researchers. Beranek (2004, p. 4 f), for example, referred to conductors adapting their style to the sound of their home hall, and Gade (1989b) denoted the concert hall as an extension of musical instruments. In view of this, it seems rather surprising that there has not been much empirical research regarding the question. The following section summarises the main findings of the existing studies.

An early field investigation was conducted by Winckel (1962), who studied dynamic and tempo characteristics of the Cleveland Orchestra directed by George Szell performing 8 musical works in 15 American concert halls. Winckel measured the reverberation time of the occupied and unoccupied auditoria by recording the decay of a musical chord in both conditions. During the concerts, he measured the maximum and minimum sound pressure level (SPL) of several musical phrases. Furthermore, he documented the duration of each movement with a stop watch to explore the playing tempo.
The upper dynamic limit was relatively constant in most rooms. As Winckel explained in this context, some rooms dampen the sound and inhibit an adequate sound level while others create a fullness of sound without actual increase of dynamic strength by the orchestra. Both cases could, however, be relatively

easily adapted to by the conductor, thus leading to a constant sound level in the audience area, where Winckel measured the SPL. The lower dynamic limit of the orchestra was more variable and was determined by the noise level of the rooms according to Winckel. The measurement method for the tempo in this study was very rudimentary and the reverberation times of the examined halls were not very heterogeneous, ranging only from 1 s to 2.1 s. It is nevertheless interesting, that the often assumed negative linear correlation between tempo and reverberation time could not be confirmed. Instead, Winckel pointed out that the halls with the slowest tempi had particularly good hearing conditions and those with the fastest tempi were not very suitable for live music performances. Hence, this implies an interrelation between the perceived quality of room acoustics and the tempo of performances.

An investigation under laboratory conditions was carried out by von Békésy (1968) who let both professional and amateur pianists play pieces of varying difficulty and familiarity in three rooms with different reverberation times (3.8 s, 1 s and 0.6 s). In the experiment, the vibration amplitude of the piano body was recorded as a measure for the played dynamic strength.
The measurements of one of the professional pianists showed an increase in vibration amplitude with decreasing reverberation time. Moreover, he showed a tendency to attenuate *forte* parts in the reverberant and to enhance the *piano* parts in the dry condition, so the maximum dynamic range of this player was found in the room with an intermediate reverberation time. Interestingly, the adjustments by all pianists in the study were less pronounced when they played difficult and unfamiliar pieces and this was most obvious for the untrained players.

Ternström (1989) measured the long-time average spectra (LTAS) of three choirs in three acoustically differing rooms and studied the resulting spectrum level differences. His main finding was that in one of the rooms the spectra of all three choirs had increased formant frequencies. He ascribed this to a raised larynx, which could be associated with a pressed phonation. The room concerned was characterised by a very short reverberation time and a high sound enhancement in the low frequency range, the reason for the raised larynx remained unclear, though. On top of this, the two choirs that were professional used more sound power (calculated from the LTAS) in the two more absorbent rooms, which reproduces the results of von Békésy (1968).

Naylor (1992) explored the effect of tempo and reverberation on synchronisation by asking musicians to tap along with tone trains, while the tempo of the tones was varied and two different decay times were used for playback to simulate a dry and a reverberant condition.
The mean tapping error of the musicians increased both with increasing tempo and, interesting in this context, with the presentation of the reverberant tones. This effect was explained with reference to a model for perceptual attack time (PAT) (Gordon, 1987), according to which the PAT occurs sooner if the gradient of the tone intensity rises above a certain threshold more quickly, that is if the attack of the tone is more defined. In the experiment, the overlap of tones caused by reverberation and increasing tempo lead to a less pronounced attack, so the PAT occurred later and tapping synchrony decreased. Naylor remarked that in real performances this effect would be less pronounced because of the high level of early energy and direct sound on stage. Nevertheless, he mentioned sharpening the attack, playing more *staccato* and reducing the tempo as strategies for performers to overcome synchronisation problems.

In a hall with variable room acoustics (Espace de Projection, IRCAM), Bolzinger et al. (1994) investigated the influence of room acoustical parameters on excerpts of piano music played on a MIDI grand piano by seven professional performers. The room acoustical conditions measured and varied during the experiment were the reverberation time, the late reverberation level, the ratio between direct sound and early reflections as well as the spectral properties of the reverberation. Based on the MIDI data of the piano, tempo and articulation were calculated from the inter-onset-intervals and duration of the tones, respectively, while the velocity was used as a measure for played intensity.
Surprisingly, no influence of any of the acoustical parameters on the mean tempo

of the music pieces could be demonstrated. The authors supposed that the investigation of shorter musical phrases and other instruments might reveal an effect, though. In accordance with the results of von Békésy (1968), the average intensity was negatively correlated with the reverberation time and late reverberation level of the room.

In an extensive laboratory study (Ueno et al., 2007), four room acoustical environments were simulated in an anechoic room with 6-channel loudspeaker reproduction while the same two musical phrases performed by several soloists (violin, oboe, flute, vocals) were recorded. From the audio signals, technical features were extracted – phrase duration, A-weighted SPL, fluctuations of fundamental frequency and SPL, spectral features – to characterise different aspects of performance – tempo, dynamic strength, vibrato, timbre/articulation.
All of the technical predictors showed a variation over the acoustical conditions while for most variables, the manner of adjustment was dependent on the respective instrument (or musician, since the two variables were confounded). Interestingly, the playing tempo was not only reduced in very reverberant rooms but also under anechoic conditions, an effect that was especially pronounced for the faster one of the two pieces. For some players, this also held for the dynamic strength of their performances, but the results were less consistent here (Kato et al., 2007). Suppressing higher harmonics as well as playing more pronounced *staccato* and prolonging pauses between notes were strategies employed by individual performers under reverberant conditions (Kato et al., 2015). A more detailed investigation of the room acoustical parameters showed that the mean dynamic strength of the slow piece of music was negatively correlated with the stage parameters early support and late support (see section 3.2) but not the dynamic strength nor the reverberation time of the rooms (Ueno et al., 2010). This is interesting, not least because the other studies mentioned above that revealed a negative relation between the dynamic strength and reverberation did not take the support parameters into account.
Interviews conducted with the performers in this study showed that the most frequently named conscious adaptations to the room acoustical conditions re-

garded dynamics and vibrato but not tempo, as one might assume. The statements regarding this performance parameter were even contradicting between different musicians in many cases. Playing shorter notes in reverberant and longer notes in dry rooms was a strategy mentioned by many performers, though (Ueno et al., 2010).

Similarly to the research by Bolzinger et al. (1994), a recent study by Kawai et al. (2013) was carried out with a MIDI grand piano. Twelve professional performers played excerpts of three different pieces in five room acoustical surroundings, of which two were simulated sound fields presented over four loudspeakers. In each virtual and real room, the reverberation time as well as the early and late support (see section 3.2) were measured. The MIDI signal of the performances was recorded to extract the duration of each piece (indicating tempo), the mean and standard deviation of the velocity (indicating dynamic strength and dynamic bandwidth) as well as the ratio of pedal use.
All of the performance characteristics were varied by the performers across the room acoustical surroundings, although this effect was weakest for the tempo. A correlation of the room acoustical parameters with the performance characteristics averaged over musicians showed a very strong negative relation between the reverberation time and the use of the pedal. While this is not surprising, the results for the tempo were rather unsystematic, just like in Bolzinger's study. The dynamic strength was negatively correlated with both stage parameters, especially the early support, which is in line with Ueno et al. (2010). The dynamic bandwidth of the pianists was also smaller in the surroundings with high early support. The authors also performed a cluster analysis with the data of the individual musicians and showed that there were different strategies among the players regarding the adjustment of certain performance characteristics.

Most of the above mentioned studies concentrated on the influence of reverberation on tempo and dynamic strength or dynamic bandwidth. In summary, it seems that the dynamic strength of performances is increased in rooms with short reverberation time and/or high support and decreased under contrary conditions. The observed tempo adjustments were much more ambiguous, so that no clear conclusions can be drawn here. This might be due to differing adjustment strategies among performers, which was implied by interviews conducted with musicians in one study and a cluster analysis regarding individual performance data in another study. It illustrates that varying performers and instruments as well as their performance concepts should be taken into account in order to reveal the effect of individual and instrument-specific differences and the strategies behind them. In the few studies where performance characteristics other than temporal or dynamic attributes were investigated, these also showed a variation over different room acoustical surroundings. It thus appears important to consider further aspects of music performance.

The above review exemplifies the challenge of operationalising music performance since the measurable parameters used as predictors for performance properties were by no means consistent among the studies. Furthermore, many of the summarised investigations used only short musical phrases for their analysis, so the validity of the results might be put into question. It was also implied by some results that the musical content may have an influence on performative adjustments. The reviewed studies thus call for further investigation by studying longer, more variable music excerpts.

Regarding the room acoustical surroundings, consideration must be given to the investigation of aptly variable room acoustical conditions, since the effects might otherwise be too small. Furthermore, it was already mentioned that only few studies have measured room acoustical parameters other than the reverberation time in the halls the performers played in. Since musicians differentiate more aspects than only the duration of reverberation regarding their perception of room acoustical surroundings (see section 3.2), it appears likely that these further aspects have an influence on their way of playing. Hence, more room acoustical parameters should be taken into account as possible influence factors on music performances.

## 3.2 Stage acoustics

Since the second half of the $20^{th}$ century there has been a growing body of research concerning the correlation between physically measurable room acoustical parameters with attributes relating to the human perception of room acoustical surroundings. In this respect, there are presumably large differences between the perspectives of the performers and the audience. A set of physical parameters has been established by now to evaluate the quality of concert hall auditoria (see e.g. Beranek, 2004; Kuttruff, 2009), while the current research is focussed on binaural parameters (Ahnert & Tennhardt, 2008) as well as advanced measurement techniques and auditory models for feature extraction (Weinzierl & Vorländer, 2015). The research regarding the acoustics on stage areas is still ongoing and there are only two widely used physical parameters relating to musicians' perception of their room acoustical surroundings. The main findings of the research on stage acoustics are summarised in this section.

If one aims at exploring and quantifying the acoustics of stage environments, the question to be answered beforehand is which perceptual aspects of room acoustics are actually relevant for musicians. In this regard, Gade (1986) presented the results of an interview survey conducted with performers of classical music. They were asked to name and rank those room acoustical properties of concert spaces that were important for them. This yielded the following attributes (in order of ranking): ‚reverberance', ‚support', ‚timbre', ‚dynamics' as soloist concerns as well as ‚hearing each other' and ‚time delay' as ensemble concerns. This list was extended by the aspects ‚clarity', ‚balance' and ‚warmth' by Sanders (2003) who then asked chamber musicians to judge specific concert spaces regarding these attributes as well as their ‚overall acoustic impression'. By correlating the judgements on the latter attribute with the ratings on the former ones, the author ranked their importance. This showed that ‚support' was by far the most relevant aspect for the chamber musicians regarding the quality of a hall while ‚clarity' had the lowest priority. Similarly, Genta et al. (2009) asked five orchestras to prioritise aspects of room acoustics that were defined by the authors. It was found that ‚clarity' and ‚tempo' (that is the ability of keeping the tempo) were the most important ones while ‚reverberance' was least relevant, but the investigation showed big differences between the orchestras. The great individuality of judgements among musicians might explain the partly conflicting results reviewed here. Without special interest in priorities, Ueno et al. (2005) found in a qualitative interview survey that an additional essential aspect for chamber music was ‚making harmony', which was described as the merging of the sound of several instruments.

Early papers on measurable acoustical conditions on stage concentrated on the preference of musicians for specific architectural features or the contribution of reflections regarding the ability to hear themselves and others: In his study of different stage configurations in the Gulbenkian Grande Auditorio, Barron (1978) found that an overhead reflector was preferred by all performers of a small ensemble. Wind players were in favour of close reflecting surfaces around them while an open stage was preferred by strings. An overhead reflector was also recommended by Allen (1980) who additionally advocated a raked stage or audience area. Studying the ease of ensemble playing under laboratory conditions, Marshall et al. (1978) concluded that there is a temporal window between 17 ms and 35 ms in which early reflections are judged positively by musicians. Their investigation also yielded that the reflection of high frequencies is crucial for the performance conditions of ensembles. According to the qualitative contribution by Fry (1980), the same holds for solo singers who furthermore need early reflections to hear themselves against the background of the accompanying orchestra. This was experimentally specified by Marshall & Meyer (1985) who found that early reflections before 40 ms are positive for singers but that generally the presence of reverberation is most important for their comfort.

Naylor was also concerned with ensemble playing (Naylor, 1988a) and experimentally found that chamber music players needed level differences of -23 dBA to 5 dBA between themselves and others for good ensemble conditions when playing polyphonically (Naylor & Craik, 1988). He furthermore suggested the measurement of a modulation transfer function on concert hall stages in order to quantify the amount of information conveyed among the musicians but assumed that the level differences mattered most (Naylor, 1988b). Most other parameters that were suggested to quantitatively describe stage acoustical properties are calculated as energy relations. A summary of these measures is given below.

With reference to the findings of Marshall et al. (1978), Jordan (1982) suggested the Early Energy Balance ($EEB$):

$$EEB = 10\log_{10}\left(\frac{\int_{0\,\mathrm{ms}}^{35\,\mathrm{ms}} p^2(t)\mathrm{d}t}{\int_{0\,\mathrm{ms}}^{5\,\mathrm{ms}} p^2(t)\mathrm{d}t}\right) \tag{3.1}$$

$p(t)$: Sound pressure measured on stage with the receiver farther away from the source than the critical distance

The $EEB$, however, was not mentioned again later. Instead, Gade pursued the search for physical measures to predict the above mentioned perceptual criteria in laboratory and field studies with soloists, ensembles and orchestras (Gade, 1989a,b). He introduced the so-called support parameters that were slightly revised later (Gade, 1992) and are listed in ISO 3382-1 since 2009. They relate the energy of different sections of an impulse response determined with 1 m distance between source and receiver to the energy of direct sound and floor reflection of the same measurement. According to the standard, the parameters are physical measures for the perceptual aspects of ‚ensemble conditions' ($ST_{\mathrm{early}}$) and ‚perceived reverberance' ($ST_{\mathrm{late}}$).

$$ST_{\mathrm{early}} = 10\log_{10}\left(\frac{\int_{20\,\mathrm{ms}}^{100\,\mathrm{ms}} p^2(t)\mathrm{d}t}{\int_{0\,\mathrm{ms}}^{10\,\mathrm{ms}} p^2(t)\mathrm{d}t}\right) \tag{3.2}$$

$$ST_{\text{late}} = 10\log_{10}\left(\frac{\int\limits_{100\,\text{ms}}^{1000\,\text{ms}} p^2(t)\mathrm{d}t}{\int\limits_{0\,\text{ms}}^{10\,\text{ms}} p^2(t)\mathrm{d}t}\right) \tag{3.3}$$

$p(t)$ : Sound pressure measured with a distance of 1 m between source and receiver, both transducers at a height of 1 m or 1.5 m (ISO 3382-1, 2009)

In the measurement procedure of these parameters, several distance related issues have to be considered: No reflections arriving before 20 ms have an influence on the calculation in the numerator of equation 3.2, so the transducers should be placed in at least 4 m distance of any surfaces that could provide early reflections of interest. Since this can be problematic on small stages, Gade (1992) recommended to reduce the time limit in the numerator if necessary. In any case, there is a lower limit of 10 ms to such a reduction, as no reflections other than the one from the floor should arrive earlier in order not to bias the reference signal in the denominators of equations 3.2 and 3.3. However, Wenmaekers et al. (2012) pointed out that additional consideration should be given to smearing effects caused by the octave filters used for the parameter calculation, especially in the low frequency bands – the lowest band of interest is the 250 Hz octave. Wenmaekers et al. came to the conclusion that a time gap of between 9 ms and 17 ms is necessary after the floor reflection if the influence of its smearing is to be kept below 1 dB or 0.1 dB, respectively. So, this should be taken into account when reducing the time limit of the $ST_{\text{early}}$ calculation. To ensure that only direct sound and floor reflection are included in the reference signal, a removal of any furniture in a radius of 2 m around the transducers is recommended (Gade, 1992; ISO 3382-1, 2009).

Some later studies comparing several stage environments found that substantial architectural or perceptual differences were not always accompanied by changed values of the support parameters (O'Keefe, 1995; Chiang et al., 2003; Berntson & Andersson, 2007; van Luxemburg et al., 2009; Dammerud et al., 2010), so there were suggestions for alternative measures. Van den Braak & van Luxemburg (2008) introduced $LQ_{7-40}$ catered to the perception of conductors and relating early energy to the energy of the rest of the impulse response:

$$LQ_{7-40} = 10\log_{10}\left(\frac{\int_{7\,\mathrm{ms}}^{40\,\mathrm{ms}} p^2(t)\mathrm{d}t}{\int_{40\,\mathrm{ms}}^{\infty} p^2(t)\mathrm{d}t}\right) \tag{3.4}$$

$p(t)$ : Sound pressure

When spatially averaged, this parameter did not correlate well with perceptual attributes but single measurement positions provided information on the ‚transverse support over the stage' (van den Braak et al., 2009). It was pointed out by Gade (2010), though, that $LQ_{7-40}$ is not correctly measurable at low frequencies because of the narrow time window in the numerator.
Dammerud (2009) carried out investigations of stage acoustics for symphony orchestras in field studies as well as laboratory experiments with scale and computer models. From these he concluded that directionally dependant measurements of impulse responses should be made for the assessment of stage acoustics, which was also recognised by others (Meyer & Biassoni de Serra, 1980; O'Keefe, 1995). Dammerud furthermore argued that the measurement of the support parameters lacked accuracy because the reference signal was measured without source rotation, thus prone to effects of source directivity, and because slight deviations from the 1 m-distance between source and receiver could cause additional errors. He thus suggested the alternatives $G_\mathrm{e}$ and $G_\mathrm{l}$ that use the free field sound level of the source at 10 m as reference and can be calculated from the in-situ measurements of sound strength ($G$) and clarity ($C_{80}$):

$$G_\mathrm{e} = 10\log_{10}\left(\frac{\int_{0\,\mathrm{ms}}^{80\,\mathrm{ms}} p^2(t)\mathrm{d}t}{\int_{0\,\mathrm{ms}}^{\infty} p_{10\,\mathrm{m}}^2(t)\mathrm{d}t}\right) = 10\log_{10}\left(\frac{10^{C_{80}/10}\cdot 10^{G/10}}{1+10^{C_{80}/10}}\right) \tag{3.5}$$

$$G_{\mathrm{l}} = 10\log_{10}\left(\frac{\int_{80\,\mathrm{ms}}^{\infty} p^2(t)\mathrm{d}t}{\int_{0\,\mathrm{ms}}^{\infty} p_{10\,\mathrm{m}}^2(t)\mathrm{d}t}\right) = 10\log_{10}\left(\frac{10^{G/10}}{1+10^{C_{80}/10}}\right) \tag{3.6}$$

$p(t)$: Sound pressure of the in-situ measured impulse response

$p_{10\,\mathrm{m}}(t)$: Sound pressure of an impulse response measured in the free field with the same sound source at a distance of 10 m to the receiver

In order to enable the measurement of the support parameters at source-receiver distances larger than 1 m – describing the benefit of reflections for the sound of other players on stage – Wenmaekers et al. (2012) suggested an extension[1] of Gade's measures:

$$ST_{\mathrm{early},d} = 10\log_{10}\left(\frac{\int_{10\,\mathrm{ms}}^{103\,\mathrm{ms}-\mathrm{delay}} p_d^2(t)\mathrm{d}t}{\int_{0\,\mathrm{ms}}^{10\,\mathrm{ms}} p_{1\,\mathrm{ms}}^2(t)\mathrm{d}t}\right) \tag{3.7}$$

$$ST_{\mathrm{late},,d} = 10\log_{10}\left(\frac{\int_{103\,\mathrm{ms}-\mathrm{delay}}^{\infty} p_d^2(t)\mathrm{d}t}{\int_{0\,\mathrm{ms}}^{10\,\mathrm{ms}} p_{1\,\mathrm{m}}^2(t)\mathrm{d}t}\right) \tag{3.8}$$

$p(t)_{1\,\mathrm{m}}$ : Sound pressure measured with a distance of 1 m between source and receiver

$p(t)_d$ : Sound pressure measured with arbitrary distance $d$ between source and receiver

delay: Delay between source and receiver in [ms]

Many studies have investigated the relation between perceptual criteria and physical measures regarding stage acoustics. In his early field study, Gade (1989b) asked two orchestras playing in various halls to rate these regarding the perceptual aspects mentioned above and measured several room acoustical parameters on stage. He found a correlation between both the concepts ‚hearing oneself' and ‚hearing others' with the support parameters as well as with pa-

[1]Note that the lower integration limit of the numerator in equation 3.7 is set to 10 ms and the upper integration limit of the numerator in equation 3.8 is set to infinity.

rameters often used in auditorium acoustics: early decay time, centre time and clarity.

Chiang et al. (2003) conducted a study with chamber groups and soloists playing in various stage configurations and positions. The musicians rated the room acoustical surroundings in terms of ‚ease of ensemble‘, ‚hearing others‘, ‚hearing oneself‘ and ‚overall impression‘. This resulted in high correlations of the latter two attributes with measures associated with early energy, including $ST_{\text{early}}$. Surprisingly, these correlations were negative, though, which was explained by very high levels of early energy on the investigated stages possibly causing overpowering that was perceived as adverse. A non-linear regression model employed by the authors even implied that an inverse quadratic function best described the relation between ‚overall impression‘ and early energy, which was more pronounced for soloists.

Using a 6-channel loudspeaker system presenting simulated sound fields (see section 3.1), Ueno et al. investigated the preference of solo and chamber music players for reverberation time, early reflections, that is $ST_{\text{early}}$, and magnitude of reverberation, that is $ST_{\text{late}}$ (Ueno & Tachibana, 2003; Ueno et al., 2005). Three increments for each of these three acoustical properties were presented to string and wind instrumentalists who were asked to express their priority for each condition. Both soloists and ensemble players disliked too strong early reflections, which is in line with the findings of Chiang et al. (2003). Almost all musicians preferred the longest reverberation time, only the solo wind players liked the intermediate condition best. The authors furthermore concluded that sufficient reverberation was necessary for the aspect of ‚making music‘ among ensemble players and that it was rather the amount and not the duration of reverberation that mattered.

In his above mentioned research, Dammerud (2009) also investigated the correlation of room acoustical and architectural parameters measured on 8 stages with perceptual criteria that were defined by the author and rated by 24 players. Quite astonishingly, his main finding was that the studied room acoustical measures (including $ST_{\text{early}}$, $ST_{\text{late}}$ and $G_{\text{l}}$) did not correlate with any of the perceptual attributes. Instead, architectural properties such as the width of reflecting surfaces or the distance between the front and back of the stage were related to aspects like ‚hearing oneself', ‚hearing others' and ‚clarity'. On the other hand, Gade (2010) recently performed a renewed analysis of his field study data (Gade, 1989b) and found no correlation of the subjective ratings of his orchestras with these architectural measures.

It turns out that the research on stage acoustics is very diverse and has yielded partly contradicting results. It was argued that reasons for this could be the lack of realism in most laboratory experiments and, more importantly, the confounding of variables in the field studies where the data of much more concert halls would be necessary to investigate the presumably large number of independent variables (Gade, 2010). Recently, there have also been efforts to establish a certain uniformity regarding the measured acoustical and architectural parameters and the questionnaires used for collecting subjective data (Gade, 2013).
It should be considered, as well, that the method of questionnaire studies could be problematic in this context. Often, there are very high correlations among musicians' ratings of specific concert hall stages regarding seemingly diverse perceptual aspects (Gade, 1989b; Sanders, 2003; Chiang et al., 2003; Dammerud, 2009). Factor analyses performed by Gade (1989b) with data related to two orchestras rating stage environments revealed only two dimensions each, which he interpreted as ‚overall quality' and ‚timbre'. One reason for this might be the great individuality of musicians' perception of room acoustical environments, challenging the use of averaged ratings, as was done here. Moreover, Gade (2010) pointed to the difficulty of performers to distinguish between several perceptual aspects when rating room acoustical environments. It must also be borne in mind that musicians are usually not concerned with the description of what they hear but rather with the performance itself. Thus, the verbalisation and rating of categories concerning their perception is difficult, the more so, as they often use a very diverse vocabulary (see chapters 5.4 and 6.5). In this respect, the interview technique employed by Ueno et al. (2005) is more promising, even though it is hardly applicable to orchestras because of the large expenditure of time. Additionally, the perception of stage acoustics is not only different among

soloists, ensembles and orchestras, as the reviewed studies have shown, but it also depends on the played instrument and even the position on stage (Jeon et al., 2011; Lim et al., 2013). These aspects must therefore be taken into account, as well, when talking about performers' perception of their acoustical surrounding.

# 4

# METHODS

## 4.1 Research design

With the aim of empirically investigating the effect of room acoustics on the way musicians play, the basic research design of this thesis was to record several performances of the same piece of music in different room acoustical surroundings. On the basis of the appropriate measurements, the influence of room acoustical parameters (see section 4.2) on quantified aspects of performance (see section 4.3) was explored with statistical methods (see section 4.4).

Regarding the musicians and instruments to be investigated, it was assumed that ensembles and orchestras would react to room acoustical conditions to a lesser extent than solo performers because they are supposedly more focussed on the musical communication among each other than on the interaction with the room. Additionally, previous studies have shown that non-professional players tend to be more concentrated on the performance itself than on their adjustment to the room acoustical surrounding (von Békésy, 1968; Ternström, 1989). It was thus decided to seek the collaboration of professional solo musicians.

There are basically two different approaches to realise the variation of room acoustical surroundings in the design described above. Either a field study can be carried out in real halls, or simulated rooms can be used in a laboratory experiment. Both methods have their distinct advantages and disadvantages: A field investigation ensures a high level of external validity but it is impossible to control all variables. A laboratory study is characterised by a more unnatural situation and the controlled variation of experimental conditions. It is apparent that the two methods complement each other, so, similarly to Gade (1989a,b) and Dammerud (2009), they were both applied in the scope of this thesis. The variables of the two studies are listed in table 4.1 and discussed below.

In the laboratory study, several standard orchestral instruments were included, covering two registers each of strings, woodwind and brass: violin, cello, clarinet, bassoon, trumpet and trombone. By recording two players for each instrument, the type of instrument and the performer were then two independent variables. The field study was carried out with only one musician, a cellist, because of the great effort of time and organisation, so the results just hold for the examined instrument and that specific performer. In both investigations, the musical content characterised by the basic tempo of the played pieces was a further independent variable: In the field study, an entire concert programme composed of many pieces was recorded, offering a variety of contents that could be grouped according to their basic tempo. In the laboratory investigation, each musician played two pieces with a calm and a lively character, respectively. This categorisation allowed for a comparison between the performed pieces, even though they were musically unique.
With regard to the most important independent variables, the room acoustical parameters, a challenge lay in the fact that only perceptually meaningful measures could be expected to have an influence on music performance. Hence, consideration had to be given to the question which perceptual aspects of room acoustics are relevant for musicians and which physically measurable parameters are suitable to characterise them. As section 3.2 revealed, the answer to this is not trivial. Seven parameters recommended by Gade (2013) for characterising the room acoustical surroundings of musicians were used: $EDT$, $RT$, $C_{80}$, $ST_{\mathrm{early}}$, $ST_{\mathrm{late}}$, $G_{\mathrm{e}}$ and $G_{\mathrm{l}}$. Since sound strength and timbre also seem to be important aspects of room acoustics for performers (Gade, 1986), a measure for the subjective sound level, $G$, and two parameters describing the timbre were additionally selected. The bass ratio, $BR$, is calculated from measurements of $RT$ and is widely used in auditorium acoustics although its perceptual relevance

| | Field investigation | | Laboratory investigation | |
|---|---|---|---|---|
| | | **Factor levels** | | **Factor levels** |
| **Independent variables** | 10 room acoustical parameters (see table 4.2) | 7 rooms | 10 room acoustical parameters (see table 4.2) | 14 rooms |
| | Basic tempo | Slow, fast, variable | Basic tempo | Slow, fast |
| | | | Instruments | Violin, cello, clarinet, bassoon, trumpet, trombone |
| | | | Musicians | 12 performers |
| **Dependent variables** | 8 performance parameters (see section 4.6) | | 8 performance parameters (see section 4.6) | |
| **Uncontrolled variables** | | **Documented aspects** | Experimental environment | |
| | Audience | Interview: behaviour, attitude<br>Measurement: size, distance to performer | | |
| | Environment | Interview: special features (e.g. atmosphere, lighting)<br>Measurement: temperature, humidity, hall volume, stage area | | |
| | Personal form | Interview: physical and emotional state during performance | | |

**Table 4.1.** – Variables in the field and laboratory study

| Room acoustical parameters | | Perceptual criteria |
|---|---|---|
| Reverberation time[1] | $RT$ | Duration of reverberation |
| Early decay time[1]<br>Late support[1]<br>Late sound strength[2] | $EDT$<br>$ST_{\text{late}}$<br>$G_{\text{l}}$ | Reverberance, late energy |
| Early support[1]<br>Early sound strength[2] | $ST_{\text{early}}$<br>$G_{\text{e}}$ | Ensemble conditions, early energy |
| Clarity[1] | $C_{80}$ | Transparency of sound |
| Sound strength[1] | $G$ | Subjective sound level |
| Bass ratio[3]<br>Bass strength[3] | $BR$<br>$G_{125}$ | Warmth |

**Table 4.2.** – Room acoustical parameters used as independent variables in the field and laboratory studies. For measurement procedures/mathematical definitions see: [1]ISO 3382-1 (2009), [2]Dammerud (2009), [3]Beranek (2004)

is doubted (Beranek, 2004; Gade, 2007), so the bass strength, $G_{125}$, was also included here. All the independent room acoustical variables are listed in table 4.2, their measurement procedure is described in section 4.2.1.

The dependent variables in both studies were determined from recordings made during the performances, which was considered to be perceptually more relevant than the documentation of MIDI signals. The method of yielding the response variables by quantifying specific aspects of music performance from audio recordings is described in section 4.3. Concerning the technical setup of the recordings, two points needed to be considered. Firstly, capturing the response of the concert halls had to be avoided since it was only the sound of the instruments that should be documented. This demand was accentuated in the laboratory experiment where the recording was additionally used as input signal for the room acoustical simulation (see section 4.2.3), thus requiring an anechoic recording. In order to prevent sound level fluctuations, it was furthermore important to ensure a constant distance between the microphone and the instruments even if the latter were moved during the performances. The technical solutions to these demands that were chosen in the investigations are described in sections 5.1 and 6.1, respectively.

The performance model introduced in section 2.2 served as a basis for identifying possible uncontrolled variables in the field study. The factors determining the performance plan in figure 2.1 were considered to be quasi-constant. Admittedly, they could, in principle, be subject to changes, but either they vary gradually over an extended period of time (personal style, performance tradition) or they were assumed to be unchanged for a limited set of performances of the same music (programme, score, practice). By contrast, the factors concerning the actual performance were uncontrolled situational variables and needed to be documented as precisely as possible to account for their possible influence on the performances. This was achieved by measuring certain aspects of these factors and by asking the performer to describe them in interviews conducted after each concert (see table 4.1).
In the laboratory study, almost all of the influencing factors in figure 2.1 were held constant for the individual subjects. Only the personal form could vary in the course of the experiment, but its effect was minimised by randomising the presentation of the room acoustical environments. The influence of the laboratory environment itself was enquired in interviews that were conducted with the test subjects.

The above mentioned interviews in both the field and the laboratory study did not only serve as source of information on the uncontrolled variables. They were also carried out to learn about the conscious adjustments of the musicians' way of playing to the room acoustical environments. Furthermore, a subjective evaluation of the room acoustics was acquired in the interviews in the field study and in questionnaires in the laboratory study. The analysis method employed for the interviews is described in section 4.5.

## 4.2 Room acoustical measurements and simulation

### 4.2.1 Room acoustical measurements

The computation of the parameters listed in table 4.2 is based on the measurement of room impulse responses, which were carried out according to ISO 3382-1 (2009) in both studies. It was important to capture the room acoustical conditions from the performers' point of view, so the measurement position of main interest was the one best reproducing the musicians' position on stage during their performance. In accordance with the source-receiver configuration required for the support parameters, this receiver position was defined at 1 m behind the measurement loudspeaker facing the audience (see sections 6.2.1 and 6.2.2 for exact positions). Additionally, the room acoustical parameters in table 4.2 were determined from impulse responses measured with sources conforming to the directivity of the instruments investigated in the studies. This was realised in room acoustical computer models (see section 4.2.2) and enabled an even more precise description of the room acoustical conditions the musicians encountered while playing. The receiver position was thereby defined at a height of 1.2 m, which was assumed as the typical ear height of a seated person, thus reflecting the situation of a solo performer. Table 4.3 shows the positions of the directional sources in relation to the receiver point. They were established by estimating the typical distance between the acoustical centre of the respective instrument and the performers' ears. The number of investigated rooms in the field study

| Instrument | x [cm] | y [cm] | z [cm] |
|---|---|---|---|
| Violin | 20 | -20 | 0 |
| Cello | 0 | -40 | -60 |
| Clarinet | 0 | -20 | -20 |
| Bassoon | 0 | -20 | -20 |
| Trumpet | 0 | -50 | 0 |
| Trombone | 20 | -30 | 0 |

**Table 4.3.** – Coordinates of the directional sources used for the measurements of room acoustical parameters given relative to the receiver position (ear height, 1.2 m above the floor). Positive x-values refer to the left hand side, negative y-values refer to the front side (both as viewed from the receiver).

was seven (see section 5.2.1), while the double amount of halls was presented to the musicians in the laboratory experiment by auralising the aforementioned computer models (see sections 4.2.3 and 6.2.1).

### 4.2.2 Room acoustical models

The room acoustical computer models in this thesis were generated with EASE 4.3. First, architectural models of the studied concert halls were constructed and scattering as well as absorption properties were assigned to all of the surfaces in the models (see sections 5.2.3 and 6.2.1 for details on this). As explained above, the room acoustical properties of the modelled halls were determined with a receiver at a height of 1.2 m and with directional sources simulating the examined instruments. For this purpose, the directivity database proposed by Schneider (2011) was used, which is based on sound power measurements of orchestral instruments conducted by Pollow et al. (2010). The source data in EASE have a horizontal and vertical resolution of 5° and are given in third octave bands between 100 Hz and 10 kHz. The directional sources were separately inserted into the room models at the positions described in table 4.3. Finally, for the calculation of room acoustical parameters, reflectograms were generated with the AURA response module of EASE, exported as .wav-files and treated as ordinary room impulse responses when calculating the parameters with EASERA 1.2 and Matlab R2012a. The AURA response computation is based on the CAESAR algorithm developed at the RWTH Aachen and is described below.

Two approaches grounded on the theory of geometrical acoustics are combined to determine the impacts of sound at a certain receiver position (Schmitz et al., 2001): Up to a reflection order specified by the user, the hybrid mirror image method is used for the early part of the reflectogram, while raytracing is applied to generate its the late part as well as early reflections involving scattering. The hybrid mirror image method employs mirror images of the source – simulating reflections on the surfaces of the model – to calculate the impacts of sound at the receiver position. The power of the mirror sources is thereby reduced depending on the absorption and scattering properties of the surfaces. The fact that scattering has an influence here is due to the raytracing method already accounting for the scattered energy fraction. Instead of generating all possible mirror sources, the hybrid mirror image method traces the path of rays emitted by the source in order to identify those surfaces that cause reflections actually hitting the receiver position so that only the respective mirror sources are generated. Raytracing assumes the emission of particles from the source that have frequency and directivity dependent energy. These particles are traced through the room and, depending on the scattering coefficient, are geometrically reflected or scattered into directions determined by Lambert's law when they reach a boundary surface. The absorption coefficient of this surface determines the energy reduction of the reflected particles that are further traced until they hit the receiver or their energy falls below a certain threshold. Whenever a particle hits the receiver, which is modelled as a sphere with defined radius, its energy is added to a bin (with a width between 1 and 10 ms) with a delay corresponding to the flight time of the particle.

The resulting AURA response eventually contains information on time delay, angle of impact and sound level in third octave bands from 100 Hz to 10 kHz for each image source and ray tracing particle, the latter being summarised in energy bins, as explained above. The further processing of these reflectograms required for the auralisation of the computer models is described in the next section.

### 4.2.3 Auralisation and acquisition of binaural room impulse responses

As Gade (2010) pointed out, when musicians are involved in the investigation of room acoustical environments in laboratory experiments, special care must be given to the quality of the simulation. Virtual acoustics can principally be realised by means of sound field synthesis involving loudspeaker reproduction or by means of dynamic binaural synthesis with headphone reproduction (Vorländer, 2008). Even though headphones might be perceived as disturbing for performing musicians, the technique of dynamic binaural synthesis is highly powerful regarding the achievable sound quality and the plausibility of the simulation (Lindau & Weinzierl, 2012). The room acoustical environments in the laboratory experiment were thus auralised with the dynamic binaural simulation system proposed by Lindau et al. (2007).

The datasets of binaural room impulse responses (BRIRs) needed for the simulations were generated from the room acoustical computer models in three steps that are explained in the following. First, reflectograms were produced by the AURA module in each of the 14 room models, separately using the directional sound sources described in the above section. They were placed at the positions in table 4.3 relative to an omni-directional receiver at 1.2 m at a central stage position 2.5 m from the stage edge. The reflectograms were then saved as text files for further processing in Matlab R2012a.

In the second step, impulse responses were generated for each reflection by calculating a frequency and a phase spectrum. For the former, the third octave band levels of the reflectogram were interpolated with the cubic splines while an extrapolation was employed below and above the highest bands, assuming a decrease of -24 dB per octave below 20 Hz and -3 dB per octave above 10 kHz. For the phase spectrum, a minimum phase was reconstructed for each spectrum to generate the impulse responses by inverse Fourier transformation.

In the third step, each impulse response – representing one reflection – was convolved with a head related transfer function (HRTF) corresponding to the angle of sound impact stored in the reflectograms. The direct sound was excluded at this stage because it was not simulated in the experiment (see section 6.3). For the convolution, a database of HRTFs (Brinkmann et al., 2013) with high spatial resolution was used. The database consisted of HRTFs measured with the FABIAN head and torso simulator (Lindau & Weinzierl, 2007) using a source grid with an azimuth range of $0°$ to $359°$ (resolution $\leq 2°$), an elevation range of $-64°$ to $90°$ (resolution $= 2°$) and employing head-over-torso rotations in steps of $10°$ between $\pm 90°$. The convolution results of all the reflections were added up taking into account their arrival time, thus yielding one complete binaural room impulse response. The convolution and summation was repeated for head-over-torso rotations of $\pm 50^\circ$ and head elevations of $-30^\circ$ to $21^\circ$ with a resolution of $2^\circ$ and $3^\circ$, respectively. According to Lindau & Weinzierl (2009), this resolution is below the minimum grid resolution necessary for the dynamic binaural synthesis of music signals. Regarding head-over-torso rotations that did not exist in the HRTF dataset, the two nearest available positions were interpolated with the inverse distance method in the frequency domain. The HRTF dataset did not contain any measurements for head elevations, so for these cases the desired head inclination was simulated by rotating the source grid, that is by virtually tilting the entire FABIAN torso. This was achieved by multiplying the Cartesian coordinates of the respective reflection angles with a rotation matrix that accounted for the rotation around the y-axis of the source grid.

$$
\begin{aligned}
\begin{pmatrix} x_{\text{rot}} \\ y_{\text{rot}} \\ z_{\text{rot}} \end{pmatrix} = \begin{pmatrix} x \\ y \\ z \end{pmatrix} \begin{pmatrix} \cos\delta_{\text{head}} & 0 & -\sin\delta_{\text{head}} \\ 0 & 1 & 0 \\ \sin\delta_{\text{head}} & 0 & \cos\delta_{\text{head}} \end{pmatrix} \\
x = \sin\delta_{\text{refl}} \cdot \cos\varphi_{\text{refl}} \\
y = \sin\delta_{\text{refl}} \cdot sin\varphi_{\text{refl}} \\
z = \cos\delta_{\text{refl}}
\end{aligned}
\tag{4.1}
$$

$x, y, z$: Cartesian coordinates of reflection angles after rotation

$x_{\text{rot}}, y_{\text{rot}}, z_{\text{rot}}$: Cartesian coordinates of reflection angles before rotation

$\delta_{\text{head}}$: Desired head elevation

$\delta_{\text{refl}}$: Elevation of reflection

$\varphi_{\text{head}}$: Azimuth of reflection

For all head orientations except the one with $0^\circ$ azimuth and $0^\circ$ elevation, it was not the whole reflectogram that was evaluated but only the reflections up to the so called perceptual mixing time. The mixing time is the boundary between the early part of a BRIR containing directional information and the diffuse part of a BRIR where the directions of the reflections are almost uniformly distributed. In the dynamic binaural synthesis system used in the laboratory experiment, it was only the early part of the BRIRs that was adjusted to the head orientations of the listeners while the diffuse part was statically convolved with the input signal. The perceptual mixing time, $t_{\mathrm{pm}}$, was calculated according to the following formula empirically determined by Lindau et al. (2012):

$$t_{\mathrm{pm}} = 0.0117 \cdot V + 50.1 \tag{4.2}$$

$V$: Volume of the simulated room

The described three-step procedure resulted in a dataset of 918 BRIRs for each room model and each instrument ($14 \times 6 = 84$ datasets).

## 4.3 Performance analysis

When attempting to describe music performances on the basis of physical measurements, a major difficulty lies in the identification of the most relevant aspects of music performance and the corresponding audio features. A pioneer in music performance research, Seashore (1938) identified four physical characteristics of a sound wave – frequency, amplitude/intensity, duration and form – and four equivalent musical qualities – pitch, loudness, time and timbre. Seashore was among the first researchers to physically measure and analyse music performances. After an interval of about 40 years, the literature on music performance research started to grow very rapidly, covering many different areas ranging from psychological aspects to computational performance models. Comprehensive reviews were, for example, given by Palmer (1997), Gabrielsson (1999, 2003) and Kopiez (2008). Regarding the measurement of music performance, Goebl et al. (2008) summarised the main approaches since Seashore's attempts. The vast majority of studies were concerned with the measurement and analysis of piano music, especially after the introduction of the MIDI standard in 1983. This facilitated the access to data acquired during the performance itself, which, by the way, is limited to intensity and duration in piano music. The analysis of recorded music and of other instruments, on the other hand, is less common, not least because of prevailing issues like the problem of tone onset- and especially of tone offset-detection, the more so if instruments with long attack times like strings are concerned (see McAdams et al., 2004).

In addition to the difficulties regarding the actual measurement of performances, it is not clear which physical parameters are best suited to describe the relevant performance aspects. This is, for example, illustrated by the fact that the studies mentioned in section 3.1 used a wide range of methods to quantify the dynamic strength of the performances: vibration amplitude (von Békésy, 1968), long-time average spectrum (Ternström, 1989), MIDI velocity (Bolzinger et al., 1994; Kawai et al., 2013) and A-weighted sound pressure level (Winckel, 1962; Ueno et al., 2010). As Nakamura (1987) showed, the perception of dynamics not only depends on intensity but also on the musical context and is possibly related to timbre, so the use of simple intensity measures is called into question. Moreover, all of the investigations reviewed in section 3.1 that studied the adjustment of tempo used the duration of musical phrases as an indicator for this performance parameter. It was demonstrated by Repp (1994), though, that listeners' perception of tempo is related to the timing micro structure in music performances.

The method for quantitatively characterising the performances in this thesis, aimed at a perceptually meaningful analysis, was based on an investigation by Weinzierl & Maempel (2011) and is described below.

The first issue addressed by Weinzierl & Maempel (2011) was to find a vocabulary suitable to characterise music performances of the classic-romantic repertoire. This was achieved by means of a panel discussion of ten experts comprised of musicians, musicologists and recording producers. Listening to excerpts of recorded chamber music performances formed the basis for their discussion and they agreed on 16 characteristics including bipolar attributes to describe the scale range.

The second question in Weinzierl & Maempel's investigation was how these qualities could be determined by a set of audio features. For this purpose, the expert listeners rated a total of 49 recorded performances, which were various interpretations of three different music pieces (a Mozart piano sonata, a Beethoven string quartet and a Schubert cello sonata), using the bipolar attributes they had previously agreed on. At the same time, technical features were extracted from the 49 audio recordings and then used as independent variables in regression models that were employed to predict the experts' ratings. Before reporting the results of this analysis, the software-based feature extraction method implemented by Lerch (2009) is described below.

In the software, a dynamic time warping algorithm is used to find the best alignment between the input audio signal and a MIDI-representation of the score, resulting in onset times, $t_\mathrm{o}(i)$, for all of the notes in the music piece. The detected onsets were verified auditorily in this thesis by playing click sounds at the instance of their occurrence together with the audio signal. If necessary, the onsets were manually corrected in the graphical user interface of the software Sonic Visualiser. From the onset times, five series of tempo related observations were calculated in the study by Weinzierl & Maempel: the micro-tempo on note- and bar-level ($TMP_\mathrm{note}$, $TMP_\mathrm{bar}$) in beats per minute (BPM), inter-onset- and inter-bar-intervals (IOIs, IBIs) as well as normalised IOIs. These calculations were based on the distance between two onsets of interest and the distance between the corresponding score events, $\tau(i)$. In the case of bar-level computations, the onset times of the first notes of two consecutive bars were used.

$$TMP_\mathrm{note}(i) \text{ or } TMP_\mathrm{bar}(i) = \frac{60\mathrm{s}}{t_\mathrm{o}(i+1) - t_\mathrm{o}(i)} \cdot \Delta\tau_{i,i+1} \tag{4.3}$$

$$IOI(i) \text{ or } IBI(i) = t_\mathrm{o}(i+1) - t_\mathrm{o}(i) \tag{4.4}$$

$$IOI_\mathrm{norm}(i) = \frac{t_\mathrm{o}(i+1) - t_\mathrm{o}(i)}{\Delta\tau_{i,i+1}} \tag{4.5}$$

$t_\mathrm{o}(i)$ : Onset time of note $i$ in [s]

$\Delta\tau_{i,i+1}$ : Distance between two score events $\tau(i)$ and $\tau(i+1)$ in beats, that is quarter note values

For the description of loudness- and timbre-related properties of the audio recordings, the software provides the features listed in table 4.4 (see Lerch, 2012). As noted before, it is again apparent that there are various approaches to measure the loudness of a recording. The first four features in table 4.4 are guided by psychoacoustical findings and employ more or less complex models of human perception whereas the last feature is typically used in the recording domain.

| Abbr. | Temporal features | |
|---|---|---|
| $TMP_{note}$ | Micro-tempo on note-level | |
| $TMP_{bar}$ | Micro-tempo on bar-level | |
| IOI | Inter-onset-interval | |
| IBI | Inter-bar-interval | |
| $IOI_{norm}$ | Normalised inter-onset-interval | |
| **Abbr.** | **Loudness features** | |
| ZwiDIN | Zwicker loudness according to DIN 45631 | |
| ZwiITU | Zwicker loudness according to ITU-R BS.1387 | |
| ITU1770 | Loudness according to ITU-R BS.1770 | |
| dBA | A-weighted RMS | |
| VUM | Volume unit meter | |
| **Abbr.** | **Timbre features** | **Description** |
| SR | Spectral roll-off | Measure for signal bandwidth |
| SF | Spectral flux | Simplified measure for roughness |
| SC | Spectral centroid | Gravity centre of spectral energy |
| SS | Spectral spread | Measure for energy spread around spectral centroid |
| MFCC0-4 | Mel frequency cepstral coefficients 0-4 (MFCCs) | Components of the spectral envelope |

**Table 4.4.** – Temporal, loudness and timbre features used for the analysis of the performance data (see Lerch (2012) for a detailed explanation of the loudness and timbre features)

The number of spectral features in table 4.4 illustrates that the concept of timbre is multi-dimensional and cannot be described by a single measure. In the software, the features are computed within time windows of $2^{15}$ samples for loudness and $2^{10}$ samples for timbre properties, each with a hop size of 441 samples. In the study, only the values in those windows containing a played note were used for the examined series of loudness and spectral observations.

Returning to the aim of the study by Weinzierl & Maempel (2011), these technically extracted features were intended to predict the performance characteristics defined by the expert listeners, yielding a meaningful description of recorded music performances. It was not the time series of the technical features, though, that were used as predictors in regression models. Instead, the statistical descriptors shown in table 4.5 were computed for the time series of each feature and z-standardised within the music pieces. The z-score was used because it was not the absolute values of the performance characteristics that were of interest but rather the comparison between several interpretations of the same pieces, which was moreover irrespective of a specific composition. It was fur-

| Abbr. | Statistical descriptors |
|---|---|
| mn | Mean |
| std | Standard deviation |
| mde | Mode |
| mdn | Median |
| gmn | Geometrical mean |
| qu10, qu90 | Quantiles 10, 90 |
| qu10-90 | Interquantile distance 10-90 |

**Table 4.5.** – Statistical descriptors calculated from the time series of the technical features extracted by the software

ther argued by Weinzierl & Maempel that the relation between the technical features and the performance characteristics was not necessarily linear. This is why the standardised statistical measures were additionally calculated as logarithmic and inverse quadratic values, both functions being of importance in human perception research. So, for each technical feature in table 4.4 there were 7 statistical descriptors calculated in 3 versions (linear (lin), inverse quadratic (qdr), logarithmic (log)), which were all used as potential predictors for the performance characteristics. This resulted in a regression model for each of the 16 performance qualities with 2 to 4 technically derived regression coefficients (see table 4.6 for predictors and coefficient values[1]). However, not all of the qualities could be predicted equally well. In this thesis, only those regression models with more than 50% explained variance were used, so it was the performance characteristics listed in table 4.6 that were predicted with the respective regression models to quantitatively describe the recordings of music performances in different room acoustical surroundings. They are printed in italics in the following to stress their use as variables in the statistical analysis.

[1]The predictors, coefficients and explained variances shown here differ from the data presented in Weinzierl & Maempel (2011) because an updated analysis method that has not been published yet was used to calculate the regression models.

| **Performance characteristics** | **Predictors** | $\beta$ | **Expl. var. [%]** |
|---|---|---|---|
| *Tempo* | Intercept | 4.833 | 89.5 |
| | IOI log mn | -0.651 | |
| | IBI log qu10 | -0.309 | |
| *Agogic* | Intercept | -2.005 | 53.2 |
| | $\mathrm{IOI}_{\mathrm{norm}}$ log qu_10-90 | 0.441 | |
| | $\mathrm{TMP}_{\mathrm{bar}}$ | 0.305 | |
| | SF qdr mdn | 0.215 | |
| *Dynamic strength* | Intercept | -1.048 | 62.8 |
| | dBA qdr mde | -0.451 | |
| | SF lin qu10 | -0.45 | |
| | ZwiDIN log mn | 0.412 | |
| | VUM qdr gmn | 0.199 | |
| *Dynamic bandwidth* | Intercept | 2.403 | 67.0 |
| | ZwiITU lin qu10-90 | 0.612 | |
| | ITU1770 log qu10 | -0.670 | |
| | dBA lin qu10-90 | -0.446 | |
| | MFCC0 qdr qu90 | 0.260 | |
| *Timbre (soft – hard)* | Intercept | 1.455 | 63.7 |
| | SR lin gmn | 1.066 | |
| | ZwiITU lin mn | 0.629 | |
| | SR log qu10 | -0.458 | |
| | ZwiITU lin qu90 | -0.508 | |
| *Timbre (dark – bright)* | Intercept | 0.955 | 56.8 |
| | SR lin qu90 | 0.515 | |
| | MFCC1 log mde | -0.230 | |
| | MFCC2 qdr mdn | 0.299 | |
| *Timbre (lean – full)* | Intercept | -0.045 | 68.2 |
| | SR lin qu90 | -0.321 | |
| | MFCC1 qdr mdn | 0.369 | |
| | MFCC3 log mde | 0.360 | |
| | $\mathrm{TMP}_{\mathrm{note}}$ log mde | -0.289 | |
| *Timbral bandwidth* | Intercept | -0.238 | 65.4 |
| | ITU1770 log qu10 | -0.364 | |
| | IBI log std | 0.316 | |
| | ITU1770 qdr qu10 | -0.284 | |
| | ZwiDIN qdr mn | 0.391 | |

**Table 4.6.** – Performance characteristics used to quantitatively describe music performances in this thesis. Technically derived audio features are used as predictors in regression models with the coefficients and explained variance listed here. The abbreviations used for the predictors are explained in tables 4.4 and 4.5.

## 4.4 Hierarchical linear models

The statistical analysis problem given in the field and laboratory experiments was basically one of multiple regression: By investigating multiple regression models with the room acoustical parameters as explanatory and the performance parameters as response variables, the standardised regression coefficients could shed light on the extent of the influence of each room acoustical parameter on each of the examined aspects of performance. There were, however, some special features in the research design and data that needed to be considered. First, as can be seen from table 4.1, there were categorical variables in addition to the room acoustical variables in both studies. Second, the research designs were multivariate ones, which the common regression analysis is not designated for. Third, the data had a nested structure, that is there were several levels to be considered: In the field study, the pieces were assumed to be nested within the rooms, as it was likely that the performer used a similar way of playing for all the pieces played in a particular room. In the laboratory study, the musicians were expected to be nested within the rooms, since they presumably all employed a similar strategy of adjustment for a particular acoustical environment. Additionally, the pieces were assumed to be nested within the musicians, since each performer had his specific way of playing. Common regression models assume the independence of the analysed observations, which is obviously violated in such a nested data structure. Fourth, the room acoustical parameters varied on the highest level. In a typical regression model, this would necessitate data aggregation by averaging the data of the pieces and musicians, which was unwanted because of the loss of information.
The first point could easily be handled by generating dummy variables for the factor levels and using them as regressors. In view of the other issues, hierarchical linear models (HLMs) – also denoted as multilevel regression models or mixed(-effects) models – were used for the statistical analysis of the data, a technique which is elaborated on below (based on the introductions by Hox, 2010 and Eid et al., 2010).

In a simple two-level HLM there is a different number of $i = 1...n_j$ first-level items in each of the $j = 1...J$ groups on the second level. Assuming one explanatory variable $X$ on the first level and one explanatory variable $Z$ on the second level, the following regression equation for the outcome variable $Y$ can be written:

$$Y_{ij} = \beta_{0j} + \beta_{1j}X_{ij} + e_{ij} \tag{4.6}$$

For each item of the $J$ groups on the second level, there is an intercept $\beta_{0j}$, a regression coefficient $\beta_{1j}$ and a residual error term $e_{ij}$. The intercepts and slopes are assumed to vary across the groups of the second level, therefore they are termed random coefficients. Their variation can partly be explained by the explanatory variable $Z$, using the following formulae:

$$\beta_{0j} = \gamma_{00} + \gamma_{01}Z_j + u_{0j} \tag{4.7}$$

$$\beta_{1j} = \gamma_{10} + \gamma_{11}Z_j + u_{1j} \tag{4.8}$$

Here, the intercepts $\gamma_{00}$ and $\gamma_{10}$ as well as the regression coefficients $\gamma_{01}$ and $\gamma_{11}$ are assumed to be the same for all groups on the second level. This is why they are called fixed coefficients. $u_{0j}$ and $u_{1j}$ are the residual errors in the respective group $j$. All residual errors are assumed to have a mean of 0 and variances $\sigma_e^2$, $\sigma_{u_0}^2$ and $\sigma_{u_1}^2$ that are estimated in the HLM. Substituting equations 4.7 and 4.8 into equation 4.6 yields the regression formula for the entire HLM:

$$Y_{ij} = \gamma_{00} + \gamma_{10}X_{ij} + \gamma_{01}Z_j + \gamma_{11}X_{ij}Zj + u_{1j}X_{ij} + u_{0j} + e_{ij} \tag{4.9}$$

The variation of the regression coefficient $\beta_{1j}$ that belongs to the level-1 variable $X_{ij}$ (equation 4.6) is modelled with the level-2 variable $Z_j$ (equation 4.8). This is why an interaction term appears in equation 4.9, showing how the level-1 variable influences the response variable as a function of the level-2 variable.

A model often employed in multilevel analysis is the so-called intercept-only model. It assumes the absence of explanatory variables, so equation 4.9 reduces to:

$$Y_{ij} = \gamma_{00} + u_{0j} + e_{ij} \tag{4.10}$$

Because this model does not explain any variance, the estimation of the error variances $\sigma_e^2$ and $\sigma_{u_0}^2$ is a decomposition of the total variance on the different levels of the data. This decomposition can be used, for example, to calculate the intraclass correlation coefficient (ICC) $\rho$. The ICC is an indication for the proportion of variance explained by the structure of levels assigned to the data and it also shows the extent of „non-independence“ (Eid et al., 2010, p. 702) of the data that is due to a grouping structure on the second level.

$$\rho = \frac{\sigma_{u_0}^2}{\sigma_{u_0}^2 + \sigma_e^2} \tag{4.11}$$

$\sigma_e^2$: Variance on the first level (residual variance) of an intercept-only HLM

$\sigma_{u_0}^2$: Variance on the second level of an intercept-only HLM

In multilevel regression analysis, the parameters of the HLM are not calculated with the least squares method like in common regression models. Instead, the maximum likelihood method is employed to estimate the intercepts, regression coefficients, variance components as well as standard errors for the parameters. By dividing a parameter through its standard deviation, its significance can be tested with the so-called Wald test (Hox, 2010, p. 46).

There are several methods to assess an HLM. One is the so called deviance, which indicates the goodness of fit of the model to the actual data. The lower the deviance, the better the fit of the model. However, two HLMs can only be compared on the basis of their deviances if they are nested, that is if one model can be derived from the other one by removing parameters. Since an intercept-only model can always be derived from any more specific HLM, these two models can always be compared. The so called likelihood ratio test is performed by using the difference between the deviances of an HLM and its intercept-only version in a chi-square test with degrees of freedom equal to the difference between the number of parameters in the two models. This is a very simple method to test whether the explanatory variables have an effect at all. To compare nonnested models there are two information criteria that are based on the deviance: Akaike's Information Criterion (AIC) and Schwarz's Bayesian Information Criterion (BIC), the use of the former being recommended by Hox (2010). In common regression analysis, the portion of explained variance $R^2$ is often stated as a criterion for assessing a given model. To estimate the explanatory power of HLMs, the so-called pseudo-$R^2$, on the grouping level 2 Snijders & Bosker (1994) have suggested the following formula:

$$R^2_{\text{level 2}} = 1 - \frac{\sigma^2_{\text{M1|level 2}} + \frac{\sigma^2_{\text{M1|res}}}{n}}{\sigma^2_{\text{M0|level 2}} + \frac{\sigma^2_{\text{M0|res}}}{n}} \tag{4.12}$$

$n$: Number of groups on level 2

$\sigma^2_{\text{M0|res}}, \sigma^2_{\text{M0|level 2}}$: Residual variance and room level variance in the intercept-only (M0)

$\sigma^2_{\text{M1|res}}, \sigma^2_{\text{M1|level 2}}$: Residual variance and room level variance in the target model (M1)

It was explained above that the design of the studies in this thesis was multivariate. As described by (Hox, 2010, p. 188 ff.) this can be accommodated in multilevel regression models by defining an additional level, the lowest one, as the response variable level. Assuming $P$ response variables and $H = P$ measures for the responses, $P$ dummy variables $d_{phij}$ are coded in the following way:

$$d_{phij} = \begin{cases} 1 & p = h \\ 0 & p \neq h \end{cases} \tag{4.13}$$

The outcome variable $Y_{hij}$ on measure $h$ of the first-level item $i$ in group $j$ is then written as:

$$Y_{hij} = \pi_{1ij} d_{1ij} + \pi_{2ij} d_{2ij} + \ldots + \pi_{pij} d_{pij} \tag{4.14}$$

Note that there is no intercept and no error term in equation 4.14 because this level only defines the multivariate structure. For simplicity, an intercept-only model is assumed in the following to derive the equation for an entire multivariate HLM. So, with no explanatory variables, the coefficients on the next two levels are calculated by:

$$\pi_{pij} = \beta_{pj} + u_{pij} \tag{4.15}$$

$$\beta_{pj} = \gamma_p + u_{pj} \tag{4.16}$$

Substituting equations 4.15 and 4.16 in equation 4.14, we receive:

$$\begin{aligned} Y_{hij} = & \gamma_1 d_{1ij} + \gamma_2 d_{2ij} + \ldots + \gamma_p d_{pij} \\ & + u_{1ij} d_{1ij} + u_{2ij} d_{2ij} + \ldots + u_{pij} d_{pij} \\ & + u_{1j} d_{1ij} + u_{2j} d_{2ij} + \ldots + u_{pj} d_{pij} \\ = & \sum_{h=1}^{P} \gamma_h d_{hij} + \sum_{h=1}^{P} u_{hij} d_{hij} + \sum_{h=1}^{P} u_{hj} d_{hij} \end{aligned} \tag{4.17}$$

Equation 4.17 states that for each response variable there is an intercept as well as two error terms for the two actual levels of the multivariate HLM. The dummy variables are equal to zero if $p \neq h$, so the coefficients in equation 4.17 only appear for the response variable they belong to.
The models and their parameters that were used in the field and laboratory study are described in detail in section 5.3 and 6.4.

## 4.5 Qualitative content analysis

To exploit the informative potential of the interviews carried out with the performers who took part in the studies, they were analysed with the method suggested by Mayring (2000): The qualitative content analysis is a systematic and theory-driven approach to extract meaning from a text that can be interpreted with regard to a certain research question. Mayring (2000, p. 54) proposed a framework with clearly defined steps to be taken. In the following, they are described with regard to the analysis conducted in this thesis.
The material to be analysed is specified as follows: It consisted of interviews conducted with professional solo musicians in the scope of the investigations carried out for this thesis. The interviews took place in addition to recordings of solo performances in real or simulated concert halls that were used to investigate the influence of room acoustics on music performances. The musicians were asked to participate in the studies by e-mail. In the case of the laboratory

study, participants of previous studies at the research institution of the author were asked to take part again. The musicians in both studies fulfilled the criteria for a collaboration: proficiency and experience with public performances and, in the field study, a schedule with concerts of the same solo repertoire in several concert halls.

With regard to the situation in which the material originated, the willingness of the performers to participate in the interviews was enquired at the beginning of the studies. The conversations followed a guideline with questions but allowed the possibility for open answers. In the field study, the interviews were conducted on the telephone as shortly after the concerts as possible (see section 5.4), in the laboratory study they were held directly after the recording in the respective virtual room.

The analysed interviews can be formally characterised as follows: They were held in German, digitally recorded and later transcribed. Since the focus of the analysis was on the content of the conversations, items like „äh“ or pauses were excluded from the transcription as a general rule.

The aim of the content analysis was to obtain a subjective description of the way of playing, the room acoustics and a potential relation between the two by each musician. These descriptions were compared to the statistically evident relation between the measured parameters of performances and room acoustics. This comparison was intended to better understand specific adjustments and reveal unconscious ones as well as possible discrepancies between performers' intentions and the measurable outcome. The conversations in the field study should additionally reveal factors other than the room acoustics that had an influence on the performances.

The performance model introduced in section 2.2 formed the theoretical framework for the analysis of the interviews. This model assumes the adjustment of musicians' way of playing dependent on the sound event they hear, which is in turn influenced by the acoustics of the surrounding room. The subjective view of each musician on these relations should be revealed by the interviews in both field and laboratory study. Furthermore, the performance model includes situational factors that possibly influence a performance and contribute to its uniqueness. In the field study, the aim was to establish a model like the one in figure 2.1 for each performance, showing the influence factors and the relations among them as reported by the musician. In the laboratory study, the focus lay on finding commonalities of adjustment strategies among musicians or instrument groups.

As specific analysis technique for the interviews, the content-related structuring method was chosen since the aim was to obtain a profile of the conversations regarding certain criteria (Mayring, 2000, p. 58). This method involves the categorisation of text elements (analysis units) that need to be initially defined. In the context of this thesis, a coding unit, that is the smallest element of the text that was coded, was a single meaningful word. A context unit, that is the largest element of the text that was coded, was a statement regarding a single aspect of the performance, the room acoustics, a relation between the two or another influence factor. An analysis unit was formed by the conversations regarding one of the concert halls under investigation. In the field study, this resulted in one interview per analysis unit while there were twelve interviews (one for each musician) in an analysis unit in the laboratory study.

In the following, the successive steps of the content-related structuring method are explained. The first part consists of the theory-driven determination of the main categories and the construction of a category system. Then, distinct coding rules including a salient example of a coded element need to be defined for each category. Subsequently, the material is worked through by marking and extracting all the text elements that fall into a category. If it appears necessary, the category system can then be revised and extended, so the analysis technique allows for the inductive formation of categories. After all meaningful text elements have been categorised and extracted, they are paraphrased. The last part of the analysis consists of summarising the paraphrased material in subcategories and, if applicable, in main categories.

The concrete realisation of these steps that was applied in the field and laboratory study is described in the respective sections 5.4 and 6.5

# 5

# FIELD STUDY

For the field study of this thesis, the outstanding opportunity emerged to collaborate with the Canadian-French cellist Jean-Guihen Queyras. He belongs to the most renowned contemporary musicians and his musical activity is characterised by a very broad repertoire as soloist, chamber musician and solo performer. For this study, seven of his performances of the Six Suites for Violoncello Solo by Johann Sebastian Bach that took place in European concert spaces between July 2010 and July 2011 were recorded. Furthermore, guided interviews were conducted with the musician after each concert. Perceptually relevant performance characteristics were extracted from the recordings to gain insight into the cellist's way of playing in each room. A qualitative content analysis of the interviews shed light on his own view of his performances and factors other than the room acoustics possibly influencing his way of playing. Separately, impulse responses were determined in each of the seven rooms to characterise their room acoustical properties. On the basis of these measurements, computer models of the halls were constructed for a more precise investigation of the particular room acoustical conditions during the concerts. Together with the performance data, this was the basis for a detailed statistical analysis of the effect of specific room acoustical measures on the music performances.

The following sections describe each of these steps while the chapter is concluded by a comprehensive discussion of the resulting findings.

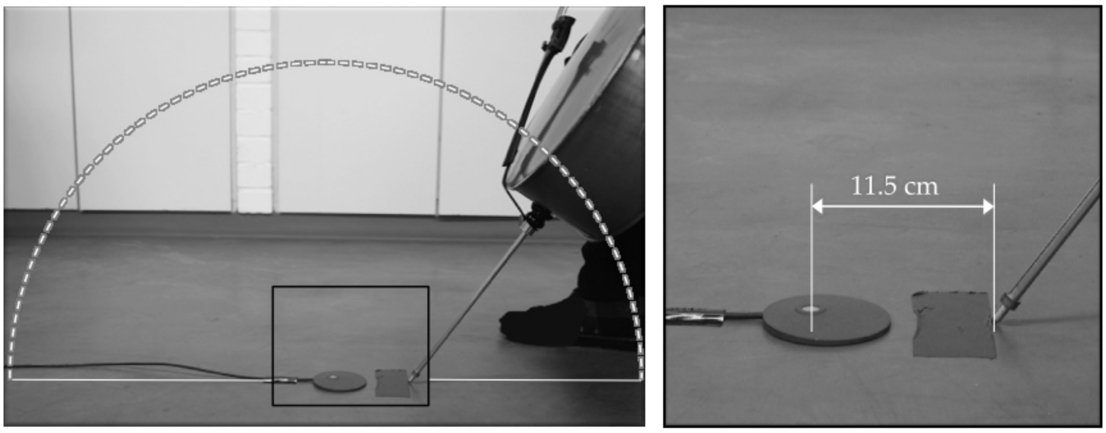



**Figure 5.1.** – Recording setup with the boundary microphone at a distance of 11.5 cm before the cello spike

## 5.1 Performances

As explained in section 4.1, the same music material was to be recorded in different room acoustical surroundings in the field study described here. As can be seen in table 5.1, the complete cycle of the cello suites by Bach was performed by the cellist in five of the seven halls while in two halls, the programme consisted of other music pieces and parts of the cycle, which resulted in missing data for these cases. The formal structure of the suites is characterised by recurring elements, which was valuable for the statistical analysis presented in section 5.3. The six suites each comprise six movements: Prélude, Allemande, Courante, Sarabande, Menuet/Bourrée/Gavotte and Gigue. The Allemandes and Sarabandes are characterised by a slow overall tempo, while the Courantes and Gigues are fast movements. The other two movement types have a more diverse overall tempo in the different suites. All movements except the Préludes have a very specific structure: the fifth movements comprise two parts with two sections each, every section being repeated once and the first part being playing again as closure. The rest of the movements have two sections that are each repeated.

Concerning the choice of the recording equipment, both the technical demands of the research design (see section 4.1) and the requirements of the musician needed to be considered. A microphone attached directly to the cello would have been a feasible solution but this setup was ruled out because it would have interfered with the musician's appearance on stage and made him greatly aware of the recording situation. Instead, a boundary microphone (Schoeps BLM 03 C) was placed at a constant distance of 11.5 cm in front of the cello spike (figure 5.1, right), which was thus almost in the centre of the hemispherical directivity of the microphone (figure 5.1, left). So, even with an inclination of the instrument during the performances, the distance to the receiver remained constant and sound level fluctuations caused by instrument movements could be disregarded. Neglecting the directivity of the cello, the level difference between the direct and diffuse sound at the microphone position was estimated by using the following formula (adapted from Ahnert & Goertz, 2008, p. 504):

$$L_{\mathrm{dir}} - L_{\mathrm{diff}} = 10\log_{10}\left(0.163 \cdot \frac{V}{T}\right) - 20\log_{10}\left(\frac{r}{1\mathrm{m}}\right) - 17\mathrm{dB} \tag{5.1}$$

$L_{\mathrm{dir}}$, $L_{\mathrm{diff}}$: Direct and diffuse sound level, respectively

$V$: Room volume

$T$: Reverberation time

$r$: Distance between source and receiver

Taking into account the additional 3 dB difference resulting from the use of a boundary microphone (Lipshitz & Vanderkooy, 1981), this estimation yielded diffuse-to-direct-sound level differences of between 29 dB and 39 dB for the recordings made with the cellist. Thus, they were only marginally influenced by the sound of the halls. At the same time, this was a very unobtrusive recording setup, barely noticed by the performer and the audience. The microphone was connected to an A/D converter (Digidesign MBox) and Laptop (MacBook with Logic Pro 9) using the same input gain settings in each room, since sound level differences between the recordings should be caused by the instrument only and not by the technical equipment.

For the further analysis, an excerpt was chosen from each of the 36 movements. A caesura of at least 22 bars after the beginning was chosen as breakpoint for the Préludes. For the fifth movement of each suite, the second section of part I including its repetition was selected. For the rest of the movements, the longer section including its repetition was chosen as excerpt (the specification of bars for each excerpt can be found in table A.1, appendix A). This eventually resulted in 187 audio signals (5 rooms with 36 movements, 1 room with 6 movements, 1 room with 1 movement; see table 5.1) with an average length of 111 s. The average number of notes and bars was 322 and 41, respectively. This data was used for the audio feature extraction and computation of performance characteristics as described in section 4.3.

## 5.2 Room acoustics

### 5.2.1 Concert venues

The performances of the cellist took place in seven concert spaces in six European countries. These venues are listed in table 5.1 together with the abbreviations used henceforth as well as some basic information about the halls and the recordings therein. The photos in figure 5.3 provide further insight into the concert halls.

| **Concert venue** | **Abbr.** | $V$ **[m$^3$]** | $A_{\text{stage}}$ **[m$^2$]** | **Seats** | **Recorded pieces** |
|---|---|---|---|---|---|
| Auditorio Nacional Sala de Cámara, Madrid (E) | ANC | 5700 | 83 | 692 | Suite I |
| Cloître du Couvent des Cordeliers, Forcalquier (F) | CCC | (open air) | 39 | 480 | Prélude, Suite VI |
| Cultuurcentrum, Hasselt (BE) | CCG | 12700 | 101 | 812 | Suites I-VI |
| Église du Collège St. Michel, Fribourg (CH) | ESM | 9600 | 30 | 440 | Suites I-VI |
| Gulbenkian Grande Auditorio, Lisbon (P) | GGA | 12600 | 108 | 1228 | Suites I-VI |
| Théâtre Jean Vilar, Vitry-Sur-Seine (F) | TJV | 11200 | 67 | 586 | Suites I-VI |
| Wigmore Hall, London (GB) | WMH | 2800 | 32 | 552 | Suites I-VI |

**Table 5.1.** – Concert venues of the field study: Abbreviations used in this thesis, hall volume, stage area, number of seats, pieces recorded with the cellist

The Sala de Cámara of the Auditorio Nacional is a chamber hall with an exposed stage and a vineyard-type audience area. In the Cloître du Couvent des Cordeliers, an abbey, there was a temporary stage and seats on the grass of the open-air courtyard for the purpose of the performance. The Cultuurcentrum is a fan-shaped multi-purpose hall with an exposed stage, an inclined audience area and balconies to the side and rear of the hall. In the baroque church Église du

Collège St. Michel, a temporary stage between the main aisle and the choir was used for the concert while the audience was seated in the pews. The Gulbenkian Grande Auditorio is a concert hall with an exposed variable stage, - the chamber music setup was used for the cellist's performance - an inclined audience area and a balcony at the back. In the Théâtre Jean Vilar, the musician played on a riser in front of the fire curtain facing the inclined audience area in the middle of the hexagonally shaped theatre. The Wigmore Hall is a chamber hall with an exposed stage in front of an apse and a plane audience area as well as a balcony at the back of the hall.

### 5.2.2 In-situ measurements

In order to determine the acoustical properties of the concert halls, measurements according to ISO 3382-1 (2009) were conducted. Figure 5.5 depicts the floor plans of stage and audience areas of each hall together with the source and receiver positions used for the measurements (denoted by $\times$ and $\square/\blacksquare$, respectively). An omni-directional source (Norsonic Nor276 with Nor280 Amplifier) was placed 1 m above the floor on stage at the position where the cello spike had been during the concerts, which was always a spot in the centre of the stage. An exception to this had to be made in ESM and CCC, where the performances of the cellist had taken place as part of festivals with temporary stages. These were no longer available when the measurements were carried out, so a suitable spot in the former stage area was chosen in these halls. In each room, impulse responses were measured at three to four positions at 1 m distance around the loudspeaker at a height of 1 m for the subsequent computation of stage measures (see section 3.2). Depending on the size and architectural structure of the halls, further measurements were carried out at 9 to 23 other receiver positions on stage and in the audience area at a height of 1.2 m. The measurements were conducted with a weighted sweep as excitation signal, using an M-Audio Fast Track Pro A/D-D/A converter and the EASERA 1.1 measurement software.

For each receiver point in the audience, the following room acoustical parameters were calculated: $EDT, RT, C_{80}, G, BR$ and $G_{125}$. For the stage positions, four

**(a)** ANC stage

**(b)** ANC audience

**(c)** CCC stage

**(d)** CCC audience

**(e)** CCG stage

**(f)** CCG audience

**(g)** ESM stage

**(h)** ESM audience

**Figure 5.2.** – Concert venues of the field study

**(i)** GGA stage

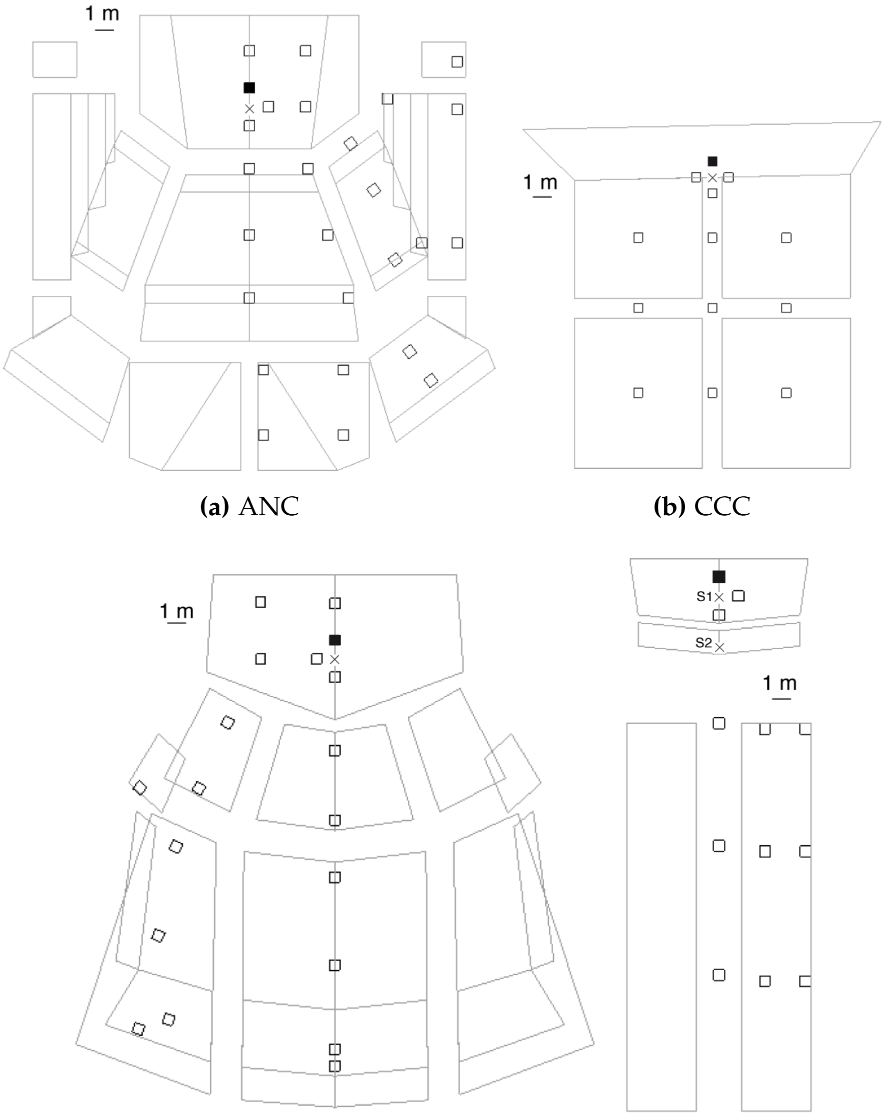
**(j)** GGA audience

**(k)** TJV stage

**(l)** TJV audience

**(m)** WMH stage

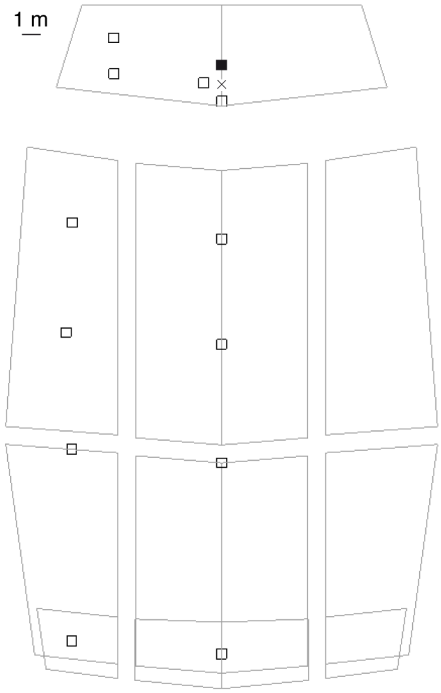
**Figure 5.3.** – (continued) Concert venues of the field study



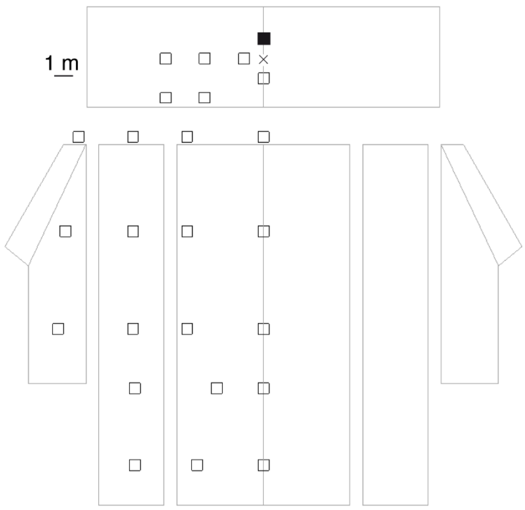

**(a)** ANC **(b)** CCC

**(c)** CCG **(d)** ESM

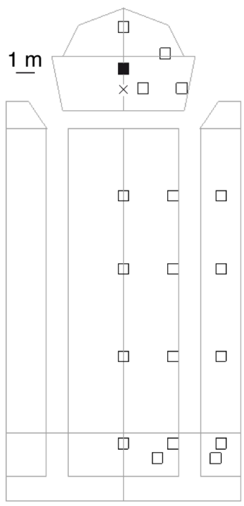
**Figure 5.4.** – Floor plans (to scale) of stage, audience area and (in CCG) balconies showing measurement positions used for the in-situ measurements in the concert halls. $\times$ denotes the position of the omni-directional source at 1 m height, ■ denotes the receiver position used for the measurement of the room acoustical parameters labelled with the subscript *solo*, □ denotes the other receiver positions. All receiver positions had a height of 1.2 m, only the ones at 1 m distance to the source were placed 1 m above the floor. In ESM the measurements in the stage area were carried out with source S1 and those in the audience area with source S2.




**(e)** GGA




**(f)** TJV




**(g)** WMH

**Figure 5.5.** – Floor plans (to scale) of stage, audience area and (in GGA and WMH) balconies showing measurement positions used for the in-situ measurements in the concert halls. $\times$ denotes the position of the omni-directional source at 1 m height, $\blacksquare$ denotes the receiver position used for the measurement of the room acoustical parameters labelled with the subscript *solo*, $\square$ denotes the other receiver positions. All receiver positions had a height of 1.2 m, only the ones at 1 m distance to the source were placed 1 m above the floor.

additional parameters were determined: $ST_{\text{early}}$, $ST_{\text{late}}$, $G_{\text{e}}$ and $G_{\text{l}}$ (see sections 3.2 and 4.1). Figure 5.6 (○, △) gives an overview of the room acoustics in the audience and stage areas of the concert spaces, respectively. The measures were computed in octave bands with EASERA 1.2 and Matlab R2012a for each receiver position, frequency-averaged according to ISO 3382-1 (2009) and averaged across positions. Only the stage measures $ST_{\text{early}}$ and $ST_{\text{late}}$ were calculated by averaging just the receiver positions at 1 m distance from the source to conform to the specifications (ISO 3382-1, 2009). The frequency behaviour of the spatially averaged parameters of the audience and stage areas is shown in figures B.2 and B.4 in appendix B.1.

As explained in section 4.1, the main focus of this study was on the room acoustical properties the cellist was confronted with during his performances, and the receiver point on stage 1 m behind the loudspeaker facing the audience (marked as ■ in figures 5.5a-g) was regarded to best describe the acoustical surrounding of the performer. The frequency-averaged room acoustical parameters shown in figure 5.6 (□) were calculated from the impulse responses determined at this position and are denoted by the subscript *solo* to indicate that these measures are not spatially averaged and determined at a short source-receiver distance. It is apparent that $G_{\text{solo}}$ and $G_{\text{e solo}}$ have a rather small range, which is due to the dominance of the direct sound at this measurement position. Similarly, the very low values for $EDT_{\text{solo}}$ in some of the halls can be explained by a high level of early reflections, which is likely in this measurement configuration.

### 5.2.3 Room acoustical models

In order to investigate the possible effects of room acoustical parameters on the cellist's way of playing, it was essential to determine the room acoustical situation during the concerts as precisely as possible. However, the measurements described above had to be conducted in unoccupied halls so they do not exactly reflect the concert conditions. Also, impulse responses determined with a directional source instead of an omni-directional loudspeaker should yield pa-

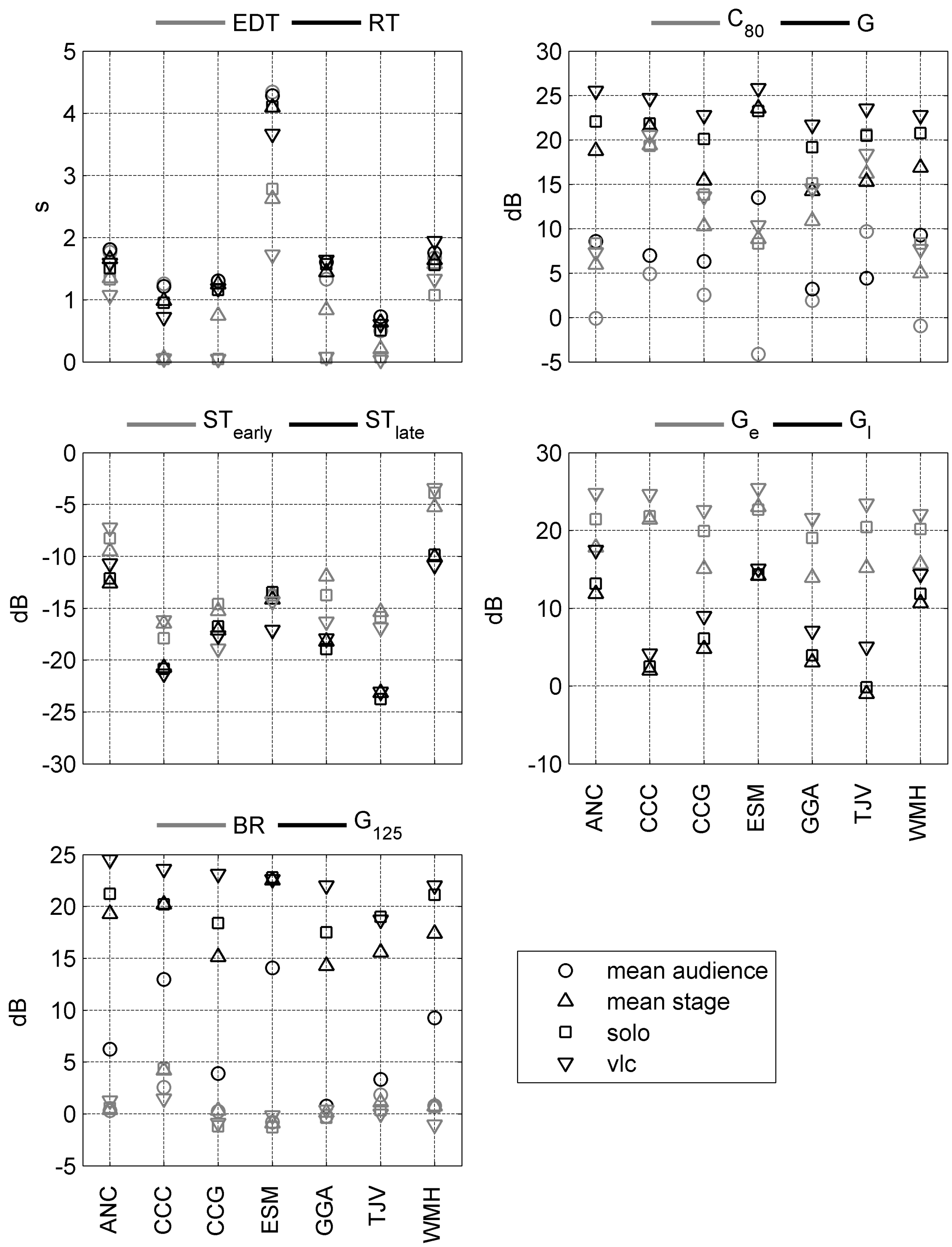



**Figure 5.6.** – Frequency-averaged room acoustical parameters measured in the real-world concert halls with an omni-directional source: ○ denotes the parameters spatially averaged over the receiver positions in the audience area, △ denotes the parameters spatially averaged over the receiver positions on stage. □ denotes the parameters determined with *solo* measurement setup, ▽ denotes the parameters that were corrected by the influence of the presence of an audience and the excitation of the hall with a directional source as determined by the *vlc* measurement setup in the computer models (section 5.2.3) and used for the statistical analysis in section 5.3.

rameters more closely related to the excitation of the halls with an instrument. Moreover, as explained, in two of the performance spaces (CCC and ESM) the stage setups of the concerts were missing when the measurements were carried out. To restore and investigate the acoustical concert conditions, computer models of the seven concert halls were generated with EASE 4.3 (see section 4.2.2). CAD-plans provided by the hall management, floor plans, in-situ dimensional measurements and other room acoustical studies (Allen, 1978; Wulfrank & Orlowski, 2006) were the basis for constructing the models shown in figure 5.7.
The wall properties of these models were specified as follows: The default scattering properties assigned to smooth surfaces are shown in figure 5.8, for more structured surfaces the slope of the curve was shifted towards lower frequencies (Christensen & Rindel, 2005). The absorption coefficients of all surfaces except the side walls in the models were set to typical values for the corresponding materials (Beranek, 2004; Egan, 1988; Fasold et al., 1987; Long, 2006; Moore, 1978; Templeton, 1997). The absorption values for both the auditorium and stage side walls were regarded as residual absorption. An impulse response was determined in each model by placing an omni-directional source in the model at a height of 1 m at the position of the cello spike and a receiver at 1 m behind it ($\times$ and $\blacksquare$ in figure 5.5), corresponding to the *solo* source-receiver configuration in the real measurements.[1] Since the further investigation was focussed on the room acoustical conditions perceived by the performer, it was this *solo* source-receiver setup that was subsequently used for the exact adjustment of the models and not a spatial average of positions. To accomplish the adjustment, the octave bands of $RT_{\text{solo}}$ in the models were fitted to the real-world measurement data by tuning the absorption values of the auditorium and stage side walls accordingly. The criterion for the fitting procedure was to achieve a difference between the simulated and the measured octave bands that was no greater than the just noticeable difference (JND) according to ISO 3382-1 (2009). The spatial average of $RT$ at the other stage measurement positions served as a second control for the fitting procedure, with errors not exceeding twice the JND.

[1]The procedure for such a simulated measurement is described in section 4.2.2 and the simulation parameters used here are reported in appendix B.2.

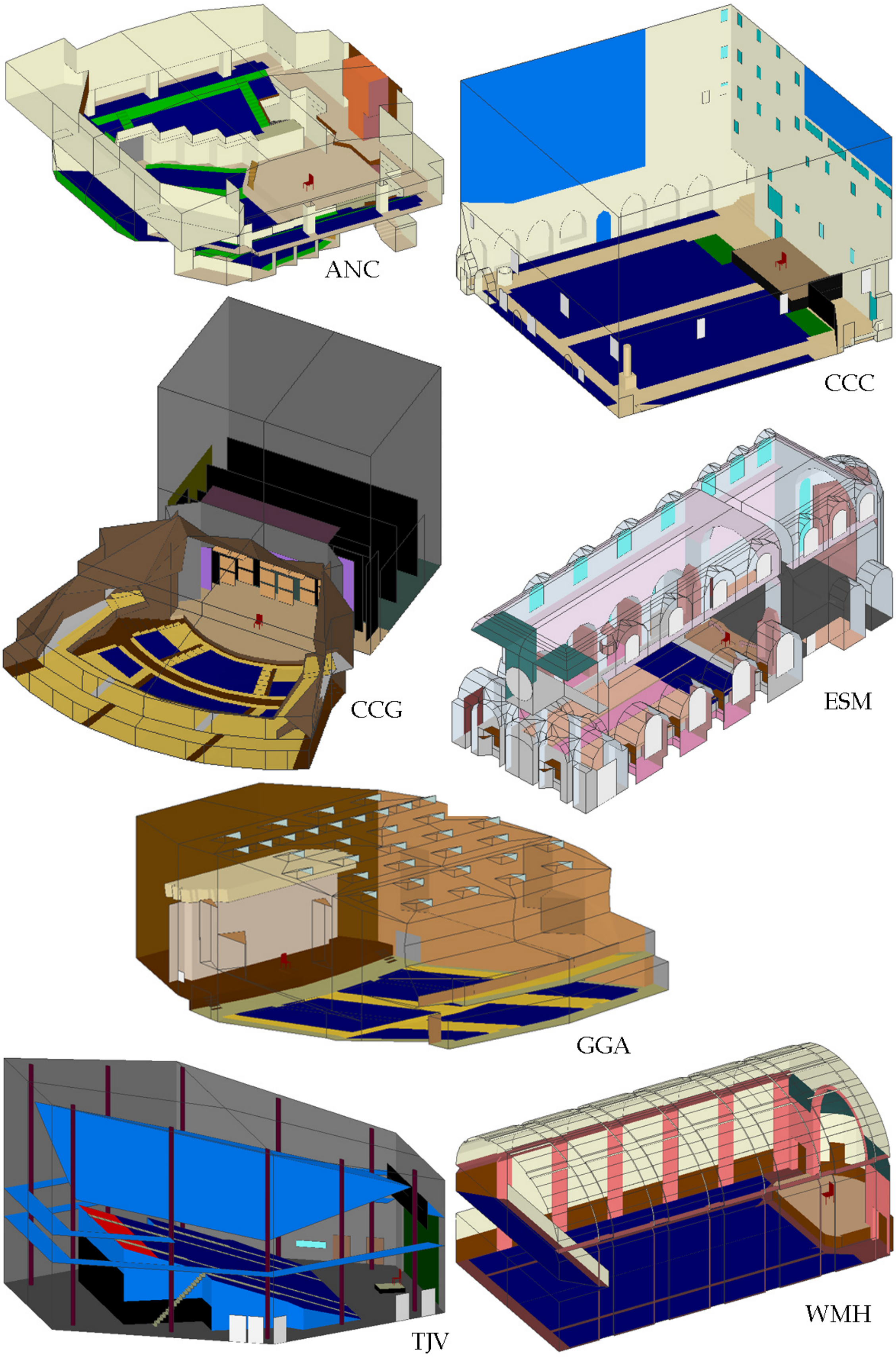



**Figure 5.7.** – Room models of the field study (not to scale). The dark blue areas denote the seats occupied by listeners during the performances of the cellist.

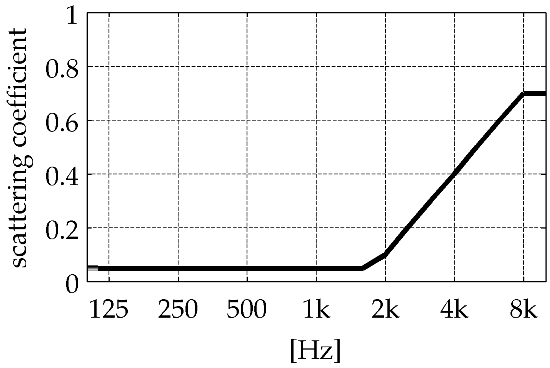



**Figure 5.8.** – Default scattering coefficient used for the surface materials in the computer models of the concert halls.

The frequency behaviour of the room acoustical parameters determined with the *solo* configuration both in the fitted models and in the real halls is shown in figure 5.10. Figure 5.12 depicts the differences between the fitted models and the real-world measurements for the octave bands of each parameter. As can be seen in figure 5.12a, the above mentioned criterion for $RT_{\text{solo}}$ was met in almost all cases. However, the reproduction of $EDT_{\text{solo}}$, $C_{80\ \text{solo}}$ and the support parameters (figures 5.12b-d) was not always satisfactory, with errors of up to four times the JND. These measures are strongly dependent on early reflections, which cannot be reliably simulated if diffraction effects play a major role.

After fitting the models to the measurement data, stages were added in the models of CCC and ESM to restore the concert setups. A further approximation of the concert situation was performed in all of the models in two steps. First, occupied audience areas corresponding to the size of the audiences during the concerts were included. They are shown as blue areas in figure 5.7. Then, a source with the directivity of a cello (Schneider, 2011) was inserted into the models, replacing the omni-directional source used so far. The acoustical centre of the simulated instrument was defined at 0.4 m behind the cello spike position and 0.6 m above the floor. Additionally, the receiver was moved to the typical ear height of a seated person (1.2 m) and 0.4 m behind the directional source. The latter was in accordance with the distance between the cello spike and the cellist's head, which was documented during the recordings. This source-receiver configuration is named *vlc* in the following, to indicate its congruence with the actual alignment of the musician and his instrument.

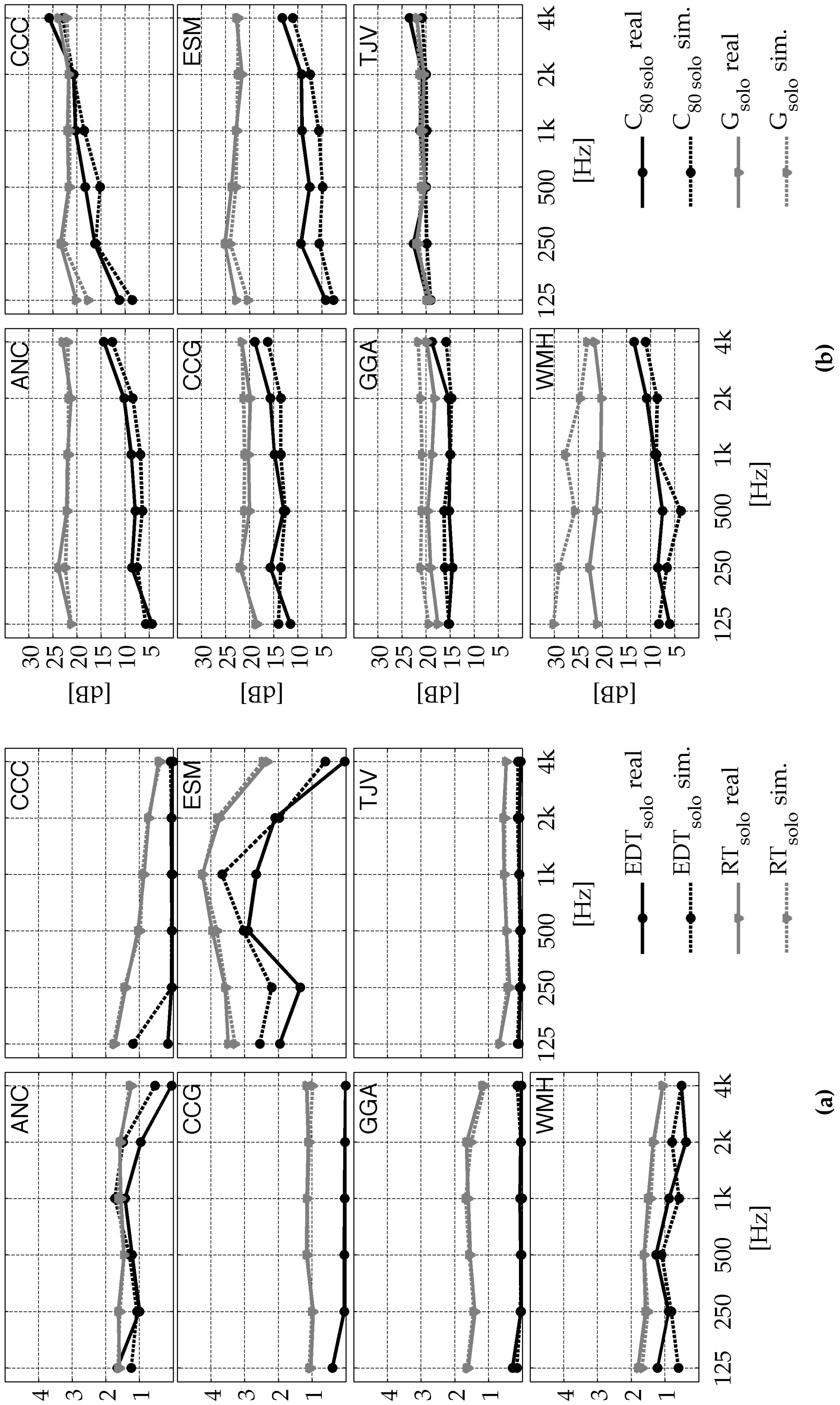
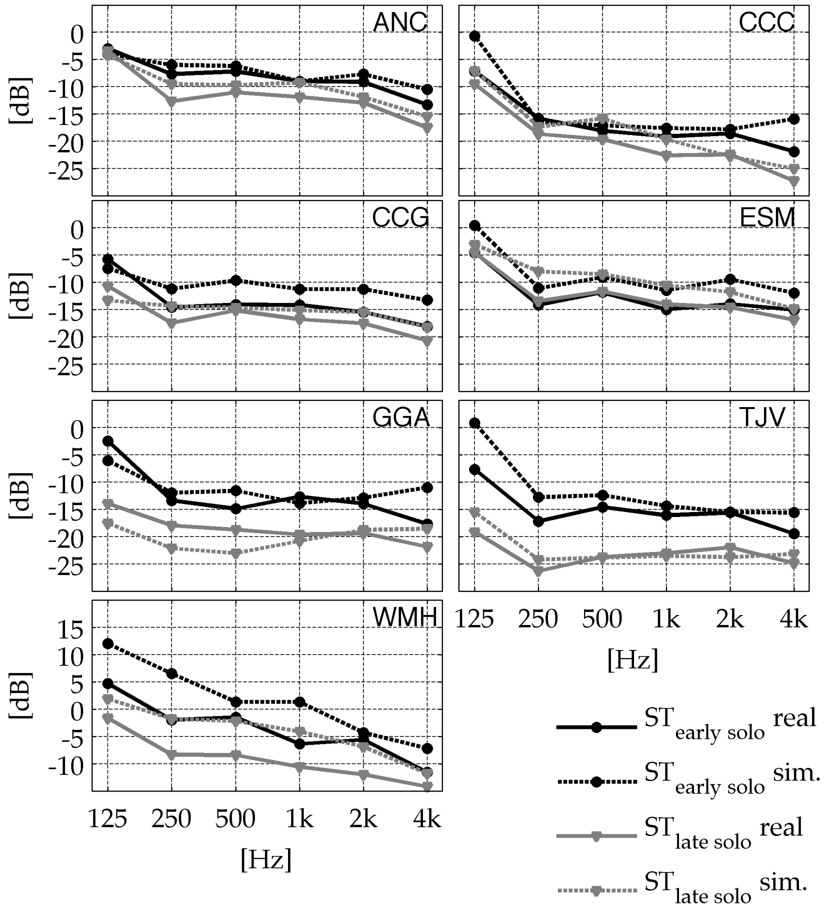



**Figure 5.9.** – Frequency behaviour of room acoustical parameters measured in real (solid lines) and simulated (dotted lines) concert halls with *solo* source-receiver configuration.




**(c)**

**Figure 5.10.** – (continued) Frequency behaviour of room acoustical parameters measured in real (solid lines) and simulated (dotted lines) concert halls with *solo* source-receiver configuration.

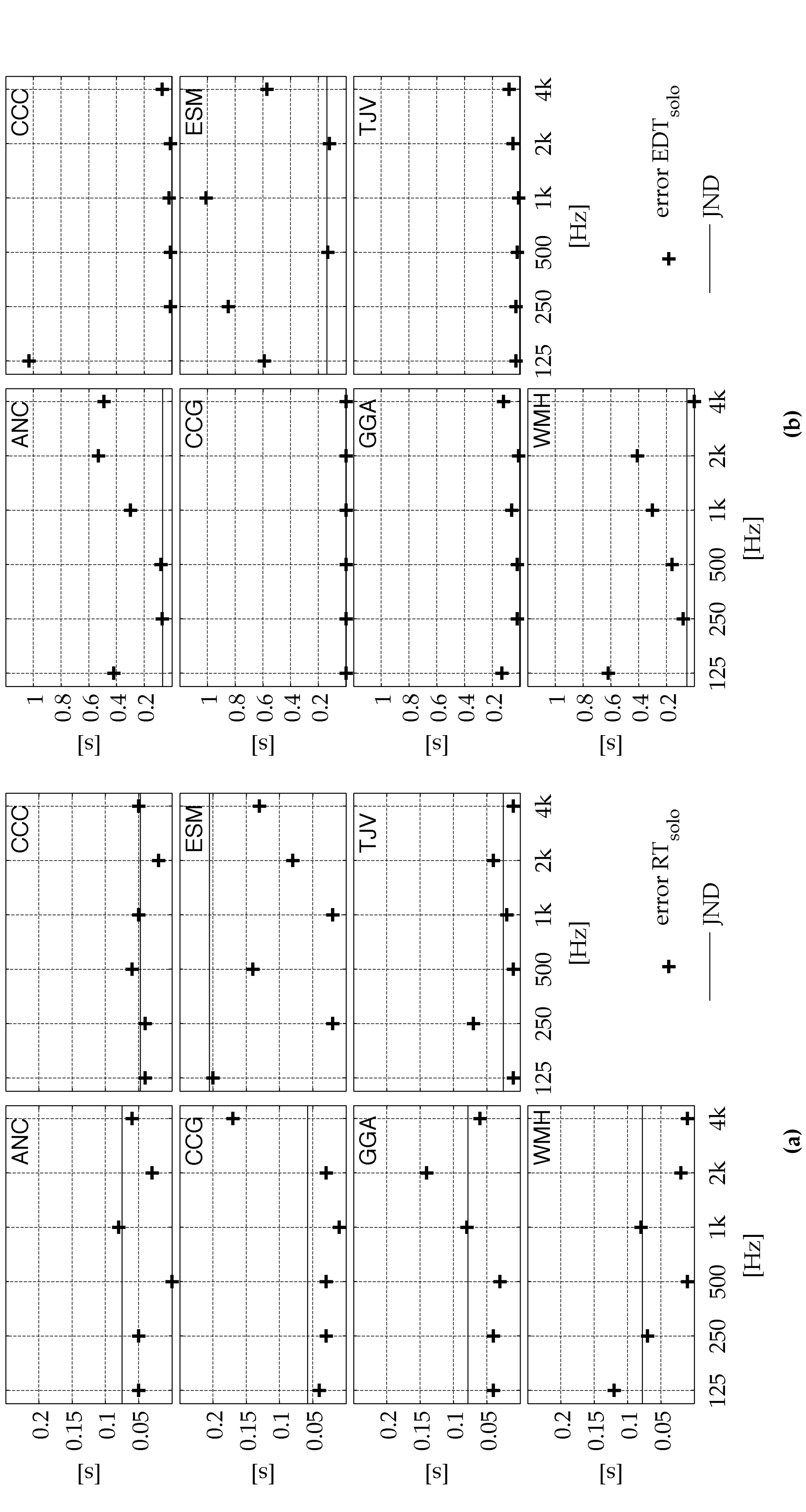
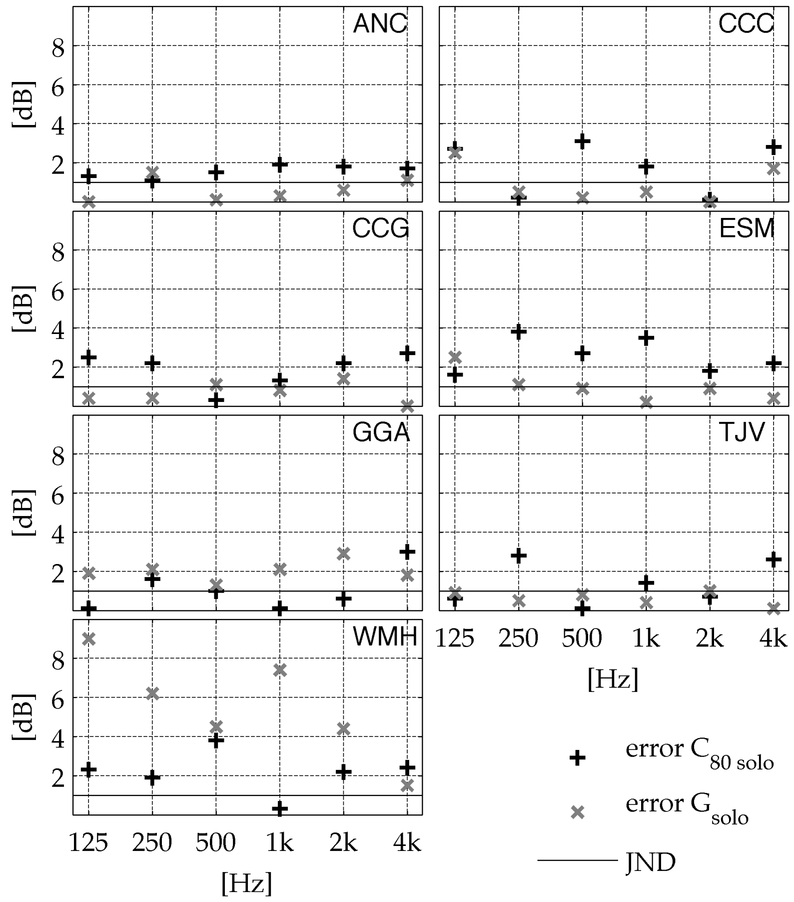
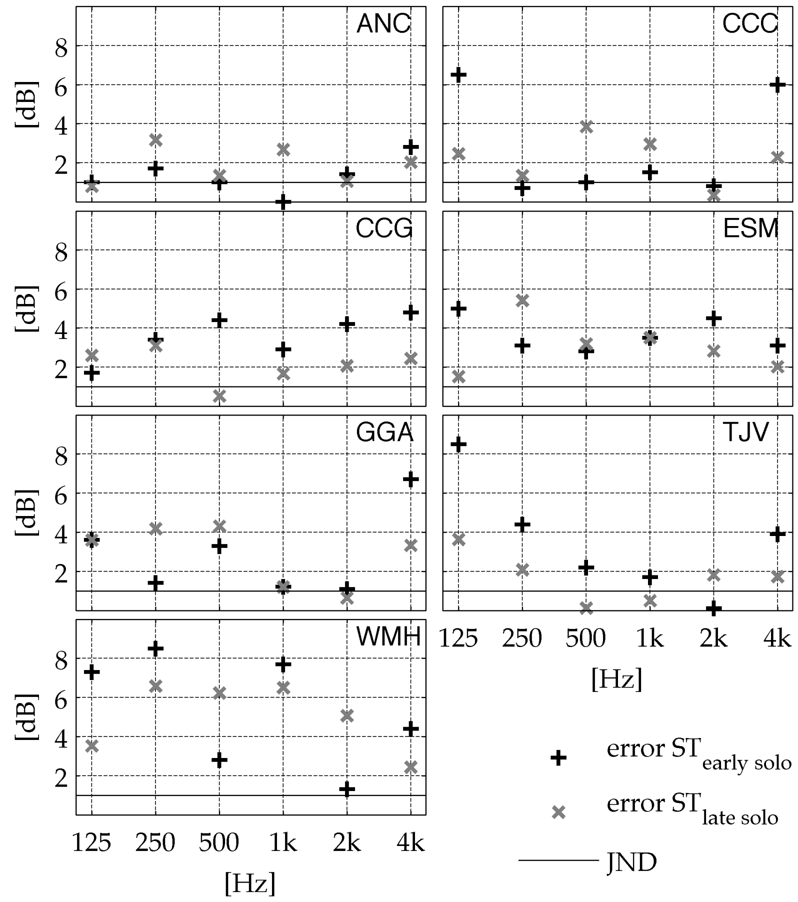



**Figure 5.11.** – Differences between the room acoustical parameters measured in the real-world concert halls and the fitted computer models using the *solo* source-receiver configuration. The JNDs of the room acoustical parameters according to ISO 3382-1 (2009) are shown as solid lines.




**(c)**




**(d)**

**Figure 5.12.** – (continued) Differences between the room acoustical parameters measured in the real-world concert halls and the fitted computer models using the *solo* source-receiver configuration. The JNDs of the room acoustical parameters according to ISO 3382-1 (2009) are shown as solid lines.

To test the effect of the presence of the audience, impulse responses were determined in the models with audience areas using the *solo* measurement configuration. The influence of the directional source was investigated by generating impulse responses with the *vlc* setup (including audience). A comparison of each of these simulated measurements with the data of the unoccupied computer models revealed that for most of the frequency-averaged room acoustical parameters the absolute differences between the unoccupied and the occupied state of the halls was smaller than or in the range of the JND ($+$'s figure 5.13). Only $RT_{\mathrm{solo}}$ was noticeably affected by the presence of an audience, which corresponds to the findings of Hidaka et al. (2001). In contrast, the absolute differences between the data of the occupied halls excited with the cello source and the unoccupied halls excited with an omni-directional source were greater than the JND for the reverberation time, the stage measures and clarity ($\times$'s in figure 5.13).
For the investigation of the effect of room acoustical parameters on the performances of the cellist, it was necessary to use the measures determined with the *vlc* source-receiver setup, which was only accessible in the models. However, as can be seen by comparing figures 5.10 and 5.13, the differences between real-world measurements and simulations were, for some parameters, in the order or higher than the differences due to the audience and the instrument's directivity. Thus, the room acoustical parameters used for the further investigation were not directly assumed from the models. Instead, all octave bands of the room acoustical parameters measured in the real halls were corrected by the differences caused by cello and audience, which were determined in the models ($\times$'s in figure 5.13). The mid-frequency measures obtained in this way are shown in figure 5.6 ($\triangledown$), their correlations are shown in table 5.2.

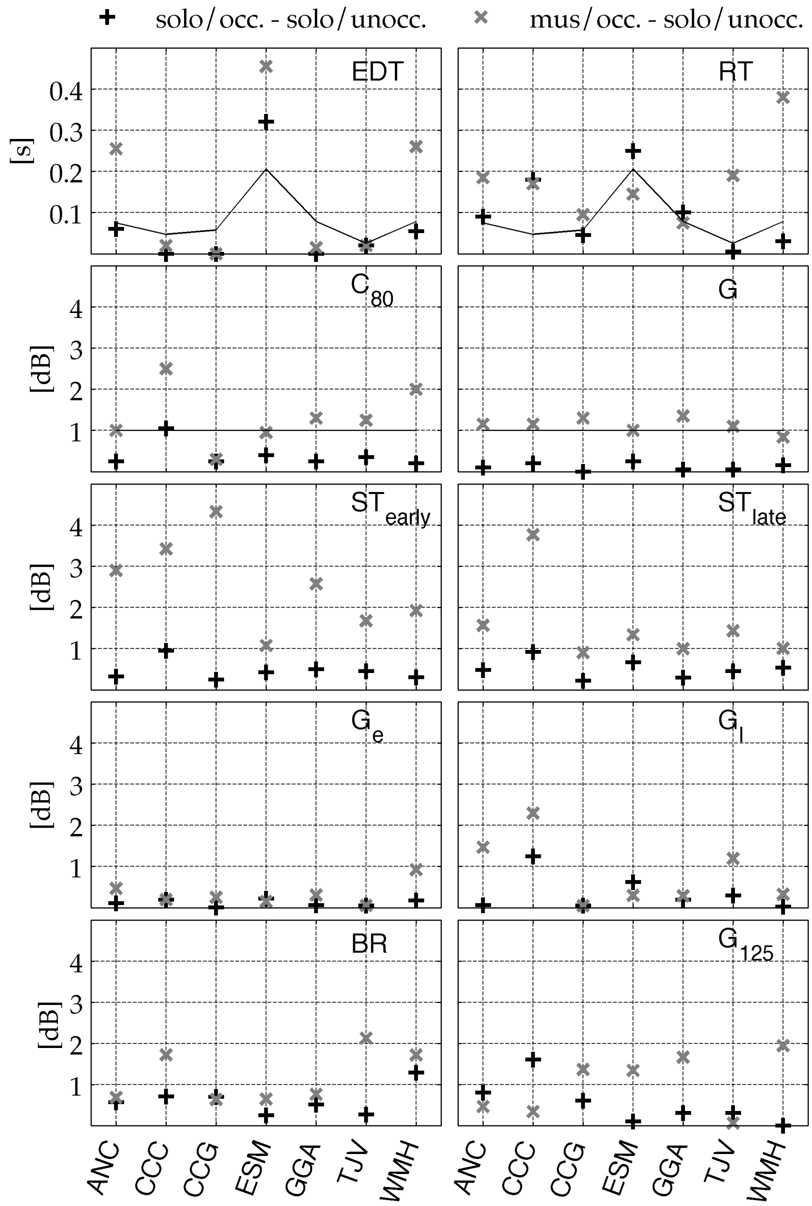



**Figure 5.13.** – Frequency-averaged absolute differences between room acoustical parameters acquired in the computer models at the musician's position under different conditions: $+$'s denote the difference between the unoccupied and the occupied rooms; $\times$'s denote the difference between the unoccupied room excited with an omni-directional source and the occupied room excited with a cello source, that is the concert situation. Sound strength parameters are normalised to a distance of 1 m between source and receiver. The JNDs of the room acoustical parameters according to ISO 3382-1 (2009) are shown as solid lines.

| | $EDT_{\mathrm{vlc}}$ | $RT_{\mathrm{vlc}}$ | $C_{80\ \mathrm{vlc}}$ | $G_{\mathrm{vlc}}$ | $ST_{\mathrm{early\ vlc}}$ | $ST_{\mathrm{late\ vlc}}$ | $G_{\mathrm{e\ vlc}}$ | $G_{\mathrm{l\ vlc}}$ | $BR_{\mathrm{vlc}}$ | $G_{125\ \mathrm{vlc}}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| $EDT_{\mathrm{vlc}}$ | 1 | | | | | | | | | |
| $RT_{\mathrm{vlc}}$ | 0.85* | 1 | | | | | | | | |
| $C_{80\ \mathrm{vlc}}$ | -0.80* | -0.62 | 1 | | | | | | | |
| $G_{\mathrm{vlc}}$ | 0.53 | 0.38 | -0.17 | 1 | | | | | | |
| $ST_{\mathrm{early\ vlc}}$ | 0.68 | 0.27 | -0.76* | 0.16 | 1 | | | | | |
| $ST_{\mathrm{late\ vlc}}$ | 0.67 | 0.41 | -0.94** | 0.11 | 0.86* | 1 | | | | |
| $G_{\mathrm{e\ vlc}}$ | 0.40 | 0.31 | 0.00 | 0.98** | -0.01 | -0.08 | 1 | | | |
| $G_{\mathrm{l\ vlc}}$ | 0.88** | 0.68 | -0.96** | 0.44 | 0.73 | 0.88** | 0.27 | 1 | | |
| $BR_{\mathrm{vlc}}$ | -0.21 | -0.30 | 0.32 | 0.48 | -0.08 | -0.16 | 0.53 | -0.16 | 1 | |
| $G_{125\ \mathrm{vlc}}$ | 0.27 | 0.23 | -0.38 | 0.39 | 0.25 | 0.53 | 0.32 | 0.46 | 0.38 | 1 |

**Table 5.2.** – Pearson correlations between the frequency-averaged room acoustical parameters measured on the seven concert hall stages with an omni-directional source at 1 m distance to the receiver (both 1 m above the floor) and corrected by the influence of the presence of an audience and the excitation of the hall with a directional source as determined by the *vlc* measurement setup in the computer models. * $p < 0.05$ (two-tailed); ** $p < 0.01$ (two-tailed)

## 5.3 Statistical analysis

The aim of the statistical analysis was to reveal the influence of the 10 room acoustical measures (independent variables, table 4.2) on the 8 performance characteristics (dependent variables, table 4.6) of the 36 pieces played in 7 concert halls. For this purpose, a multivariate HLM (see section 4.4) was employed using IBM SPSS Statistics 22.

### 5.3.1 Predictor variables

The room acoustical measures describing the musician's acoustical surroundings (figure 5.6,▽) were to be used as predictors for this HLM. Because of the relatively few cases ($n$ = 7 halls) and the high correlations between the potential regressors (see table 5.2), however, the number of predictors in the HLM had to be reduced. A principal component analysis (PCA) performed with the room acoustical parameters allowed to describe the information contained in the data with a smaller number of components that, at the same time, explained as much variance as possible. The criterion for the number of components to be extracted with this PCA was set to a minimum of 95% cumulative proportion of explained variance. After varimax rotation, the PCA yielded four components characterising 97.74% of the room acoustical variance in the concert halls. The loadings and the explained variance of these components are listed in table 5.3.

Two strategies were pursued to choose regressors for the HLM on the basis of this PCA: On the one hand, the four components themselves were used, since they could possibly reveal strong effects on the performance characteristics because of their multidimensional nature. This approach also eliminated the problem of correlated predictors, since PCA components are linearly independent. The four components in table 5.3 were interpreted as *late energy*, *early energy*, *warmth* and *duration of reverberation* and are printed in italics here to stress their use as variables. The model calculated with these regressors is called $\mathrm{HLM}_{\mathrm{comp}}$ in the following. The second strategy for choosing HLM regressors involved selecting specific room acoustical parameters as predictors in order to explore the

| Parameters | Components 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| $ST_{\text{early vlc}}$ | **<u>0.97</u>** | 0.05 | 0.10 | 0.02 |
| $ST_{\text{late vlc}}$ | **0.87** | -0.12 | 0.40 | 0.25 |
| $C_{80\text{ vlc}}$ | **-0.81** | 0.06 | -0.20 | -0.50 |
| $G_{\text{l vlc}}$ | **0.76** | 0.22 | 0.24 | 0.52 |
| $EDT_{\text{vlc}}$ | **0.65** | 0.37 | 0.03 | **0.64** |
| $G_{\text{e vlc}}$ | -0.06 | **<u>0.98</u>** | 0.15 | 0.13 |
| $G_{\text{vlc}}$ | 0.11 | **0.96** | 0.18 | 0.17 |
| $G_{125\text{ vlc}}$ | 0.15 | 0.17 | **<u>0.96</u>** | 0.14 |
| $BR_{\text{vlc}}$ | 0.28 | 0.18 | **0.93** | -0.04 |
| $RT_{\text{vlc}}$ | 0.23 | 0.20 | 0.03 | **<u>0.94</u>** |
| Expl. var. [%] | 35.26 | 21.85 | 21.23 | 19.40 |

**Table 5.3.** – Loadings and explained variance for components resulting from a PCA with varimax rotation conducted with 10 room acoustical parameters. Factor loadings $> |0.5|$ are marked bold, highest loadings are underlined.

direct relationship between performance characteristics and measurable parameters. Therefore, those room acoustical parameters with the highest loading on each component were selected and multicollinearity between regressors could be reduced to a minimum: $RT_{\text{vlc}}$, $ST_{\text{late vlc}}$, $G_{\text{e vlc}}$ and $G_{125\text{ vlc}}$. Despite the higher loading of $ST_{\text{early vlc}}$, it was the highly correlated $ST_{\text{late vlc}}$ (see table 5.2) that was selected because according to ISO 3382-1 (2009) the former describes ensemble conditions and was therefore expected to be less relevant for a solo performer. The model calculated with these regressors is called $\text{HLM}_{\text{par}}$ in the following. To summarise, the ten possible room acoustical predictors were reduced to two sets of four salient predictors each that were entered as explanatory variables into two multilevel analyses ($\text{HLM}_{\text{comp}}$ and $\text{HLM}_{\text{par}}$).

Previous studies have found indications that the relation between reverberation time and tempo (Kato et al., 2007), dynamic bandwidth (von Békésy, 1968) and, at least for some musicians, dynamic strength (Kato et al., 2007) could be approximated by an inverse quadratic function. To explore this evidence and to investigate whether a quadratic function might also be used to describe the relation between other predictors and performance characteristics, different HLMs were compared. Considering all the possible combinations of the two versions (linear and quadratic) of the four predictors for the eight response vari-

| Response Variables | Predictors $RT_{\mathrm{vlc}}$ | $ST_{\mathrm{late\ vlc}}$ | $G_{\mathrm{e\ vlc}}$ | $G_{125\ \mathrm{vlc}}$ |
|---|---|---|---|---|
| *Tempo* | qdr | qdr | lin | lin |
| *Agogic* | qdr | lin | qdr | lin |
| *Dynamic strength* | qdr | lin | lin | lin |
| *Dynamic bandwidth* | lin | lin | lin | lin |
| *Timbre (soft – hard)* | lin | lin | qdr | qdr |
| *Timbre (dark – bright)* | qdr | lin | qdr | qdr |
| *Timbre (lean – full)* | lin | qdr | qdr | lin |
| *Timbral bandwidth* | lin | lin | qdr | lin |

**Table 5.4.** – $\mathrm{HLM_{par}}$: The columns show the optimum combination of functions (qdr: quadratic; lin: linear) describing the relation between the performance characteristics and each room acoustical predictor in models with the other three predictors being used as linear variables. The final full $\mathrm{HLM_{par}}$ was calculated with those functions shown in the table.

ables would require calculating $2^{4^8}$ models, for each of the two HLMs ($\mathrm{HLM_{par}}$, $\mathrm{HLM_{comp}}$). Instead of comparing this immense number of HLMs a different approach was followed: The possible combinations of the linear and/or quadratic version of *one* predictor for the eight performance characteristics were calculated with the other three predictors being entered as linear regressors. The model with the highest explanatory power (pseudo-$R^2$, equation 4.12) was chosen from the $2^8$ possibilities and this comparison was performed for each of the four room acoustical predictors. The resulting four models thus each included the most suitable function (linear/quadratic) for one of the four predictors regarding each performance quality. In the respective final HLM, these four linear/quadratic-combinations were merged to one model. Tables 5.4 and 5.5 show the optimum relations between the predictors and response variables for $\mathrm{HLM_{par}}$ and $\mathrm{HLM_{comp}}$, respectively.

### 5.3.2 Data structure

The HLMs calculated for the analysis of the data were based on the assumption that the adjustments of the way of playing adopted by the performer in one room were similar for all pieces. In other words, it was expected that the performance qualities calculated for all the 187 played pieces could be grouped according to the rooms they had been performed in. This is why two-level HLMs were

| Response Variables | Predictors | | | |
|---|---|---|---|---|
| | *Rev. duration* | *Late energy* | *Early energy* | *Warmth* |
| *Tempo* | lin | qdr | qdr | lin |
| *Agogic* | lin | lin | qdr | qdr |
| *Dynamic strength* | lin | qdr | lin | lin |
| *Dynamic bandwidth* | lin | lin | qdr | qdr |
| *Timbre (soft – hard)* | lin | lin | lin | qdr |
| *Timbre (dark – bright)* | lin | qdr | qdr | qdr |
| *Timbre (lean – full)* | lin | qdr | qdr | lin |
| *Timbral bandwidth* | qdr | lin | lin | lin |

**Table 5.5.** – $\mathrm{HLM_{comp}}$: The columns show the optimum combination of functions (qdr: quadratic; lin: linear) describing the relation between the performance characteristics and each room acoustical predictor in models with the other three predictors being used as linear variables. The final full $\mathrm{HLM_{comp}}$ was calculated with those functions shown in the table.

calculated with the pieces constituting the first and the rooms constituting the second level.

To verify the above assumption and assess the correlation of the pieces within one room, intraclass correlation coefficients $\rho_v$ were calculated for each response variable $v$ on the basis of the estimated room level and residual variances, $\sigma^2_{v|\mathrm{room}}$ and $\sigma^2_{v|\mathrm{res}}$, in univariate intercept-only HLMs, that is models with no regressors that only consider the grouping structure:

$$\rho_v = \frac{\sigma^2_{v|\mathrm{room}}}{\sigma^2_{v|\mathrm{room}} + \sigma^2_{v|\mathrm{res}}} \tag{5.2}$$

As can bee seen in table 5.6, $\rho_v$ is between 0.30 and 0.77 for the response variables. This indicates that the data is clearly structured into groups[2] on the room level and supports the use of a multilevel model for the analysis of the data.

In a next step, a multivariate intercept-only model was calculated by adding a variable level (see section 4.4) below the piece and room levels. The estimation of the variances on the three levels showed that the piece level variance was too small to be estimated, which is not surprising when considering the z-transformation that was employed within the music pieces (see section 4.3).

[2]According to Maas & Hox (2004) ICCs above 0.3 can be considered as high.

| Response Variables | $\sigma^2_{v\|\text{room}}$ | $\sigma^2_{v\|\text{res}}$ | $\rho_v$ |
|---|---|---|---|
| *Tempo* | 0.49 | 0.49 | **0.50** |
| *Agogic* | 0.32 | 0.74 | **0.30** |
| *Dynamic strength* | 0.57 | 0.49 | **0.54** |
| *Dynamic bandwidth* | 0.57 | 0.46 | **0.55** |
| *Timbre (soft – hard)* | 0.71 | 0.22 | **0.77** |
| *Timbre (dark – bright)* | 0.41 | 0.61 | **0.40** |
| *Timbre (lean – full)* | 0.49 | 0.67 | **0.42** |
| *Timbral bandwidth* | 0.33 | 0.70 | **0.32** |

**Table 5.6.** – Variance on room level $\sigma^2_{v|\text{room}}$, residual variance $\sigma^2_{v|\text{res}}$ and intraclass correlation coefficients $\rho_v$ for the eight response variables.

Thus, this level was omitted (Hox, 2010, p. 18) and the multivariate HLMs described in the following were calculated with the room and the variable levels only.

### 5.3.3 Results[3]

To assess the explanatory power of the models, pseudo-$R^2$ was calculated according to equation 4.12. The explained variance amounted to 52.55% for $\text{HLM}_{\text{par}}$ and 52.53% for $\text{HLM}_{\text{comp}}$. Since the difference between the two models was so small, only $\text{HLM}_{\text{par}}$ was considered in the following, focussing on the influence of specific room acoustical parameters. It should be noted that the explained variance calculated here might be higher if some of the regressors were excluded from the prediction of some of the response variables, leading to a better fit of the model. However, the purpose of this analysis was to explore the extent of the effect of each room acoustical predictor rather than finding the best suitable model. Taking into account that the response variables were measured in real-world concert situations with many other influencing factors (see section 5.4.2), the pseudo-$R^2$ calculated here show a very high explanatory power of room acoustical properties for the variance of performance characteristics.

The parameters of the HLM were calculated with the restricted maximum likelihood method with standardised explanatory and response variables. The stan-

[3]Note that the results presented here slightly differ from the ones shown in Schärer Kalkandjiev & Weinzierl (2013) because an updated, unpublished version of the regression models was used for calculating the performance characteristics (see table 4.6).

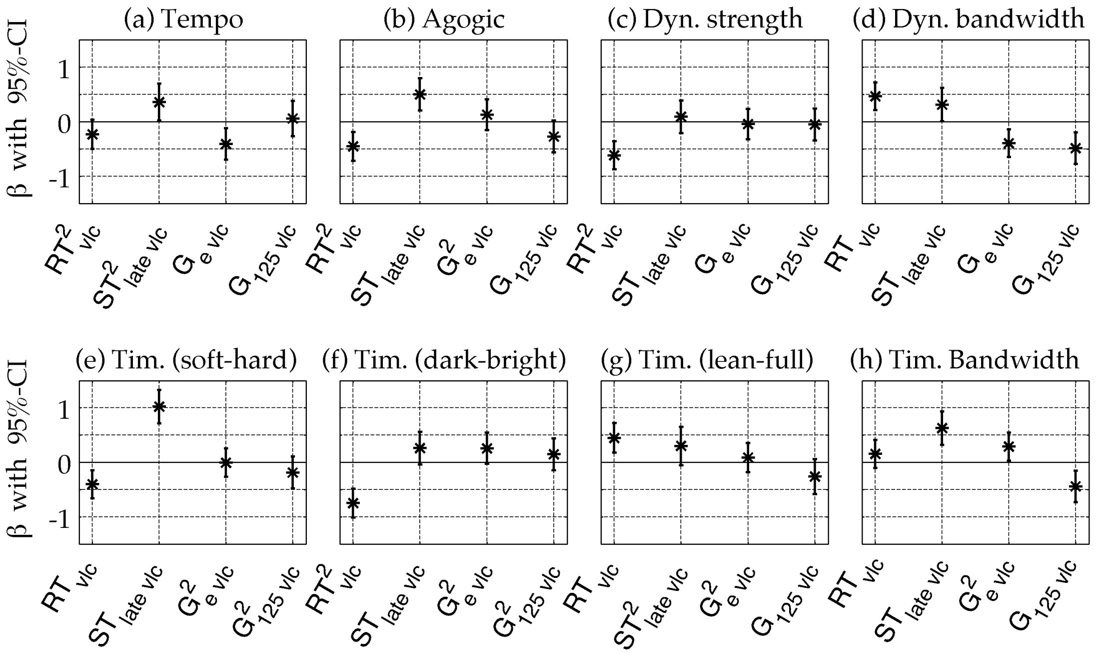



**Figure 5.14.** – Standardised regression coefficients with 95% confidence intervals (CIs) for the four room acoustical parameters (x-axes) predicting the eight performance characteristics (a-h). CIs not crossing the zero-line indicate significant coefficients ($p < 0.05$).

dardised regression coefficients with 95% confidence intervals for each explanatory and response variable of the $HLM_{par}$ are given in figure 5.14. They show the extent and the significance of the influence of the room acoustical predictors on the studied performance qualities. Figure 5.15 depicts the regression curves resulting from those coefficients indicating a significant quadratic interaction (or a strong tendency). Since the explanatory variables plotted on the x-axes in figure 5.15 are z-transformed, the zero point indicates the mean value of the respective room acoustical parameter.

**Tempo** As can be seen in figure 5.14a, there was a tendency ($p = 0.078$) for both short and long reverberation times leading to a slower *tempo* and figure 5.15a (solid black line) illustrates that the reduction of the *tempo* in the hall with the shortest reverberation time was less pronounced than in the hall with the longest reverberation time. Slowing down in reverberant environments is a response strategy frequently named by musicians and it was also mentioned by the cellist in the current study in guided interviews that were conducted after each concert (see section 5.4). It appears intuitively plausible that a reduced

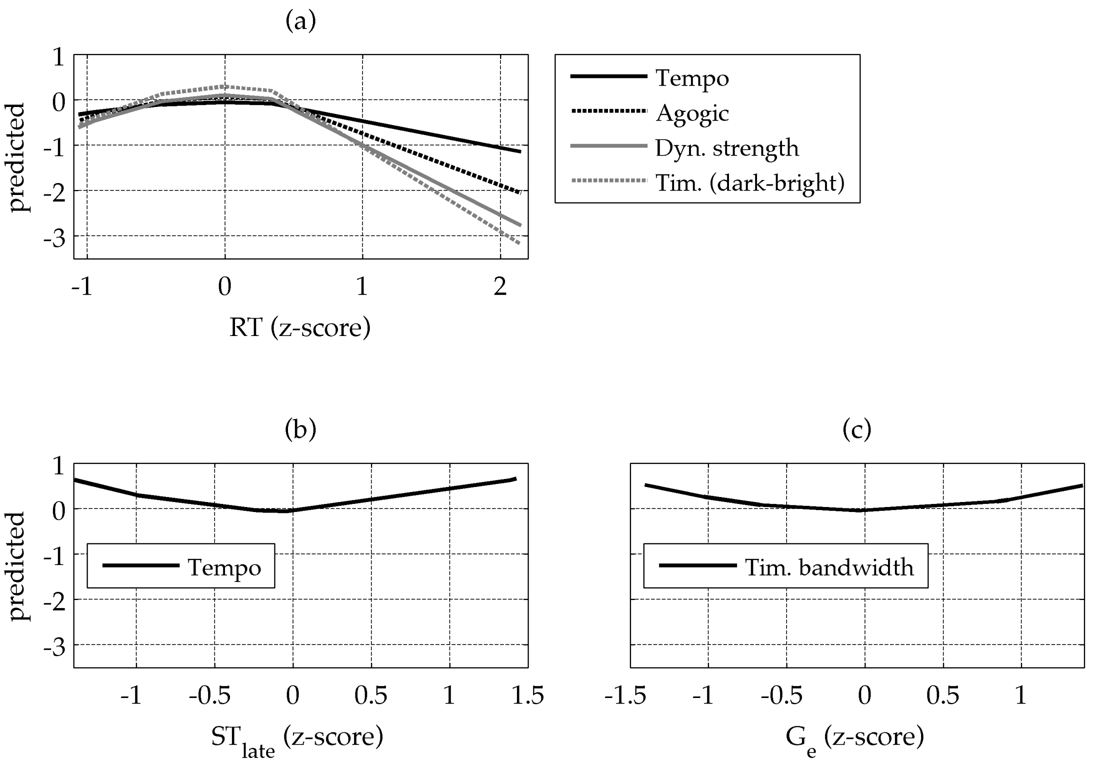



**Figure 5.15.** – Regression curves resulting from the coefficients with a significant effect or strong tendency for (a) $RT^2_{\mathrm{vlc}}$, (b) $ST^2_{\mathrm{lat\ vlc}}$ and (c) $G^2_{\mathrm{e\ vlc}}$. The zero point of the x-axes indicates the mean value of the predictors since these are z-transformed.

tempo is necessary to avoid the excessive blurring of consecutive tones. The slowing down at short reverberation times could, on the other hand, be the result of prolonging tones which are not carried by the reverberation of the room. The relation between *tempo* and reverberation time was explored in more detail by making use of the similar character of the each movement type across the six suites (see section 5.1): A factor ‚basic tempo‘ was defined (see table 4.1) and the levels ‚slow‘, ‚fast‘ and ‚variable‘ were assigned to the second/fourth, third/sixth and first/fifth movements, respectively. This factor was introduced to the interaction between *tempo* and $RT^2_{\mathrm{vlc}}$ in order to test whether the effect of the reverberation time on this performance characteristic was dependent on the basic tempo of the pieces. The standardised regression coefficients with 95% confidence intervals are shown in figure 5.16 separately for each of the three factor levels. The results demonstrate that the influence of the reverberation time was significant for the fast movements only. Possibly the blurring of tones was less problematic for slow pieces because the progression of notes was slow any-

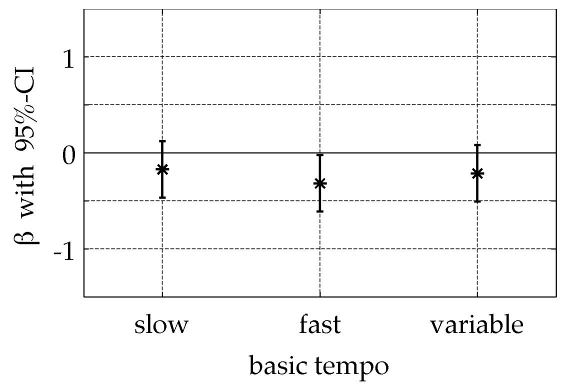



**Figure 5.16.** – Standardised regression coefficients with 95% confidence intervals for $RT^2_{vlc}$ separately predicting the *tempo* of the movements classified by the factor ‚basic tempo'. CIs not crossing the zero-line indicate significant coefficients ($p < 0.05$).

way and did not require any tempo reduction.

Figure 5.14a also shows that there was a significant positive influence of $ST^2_{\text{late vlc}}$ on *tempo*. As figure 5.15b illustrates, the cellist played slightly faster at low and high levels of late support. Surprisingly, it was none of the room acoustical parameters related to reverberation that had the strongest influence on *tempo* but $G_{\text{e vlc}}$ (figure 5.14a). The significant negative effect suggests that the performances were slowed down at high levels of early energy.

**Agogic** The use of tempo modulations by the cellist was significantly influenced by the reverberation time (figure 5.14b), with a maximum of *agogic* at an intermediate duration of reverberation and less tempo modulations towards shorter and longer $RT_{\text{vlc}}$. Similarly to the relation between $RT_{\text{vlc}}$ and *tempo,* it must be noted that the decrease of *agogic* was less pronounced in the room with the shortest than in the room with the longest reverberation time (see figure 5.15a, dashed black line). The decrease of *tempo* under reverberant conditions (see figure 5.14a) might have simultaneously inhibited the use of tempo modulations. As indicated by the significant positive effect of $ST_{\text{late vlc}}$, the cellist also used more *agogic* when the late support in the room was high.

**Dynamic strength** Some previous studies found a negative linear correlation between the dynamic strength of performances and the reverberation time (von Békésy, 1968; Bolzinger et al., 1994), while others suggested a that the relation was better approximated by a quadratic function (Kato et al., 2007). The current study reveals a more differentiated picture: Figure 5.14c shows a strong and significant negative effect of $RT^2_{\mathrm{vlc}}$ on *dynamic strength*. As figure 5.15a (solid grey line) illustrates, the cellist played clearly more piano in rooms with very long $RT_{\mathrm{vlc}}$ and slightly more piano in rooms with short $RT_{\mathrm{vlc}}$. The latter response strategy may be explained by one of the interviews after the concerts, in which the musician explained that he had learnt to respond to a lack of acoustical liveliness (also described as „not swimming in sound") with soft playing rather than forcing the sound of the instrument. The clear reduction of *dynamic strength* at long reverberation times might be due to the notion of „holding back" the sound and is in line with the findings of previous studies. It is surprising that the *dynamic strength* was not influenced by the early energy of the rooms, as one might expect a performer to play more piano in acoustically enhanced rooms.

**Dynamic bandwidth** The *dynamic bandwidth* of the performances was significantly influenced by all four investigated room acoustical parameters. The cellist used a greater *dynamic bandwidth* in rooms with long reverberation time and high late support, while he reduced the *dynamic bandwidth* in halls with high early energy and high bass strength.

**Timbre attributes** As can be seen in figures 5.14e-g, a long reverberation time lead to a *softer*, *darker* and *fuller* tonal rendition. The first two effects might be associated wit the reduction of *dynamic strength* under these conditions (figure 5.14c) and correspond to one of the interviews held after the concerts, in which the cellist stated that he felt the need to „hold back" when playing in rooms with a very long reverberation time. As indicated by the quadratic function describing the relation between the reverberation time and *timbre (dark – bright)* (see figure 5.15a, dashed grey line), the cellist also played slightly *darker* in rooms with short $RT_{\mathrm{vlc}}$.

An increasing perceived amount of reverberance (as indicated by $ST_{\mathrm{late\ vlc}}$) led to a significantly *harder* and in tendency *brighter* ($p = 0.078$) tonal rendition, a playing technique described by the performer as „trenchant" and adopted in very diffuse environments. These timbre attributes might also be related to a more defined attack in articulation, which was mentioned by the cellist as a playing strategy in reverberant rooms, as well.

Figure 5.14h shows that the *timbral bandwidth* was significantly increased with high late support and both low and high early energy (figure 5.15c). A high bass strength, on the other hand, lead to a reduced *timbral bandwidth*.

| *Tempo* | | *Agogic* | | *Dyn. strength* | | *Dyn. bandwidth* | |
|---|---|---|---|---|---|---|---|
| Pred. | $\lvert\beta\rvert$ | Pred. | $\lvert\beta\rvert$ | Pred. | $\lvert\beta\rvert$ | Pred. | $\lvert\beta\rvert$ |
| $G_{\mathrm{e\ vlc}}^{**}$ | 0.41 | $ST_{\mathrm{late\ vlc}}^{**}$ | 0.50 | $RT^{2\ **}_{\mathrm{vlc}}$ | 0.62 | $G_{\mathrm{125\ vlc}}^{**}$ | 0.49 |
| $ST^{2\ **}_{\mathrm{late\ vlc}}$ | 0.35 | $RT^{2\ **}_{\mathrm{vlc}}$ | 0.46 | $ST_{\mathrm{late\ vlc}}$ | 0.08 | $RT_{\mathrm{vlc}}^{**}$ | 0.46 |
| $RT^2_{\mathrm{vlc}}$ | 0.24 | $G_{\mathrm{125\ vlc}}$ | 0.28 | $G_{\mathrm{125\ vlc}}$ | 0.06 | $G_{\mathrm{e\ vlc}}^{**}$ | 0.40 |
| $G_{\mathrm{125\ vlc}}$ | 0.05 | $G^2_{\mathrm{e\ vlc}}$ | 0.12 | $G_{\mathrm{e\ vlc}}$ | 0.05 | $ST_{\mathrm{late\ vlc}}^{*}$ | 0.31 |
| *Tim. (soft – hard)* | | *Tim. (dark – bright)* | | *Tim. (lean – full)* | | *Tim. bandwidth* | |
| Pred. | $\lvert\beta\rvert$ | Pred. | $\lvert\beta\rvert$ | Pred. | $\lvert\beta\rvert$ | Pred. | $\lvert\beta\rvert$ |
| $ST_{\mathrm{late\ vlc}}^{**}$ | 1.02 | $RT^{2\ **}_{\mathrm{vlc}}$ | 0.75 | $RT_{\mathrm{vlc}}^{**}$ | 0.45 | $ST_{\mathrm{late\ vlc}}^{**}$ | 0.63 |
| $RT_{\mathrm{vlc}}^{**}$ | 0.40 | $ST_{\mathrm{late\ vlc}}$ | 0.26 | $ST^2_{\mathrm{late\ vlc}}$ | 0.30 | $G_{\mathrm{125\ vlc}}^{**}$ | 0.44 |
| $G^2_{\mathrm{125\ vlc}}$ | 0.19 | $G_{\mathrm{e\ vlc}}$ | 0.26 | $G_{\mathrm{125\ vlc}}$ | 0.26 | $G^{2\ *}_{\mathrm{e\ vlc}}$ | 0.29 |
| $G^2_{\mathrm{e\ vlc}}$ | 0.01 | $G^2_{\mathrm{125\ vlc}}$ | 0.14 | $G^2_{\mathrm{e\ vlc}}$ | 0.09 | $RT_{\mathrm{vlc}}$ | 0.15 |

**Table 5.7.** – Absolute regression coefficients ($\lvert\beta\rvert$) of the room acoustical predictors. The predictors are ordered according to their influence on each performance attribute. Significant coefficients are highlighted (*: $p < 0.05$, **: $p < 0.01$).

To explore the importance of the four room acoustical predictors for the performative adjustments, the absolute regression coefficients were used to order the room acoustical predictors according to their impact on the respective performance quality. As table 5.7 shows, each predictor had a strong impact on at least one performance characteristic, but it was the reverberation time and the late support that had the greatest effect in most cases. The early sound strength and the bass strength, in turn, were of minor importance. It thus seems that the cellist mostly adjusted his way of playing based on the duration of reverberation and strength of reverberant energy in the concert spaces. When the absolute regression coefficients $\lvert\beta\rvert$ are compared among each other, it can be seen that the highest value resulted for the effect of $ST_{\mathrm{late\ vlc}}$ on *timbre (soft – hard)*. Hence, this performance characteristic was the one most strongly affected by the room acoustical conditions of the concert spaces.

## 5.4 Guided interviews

It was established in section 2.3 that some performers have clear concepts about how to deal with certain room acoustical conditions, if only about how to react to „bad“ acoustics. The sections above demonstrated empirical evidence on the occurrence of adjustments to the room acoustics by the cellist in this study. This did, however, not answer the question on the consciousness of these adaptations, nor on the strategies behind them or the performer's perception of the room acoustics. A further point that was important to consider in this field study was the presence of other factors influencing the performances, as elaborated in section 4.1. The aim of the interviews that were held with the cellist after each concert was to shed light on these aspects and to obtain a description of each concert situation from the performer's point of view.

### 5.4.1 Methods

The following questions were used as a guide for the interviews:

- Please describe your performance. Were there any peculiarities? If yes, what do you ascribe them to?
- How did you find the room acoustics in the hall? Please give a rating between 1 and 20?
- Was your performance influenced by the room acoustics in the hall? If yes, in what way?
- How did you experience the audience?
- Was your performance influenced by the audience? If yes, in what way?

- How did you feel during the performance?
- Was your performance influenced by the way you felt? If yes, in what way?

The performance model introduced in section 2.2 assumes three main situational factors in a solo music performance: environment, personal form and audience. With the above questions, it was possible to obtain a description of the two latter factors and, instead of addressing the environment factor generally, the cellist was asked about the influence and his rating of room acoustics since this was evidently the main focus of the study. The open interview technique allowed for further statements on the other environmental factors shown in figure 2.1 as well as unforeseen aspects. The information drawn from the interviews was furthermore augmented by quantitative measurements of the situational factors: Concerning the audience, its size and distance to the performer were determined in each concert. The temperature and humidity of the hall, its volume as well as the area of the stage were measured as environmental variables and of course also the room acoustical parameters described in section 5.2 served as quantitative information on the environments. Only the personal form of the performer was not accessible through measurement.
The interviews were conducted on the telephone and lasted about 15 minutes. In one case, a telephone interview was not possible because of the time schedule of the performer, so he responded to the questions in writing. The conversations were held in German, which the performer is fluent in, and took place between 1 and 41 days after the concerts (see tables 5.10 to 5.16). Despite the big time span in some cases, the cellist always answered the questions very precisely and elaborately. The interviews were recorded and transcribed for analysis.

The conversations were analysed separately for each room by means of qualitative content analysis with the content-related structuring technique, that is by categorising meaningful elements in the text, paraphrasing and eventually summarising these passages (see section 4.5). As a starting-point of the analysis process, each element of the performance model of section 2.2 represented a category or subcategory (core elements and situational factors). The qualitative

| Main category | Subcategory | Definition |
|---|---|---|
| Performance concept | | General rules or views concerning performance conditions or the performance of the cello suites |
| Programme | | Pieces played in the concerts |
| Performance | | Sound production during the concerts |
| Instrument | | Cello played in the concerts |
| Audience | | Listeners in the concert halls |
| Personal form | Physical state | Physical constitution of the performer |
| | Emotional state | Emotional constitution of the performer |
| Environment | Room acoustics | Room acoustical conditions in the concert halls |
| | Room dimensions | Size of the concert halls |
| | Climatic conditions | Temperature and humidity in the concert halls |
| | Atmosphere | Ambience during the concerts |
| | Lighting | Lighting of the stage and audience areas |
| External factors | | Circumstances occurring outside of the actual concerts |
| Connection | | Influence of one category on another category |

**Table 5.8.** – Definition of categories and subcategories used in the qualitative content analysis of the interviews held with the performer.

content analysis explicitly allows for introducing new categories in the course of the analysis, so whenever the performer mentioned further aspects of situational influences, these were included as new (sub)categories. References to a connection between any two elements of the performance model formed an additional category. The categorisation system that was finally used is shown in table 5.8 and coding rules was well as examples are given in table C.2, appendix C.1. The categorised text elements were paraphrased and summarised within each interview, only the category ‚performance concept‘ was summarised across interviews, since these statements were assumed to relate to all performances and not a specific one. Together with the quantitative measurements mentioned above, this was the basis for a detailed description of the influencing factors and their interrelations in the individual concert situations. These descriptions as well as an analysis of the subjective effect of room acoustical conditions are presented in the next section.

### 5.4.2 Results

**Individual performance situations** The summarised statements assigned to the category ‚performance concept‘ are shown in table 5.9 and give an overview

| | |
|---|---|
| **Performance concept** | - Intimacy important for music for cello solo, large halls are less suitable<br>- For performance of Bach suites focus on temporal aspects and articulation, less focus on timbre<br>- Bach music suitable for speech-like playing<br>- Bach music demands unemotional use of timbre and vibrato<br>- Allemande of suite I demands reserved playing, no exaggerated effects<br>- Prelude of suite I demands relaxed sound<br>- Avoids being guided by imagined sound in auditorium, especially in halls with lacking room acoustical sonority/liveliness concentration on inner performance concept<br>- Fingering in Bach suites mainly in lower positions for more vibration, not much variation, not affected by room acoustics<br>- Bowing and articulation with many variations (e.g. in repetitions), *affected by room acoustical support/reverberation*<br>- Prolongation of pauses as a general tactic to surprise audience and regain attention<br>- Some repetitions in Bach suites are skipped if musically/dramaturgically reasonable and depending on overall tension<br>- Audience generally has little effect on playing<br>- Lighting is an important aspect in concert, before interviews no conscious attention, though<br>- New performance concept since concert TJV: less dependent on room acoustics, less resonant, more speech-like *because of experience with room acoustics in that hall*<br>- Tempo of Bach suites rather quick, dance-like since concert in TJV |

**Table 5.9.** – Performance concept of the cellist regarding the performance of the *Suites for Violoncello Solo* by J. S. Bach

of the cellist's ideas on performing Bach's cello suites. Tables 5.10 to 5.16 are in chronological order of the performances and give an account of the situational factors in each concert that were described by the performer in the interviews (denoted by I), determined by measurement (denoted by M) or observed by the author (denoted by O). Statements that were assigned to the ‚connection' category are printed in italics in the tables and stand for an influence of the respective factor as reported by the performer. Figures 5.20a-g are a visualisation of the performance situations: they show the performance model introduced in section 2.2 adapted to each individual concert with those situational factors and interrelations that were brought up by the musician in the interviews.

| | | |
|---|---|---|
| **Programme** | O | Performance 1 (evening 1): Suites I, IV, V<br>Performance 2 (evening 2): Suites II, III, VI |
| **Audience** | M | Occupied: 70 seats / 140 seats (of 440)<br>Distance to performer: 1.6 m |
| | I | - Before beginning of concert, audience moved to front seating rows, which was good for room acoustics<br>- Audience occupied about 1/3 of hall |
| **Personal form** | | |
| Emotional state | I | - Liked playing in hall |
| Physical state | O | - Strong transpiration, performer changed to T-shirt in interval *because of climatic conditions* |
| **Instrument** | I | - Arduous response of cello *because of climatic conditions* |
| **Environment** | | |
| Climatic conditions | M | Temperature: 25.72 °C / 26.34 °C<br>Rel. humidity: 61.07 % / 61.26 % |
| | I | - Hall was extraordinarily warm and humid |
| Room dimensions | M | Hall volume: 9600 $m^3$<br>Stage area: 30 $m^2$ |
| Room acoustics | M | $EDT_{\mathrm{vlc}}$ 1.72 s; $RT_{\mathrm{vlc}}$ 3.66 s; $C_{80\mathrm{vlc}}$ 10.35 dB; $G_{\mathrm{vlc}}$ 25.80 dB; $BR_{\mathrm{vlc}}$ 0.15 dB |
| | | $ST_{\mathrm{early\ vlc}}$ -14.35 dB; $ST_{\mathrm{late\ vlc}}$ -17.11 dB; $G_{\mathrm{e\ vlc}}$ 25.42 dB; $G_{\mathrm{l\ vlc}}$ 15.07 dB |
| | I | - Arduous sound *because of climatic conditions*<br>- Long reverberation time (estimated 2.5 s), muddled sound, lack of silence, hall easy to fill with sound<br>- Suitable for concerts but not recordings<br>- Changed considerably *with presence of audience*<br>- In retrospective comparison to concerts in TJV and GGA, room acoustical situation was hindering<br>- Rating: 15; in retrospective comparison to concerts in TJV and GGA: 8.5 |
| **Performance** | I | - Light playing<br>- Slowing down in many (but not all) parts of the music *because of muddled sound*<br>- Need to reduce dynamics, hold back while playing *because of long reverberation time/easily filling hall*<br>- Prolongation of pauses in slow movements *due to lack of silence*<br>- Use of focussed sound, not a lot of dolce<br>- Trenchant (articulation/dynamics/timbre), clear, precise playing *because of arduous sound*<br>- Focus on attack *because of arduous sound (of cello and hall)* |

**Table 5.10.** – Situational factors in ESM. The interview was held on the day after the first concert.

| | | | | | | |
|---|---|---|---|---|---|---|
| **Programme** | O | Prélude of suite VI; part of diverse festival programme with various performers | | | | |
| **Audience** | M | Occupied: 480 seats (of 480), additionally standing listeners on the sides<br>Distance to performer: 2.1 m | | | | |
| **Personal form** | | | | | | |
| Emotional state | I | - Disappointment *because of stage acoustics* | | | | |
| **Environment** | | | | | | |
| Climatic conditions | M | Temperature: 21.20 °C<br>Rel. humidity: 43.32 % | | | | |
| | O | - Open-air concert | | | | |
| Room dimensions | M | Yard area: 560 $m^2$<br>Stage area: 39 $m^2$ | | | | |
| Room acoustics | M | $EDT_{\text{vlc}}$<br>0.05 s | $RT_{\text{vlc}}$<br>0.72 s | $C_{80\text{vlc}}$<br>20.50 dB | $G_{\text{vlc}}$<br>24.70 dB | $BR_{\text{vlc}}$<br>0.99 dB |
| | | $ST_{\text{early vlc}}$<br>-16.20 dB | $ST_{\text{late vlc}}$<br>-21.31 dB | $G_{\text{e vlc}}$<br>-24.66 dB | $G_{\text{l vlc}}$<br>4.16 dB | |
| | I | - Lack of sonority in some frequency regions<br>- Dryness<br>- Rating: 12 | | | | |
| **Performance** | I | - No big adjustment of performance<br>- Trying not to force sound *despite dryness of room acoustics* | | | | |

**Table 5.11.** – Situational factors in CCC. The interview questions were answered in writing after 11 days.

| | | | | | | |
|---|---|---|---|---|---|---|
| **Programme** | O | Suites I, IV, V - interval - Suites II, III, VI | | | | |
| **Audience** | M | Occupied: 526 seats (of 586)<br>Distance to performer: 3.8 m | | | | |
| | I | - Good, attentive, concentrated<br>- Diversity concerning social status and age (including young music students) | | | | |
| **Personal form** | | | | | | |
| Emotional state | I | - Very good mood during concert *because of diversity of audience*<br>- Pleasantly surprised, enthusiastic *about room acoustics*<br>- Carefree during playing *due to room acoustics* | | | | |
| **Environment** | | | | | | |
| Climatic conditions | M | Temperature: 22.11 °C<br>Rel. humidity: 41,.21 % | | | | |
| Room dimensions | M | Hall volume: 11200 $m^3$<br>Stage area: 67 $m^2$ | | | | |
| Atmosphere | I | - Great intimacy between performer and audience<br>- Atmospheric pauses | | | | |
| Lighting | I | - Theatre-like lighting, focussed on stage (spotlight) | | | | |
| Room acoustics | M | $EDT_{\mathrm{vlc}}$<br>0.03 s | $RT_{\mathrm{vlc}}$<br>0.60 s | $C_{80\mathrm{vlc}}$<br>18.40 dB | $G_{\mathrm{vlc}}$<br>23.50 dB | $BR_{\mathrm{vlc}}$<br>-1.18 dB |
| | | $ST_{\mathrm{early\ vlc}}$<br>-16.88 dB | $ST_{\mathrm{late\ vlc}}$<br>-23.06 dB | $G_{\mathrm{e\ vlc}}$<br>23.44 dB | $G_{\mathrm{l\ vlc}}$<br>5.04 dB | |
| | I | - Nicely shaped, warm sound<br>- Cohesive, extraordinarily dense sound, like a spotlight<br>- Great clarity<br>- Not dry despite clarity (contrary to first impression upon arrival)<br>- Little resonance<br>- Rating: 16.5 | | | | |
| **Performance** | I | - No resonant playing ("artificial reverberation", vibrato, bowing) *since not suitable for room acoustics*<br>- Free, clear playing *because of room acoustics*<br>- Speech-like playing, *inspired by room acoustics*<br>- Playing with silence *because of intimate atmosphere*<br>- Faster tempo than in ESM<br>- Great reduction of dynamics *because of sound density* | | | | |

**Table 5.12.** – Situational factors in TJV. The interview was held after 41 days.

| | | | | | | |
|---|---|---|---|---|---|---|
| **Programme** | O | Suites I, IV, V - interval - Suites II, III, VI | | | | |
| **Audience** | M | Occupied: 750 seats (of 1228)<br>Distance to performer: 4.36 m | | | | |
| | I | - Nice, good, attentive<br>- Many empty seats | | | | |
| **Personal form** | | | | | | |
| Emotional state | I | - Good mood, enjoyed concert<br>- Lacking feeling of nearness to audience/less enjoyment of audience *because of empty seats*<br>- High concentration on music *despite/because of external factors* | | | | |
| **External factors** | I | - Troublesome journey to city of concert | | | | |
| **Environment** | | | | | | |
| Climatic conditions | M | Temperature: 21.38 °C<br>Rel. humidity: 45.27 % | | | | |
| Room dimensions | M | Hall volume: 12600 $m^3$<br>Stage area: 108 $m^2$ | | | | |
| | I | - Large, wide hall | | | | |
| Atmosphere | I | - Lack of intimacy *due to size of hall* | | | | |
| Lighting | I | - Stage lighting integrated into auditorium, no spotlight | | | | |
| Room acoustics | M | $EDT_{\text{vlc}}$<br>0.07 s | $RT_{\text{vlc}}$<br>1.63 s | $C_{80\text{vlc}}$<br>14.50 dB | $G_{\text{vlc}}$<br>21.70 dB | $BR_{\text{vlc}}$<br>-0.03 dB |
| | | $ST_{\text{early vlc}}$<br>-16.32 dB | $ST_{\text{late vlc}}$<br>-17.94 dB | $G_{\text{e vlc}}$<br>21.55 dB | $G_{\text{l vlc}}$<br>7.05 dB | |
| | I | - Nice, focussed sound quality despite size of hall<br>- Stage was part of auditorium in terms of room acoustics, sound came back to stage from hall<br>- Less flattering than TJV<br>- Beautiful despite size of hall<br>- Rating: 16.5 | | | | |
| **Performance** | I | - Performance not particularly slow, quicker than ESM<br>- Performance not particularly grand<br>- Greater independence from room acoustics *because of new performance concept since concert in TJV* | | | | |

**Table 5.13.** – Situational factors in GGA. The interview was held after 26 days.

| | | | | | | |
|---|---|---|---|---|---|---|
| **Programme** | O | Suite I as second item on programme consisting of pieces by Vitali, Britten, Berio, Henze, Dutilleux, Crumb | | | | |
| **Audience** | M | Occupied: 545 seats (of 692)<br>Distance to performer: 3.51 m | | | | |
| | I | - Liked audience<br>- Well visible | | | | |
| **Personal form** | | | | | | |
| Physical state | I | - Physical tension (arm/bow) *because of mental tension* | | | | |
| Emotional state | I | - Rather nervous, tense *because of many new pieces in programme*, alleviate *by relaxed atmosphere*<br>- Difficulties "letting go" at beginning of concert/in first part of suite, relieved *by positive room acoustics and well-known Bach suite*<br>- Mental focus on new pieces rather than on Bach suite<br>- Feeling of nearness to audience *because of lighting in auditorium* | | | | |
| **Environment** | | | | | | |
| Climatic conditions | M | Temperature: 23.59 °C<br>Rel. humidity: 22.15 % | | | | |
| Room dimensions | M | Hall volume: 5700 $m^3$<br>Stage area: 83 $m^2$ | | | | |
| Atmosphere | I | - Relaxed atmosphere<br>- Less "concert atmosphere" *because of lighting in auditorium* | | | | |
| Lighting | I | - Rather bright auditorium, little contrast to stage lighting | | | | |
| Room acoustics | M | $EDT_{\mathrm{vlc}}$<br>1.07 s | $RT_{\mathrm{vlc}}$<br>1.59 s | $C_{80\mathrm{vlc}}$<br>7.30 dB | $G_{\mathrm{vlc}}$<br>25.50 dB | $BR_{\mathrm{vlc}}$<br>1.12 dB |
| | | $ST_{\mathrm{early\ vlc}}$<br>-7.25 dB | $ST_{\mathrm{late\ vlc}}$<br>-10.70 dB | $G_{\mathrm{e\ vlc}}$<br>24.76 dB | $G_{\mathrm{l\ vlc}}$<br>17.46 dB | |
| | I | - Good audibility of music in auditorium<br>- Ideal extent of reverberation coming back to stage from hall<br>- Natural sound<br>- Nice size of hall<br>- Ideal, fantastic, wonderful<br>- Rating: 20 | | | | |
| **Performance** | I | - Performance without peculiarities<br>- Good performance, *supported by positive room acoustics*<br>- In Prelude rather tense playing *because of physical tension*<br>- Specific pattern in Courante less rhythmically precise *because of physical tension*<br>- In Allemande unnecessary effects (tempo/dynamics), not reserved playing | | | | |

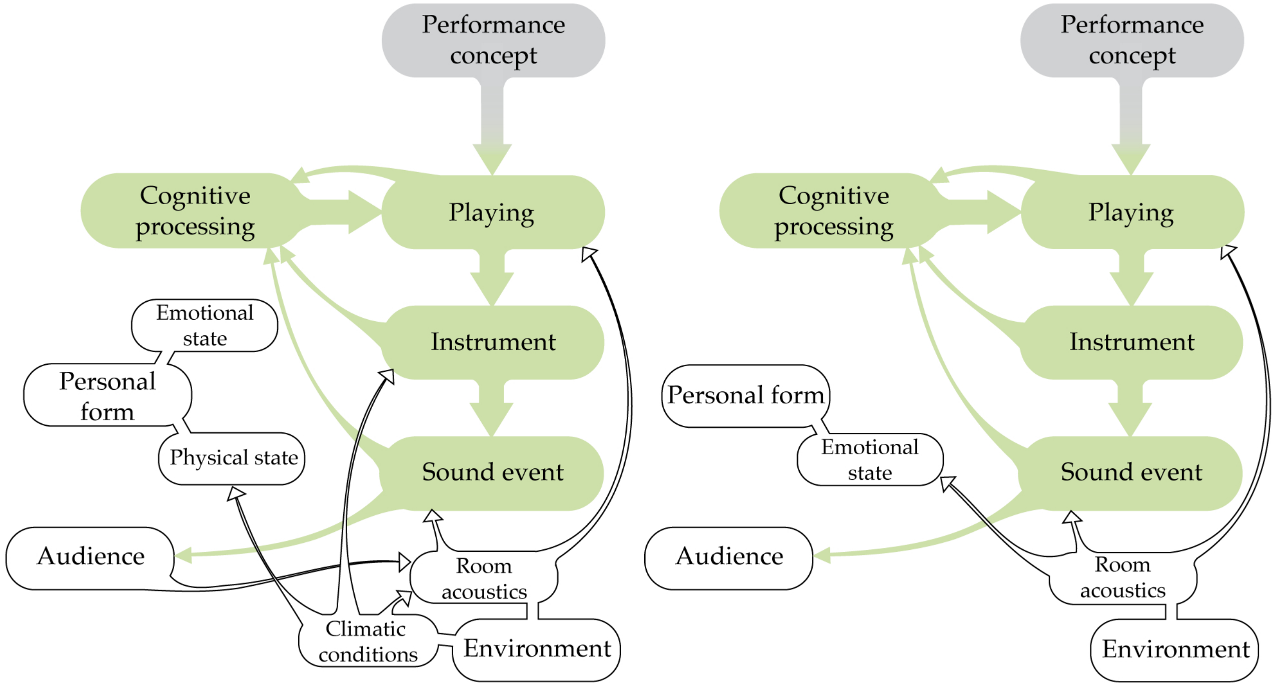
**Table 5.14.** – Situational factors in ANC. The interview was held after 15 days.

| | | |
|---|---|---|
| **Programme** | O | Suites I, IV - interval - Suites III, V - interval - Suites II, VI |
| **Audience** | M | Occupied: 230 seats (of 812)<br>Distance to performer: 3.84 m |
| | I | - Very quiet, except for strong coughing in the beginning |
| **Personal form** | | |
| Physical state | I | - Tired constitution *because of health impairment prior to concert* |
| Emotional state | I | - Discontent *with sound of cello*<br>- During rehearsal/at beginning of concert slightly unpropitious disposition and inner distance to music *because of external factors*<br>- Enjoyment of concert *because of quiet audience* |
| **External factors** | I | - Extreme external circumstances<br>- Serious health impairment prior to concert<br>- Numerous engagements prior to concert<br>- Troublesome journey to city of concert, delayed arrival for rehearsal<br>- Missing/cold meals on day of concert |
| **Instrument** | I | - Sound of cello slightly empty/dissatisfying after maintenance |
| **Environment** | | |
| Climatic conditions | M | Temperature: 23.77 °C<br>Rel. humidity: 38.21 % |
| Room dimensions | M | Hall volume: 12700 $m^3$<br>Stage area: 101 $m^2$ |
| Atmosphere | I | - Communication between performer and audience on the level of the music |
| Room acoustics | M | $EDT_{\text{vlc}}$: 0.04 s<br>$RT_{\text{vlc}}$: 1.18 s<br>$C_{80\text{vlc}}$: 13.60 dB<br>$G_{\text{vlc}}$: 22.75 dB<br>$BR_{\text{vlc}}$: 0.37 dB |
| | | $ST_{\text{early vlc}}$: -18.92 dB<br>$ST_{\text{late vlc}}$: -17.65 dB<br>$G_{\text{e vlc}}$: 22.56 dB<br>$G_{\text{l vlc}}$: 8.96 dB |
| | I | - Room acoustics in auditorium not bad (according to members of audience)<br>- Pale sound<br>- Anonymous room acoustics with no atmosphere<br>- Neutral sound/colour<br>- Lack of sonority/liveliness<br>- Rating: 12 |
| **Performance** | I | - Good performance<br>- Slightly missing overall tension *because of unpropitious disposition*<br>- Left out more repetitions than usual *because of unpropitious disposition*<br>- Concentration on inner concept of articulation and tempo *because of lacking sonority*<br>- Soft playing *because of pale sound*<br>- Dynamic contrasts *because of lacking liveliness* |

**Table 5.15.** – Situational factors in CCG. The interview was held after 3 days.

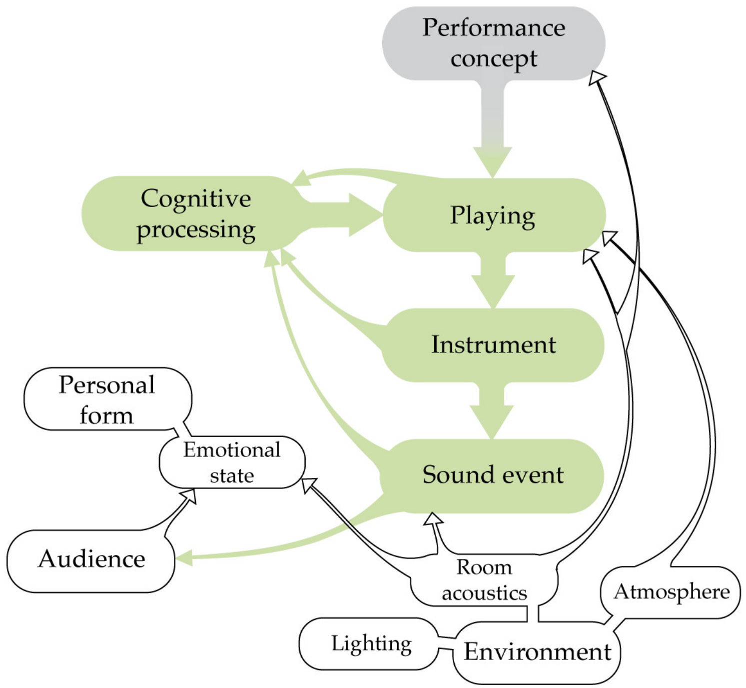
| | | | | | | |
|---|---|---|---|---|---|---|
| **Programme** | O | Performance 1 (morning): Suites I, IV, V<br>Performance 2 (afternoon): Suites II, III - interval - VI | | | | |
| **Audience** | M | Occupied: both performances 552 seats (of 552)<br>Distance to performer: 2.27 m | | | | |
| | I | - Pleasant, attentive, cultured, unpretentious<br>- Audience enjoyed listening | | | | |
| **Personal form** | | | | | | |
| Emotional state | I | - Generally good mood<br>- Concert was a pleasure *because of delighted audience* and *because of beautiful sound of hall*<br>- Inner distance to music *because of external factors* | | | | |
| **External factors** | I | - Short-term arrival in city of concert<br>- Many engagements prior to concert | | | | |
| **Instrument** | I | - Despite maintenance (see table 5.15) great satisfaction with sound of instrument | | | | |
| **Environment** | | | | | | |
| Climatic conditions | M | Temperature: 23.60 °C<br>Rel. humidity: 47 % | | | | |
| Room dimensions | M | Hall volume: 2800 $m^3$<br>Stage area: 32 $m^2$ | | | | |
| Atmosphere | I | - Lacking warmth *due to daylight*<br>- Little intimacy *due to daylight*<br>- Not much "concert atmosphere" *due to daylight* | | | | |
| Lighting | I | - A lot of daylight from windows in ceiling of hall | | | | |
| Room acoustics | M | $EDT_{\mathrm{vlc}}$<br>1.33 s | $RT_{\mathrm{vlc}}$<br>1.946 s | $C_{80\mathrm{vlc}}$<br>7.70 dB | $G_{\mathrm{vlc}}$<br>22.75 dB | $BR_{\mathrm{vlc}}$<br>0.46 dB |
| | | $ST_{\mathrm{early\ vlc}}$<br>-3.45 dB | $ST_{\mathrm{late\ vlc}}$<br>-10.86 dB | $G_{\mathrm{e\ vlc}}$<br>22.07 dB | $G_{\mathrm{l\ vlc}}$<br>14.37 dB | |
| | I | - Slight over-emphasis of mid-frequency range because of round rear wall of stage<br>- Coolness, possibly because of high amount of stone surfaces in hall<br>- Nice room size<br>- Generous support from auditorium, amplification on stage<br>- Nice reverberation<br>- Extraordinary room, beautiful, free, comfortable, delightful room acoustics (for Bach suites)<br>- Rating: 18 | | | | |
| **Performance** | I | - Light playing *due to reverberation/support*<br>- Short articulation *due to reverberation* | | | | |

**Table 5.16.** – Situational factors in WMH. The interview was held after 36 days.

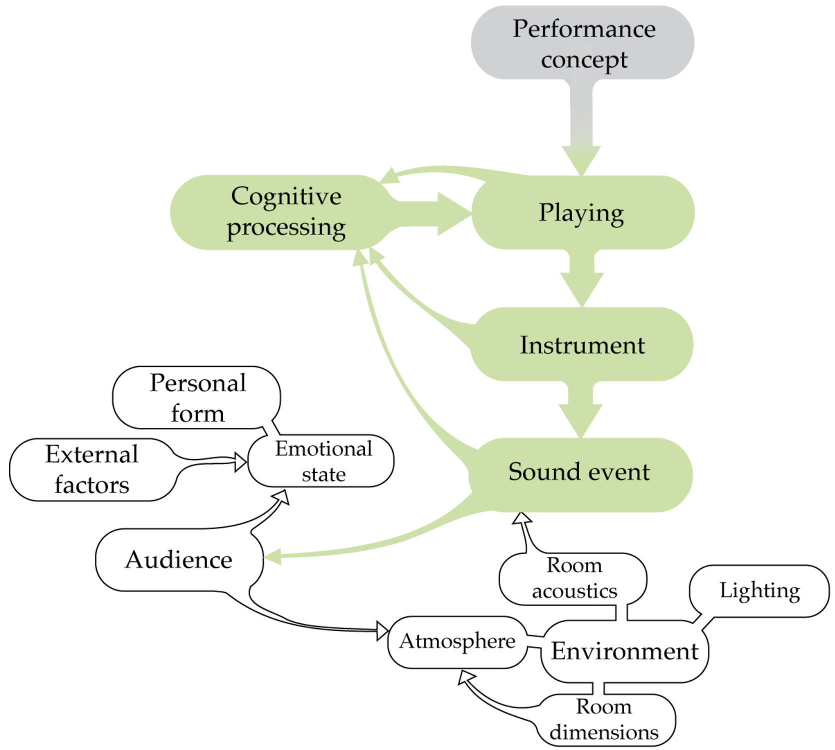



**(a)** ESM **(b)** CCC

**Figure 5.17.** – Performance models for each concert showing the situational factors and their interrelations that were mentioned by the performer in the interviews.

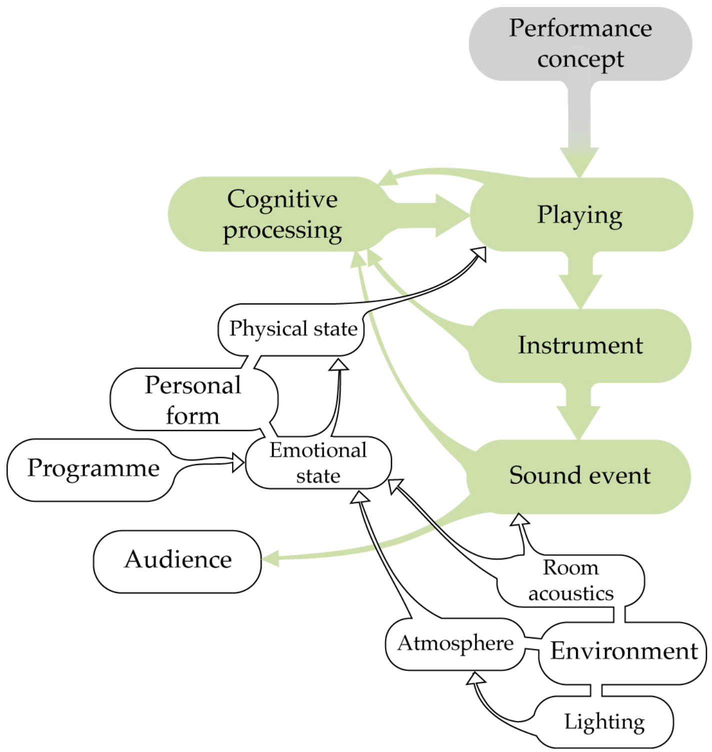



**(c)** TJV

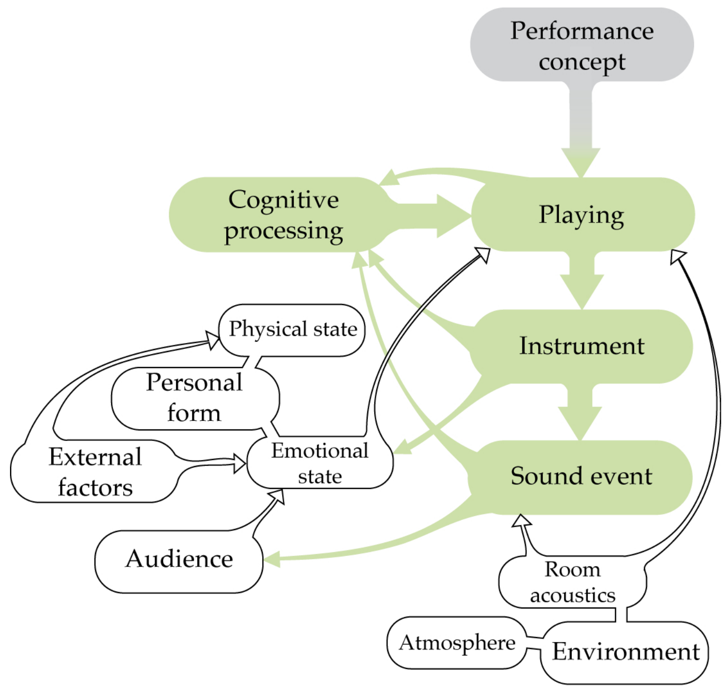



**(d)** GGA

**Figure 5.18.** – (continued) Performance models for each concert showing the situational factors and their interrelations that were mentioned by the performer in the interviews.

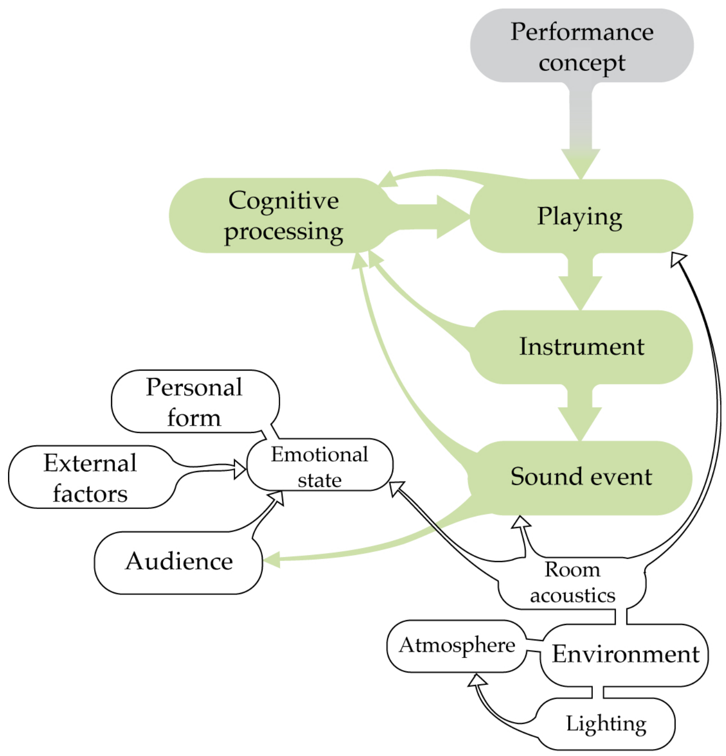



**(e)** ANC




**(f)** CCG

**Figure 5.19.** – (continued) Performance models for each concert showing the situational factors and their interrelations that were mentioned by the performer in the interviews.




**(g)** WMH

**Figure 5.20.** – (continued) Performance models for each concert showing the situational factors and their interrelations that were mentioned by the performer in the interviews.

**Assessment and subjective effect of room acoustics** One aim of the interviews was to determine which properties of the room acoustical surrounding were relevant for the performer and lead to an adjustment of certain aspects of the music performance. As described above, the cellist was asked to rate the acoustics of each hall on a scale from 1 to 20. His lowest rating was 8.5 (in retrospective comparison with other rooms), the highest one was 20 and the average was 14.79. These ratings certainly need to be treated with caution since they were not made in direct comparison of the rooms. Together with the qualitative description of the room acoustics given by the performer, they do, however, provide some information on which aspects were relevant for him when evaluating the performance spaces.

An aspect that was frequently mentioned in different contexts was reverberance. The musician sometimes directly referred to the reverberation time but also spoke of the opposite condition, dryness. The hall with the longest reverberation time received the lowest rating, but the same room was also characterised by low sustainability, which was described as arduous sound and „thick air" („dicke Luft") by the cellist (table 5.10). Closely related to the aspect of reverberance are the terms sonority and liveliness, which were mentioned when they were lacking. The two halls with absence of sonority were given quite low ratings, that is 12 in both cases (tables 5.11 and 5.15). The notion of missing resonance and the aspect of dryness were explicitly distinguished by the cellist when he stated that one room had little resonance but was not dry (table 5.12). Further qualities that were mentioned are density, clarity and the response from the auditorium. The latter was named several times (tables 5.13, 5.14 and 5.16) and seems to be of great importance for the performer, since he positively mentioned it in the two rooms at the top end of the rating scale. The size of the hall was named twice in the context of room acoustics, so it seems to play a role in the cellist's perception of room acoustical surroundings. Apart from one direct reference to certain frequency regions of the sound, the performer talked about various facets of sound quality, e.g. pale, warm, focussed or natural sound.

Concerning the influence of room acoustics on his way of playing, the cellist indicated as a general performance concept that his use of articulation and bowing may be determined by reverberation and the response from the auditorium. Also, an influence of the room acoustics on the use of vibrato was mentioned but not further specified. Turning to the more specific relations, the cellist described a long reverberation time to have caused both a slower tempo and a prolongation of pauses (table 5.10). The former is in line with the empirical findings shown in section 5.3.3. The musician also expressed that a very long reverberation time forced him to reduce the dynamic strength of his playing and that he felt the need to hold back while playing. The empirical results correspond to these statements and suggest that the second playing technique was also related to aspects of timbre. A further reference to the reverberation time was made in connection with the articulation, which the performer described as being short in the respective concert hall with a moderately long reverberation time (table 5.16). In the two rooms that were described as lacking sonority, the musician stated that he avoided forcing the sound (tables 5.11 and 5.15), which coincides with the quantitative data in section 5.3.3, as well. Interestingly, this is a strategy he said to have acquired with experience. In the room with missing sustainability the musician described his playing as „trenchant" („bissig"), which he further specified as including aspects of articulation, dynamics and timbre (table 5.10). In the room with great sound density, the cellist again mentioned a reduction of dynamic strength (table 5.12), which he assessed positively here in contrast to „holding back" the sound in the case mentioned above (table 5.10).

**Interaction of influential factors** To analyse the interactions between the various situational factors, the number of occurrences in which the interviews revealed a relation between two factors was counted (that is the white arrows in figures 5.20a-g) and is shown in table 5.17. When merely looking at the quantity of interactions between the pairs of elements, it must be born in mind that the interview questions directed specific attention on how the performance was affected by the audience, the personal form of the performer and the room acoustics. The counted influences are thus probably biased towards these factors. Nevertheless, the table illustrates a certain pattern of interactions.

| | Performance | Performance concept | Physical state | Emotional state | Atmosphere | Instrument | Room acoustics | Total effect |
|---|---|---|---|---|---|---|---|---|
| Room acoustics | 5 | 1 | | 4 | | | | 10 |
| Physical state | 1 | | | | | | | 1 |
| Emotional state | 1 | | 1 | | | | | 2 |
| Audience | | | | 4 | 1 | | 1 | 6 |
| Atmosphere | 1 | | | 1 | | | | 2 |
| Climatic conditions | | | 1 | | | 1 | 1 | 3 |
| Lighting | | | | | 2 | | | 2 |
| Room dimensions | | | | | 1 | | | 1 |
| Instrument | | | | 1 | | | | 1 |
| Programme | | | | 1 | | | | 1 |
| External factors | | | 1 | 3 | | | | 4 |
| Total affected | 8 | 1 | 3 | 14 | 4 | 1 | 2 | |

**Table 5.17.** – Number of times there was an interaction between elements of the performance model. Those elements that had an effect on others are shown in the rows, the ones that were affected are shown in the columns.

In five of the seven concerts there was a conscious adjustment of the performance to account for the room acoustical situation. The two concerts in which this was not the case were the one in which the mental and physical tension played a rather dominant role (table 5.14) as well as the one that followed directly after the development of a new performance concept which involved playing more independently of the room acoustics (table 5.9). The former was the only occasion where the performer reported to have been influenced in his playing by his physical condition. This was dictated by his emotional state, which was in turn determined by the compilation of the programme, so a longer chain of links can be observed here (figure 5.20e). A direct effect of the emotional constitution on the playing was described in a concert where the musician's emotions were primarily contingent on extreme external factors (table 5.15 and figure 5.20f). Furthermore, the performance was influenced by the atmosphere in a concert with great intimacy between performer and audience (table 5.12). The same concert situation is also a remarkable example for an acoustical surrounding that inspired the performer to adopt a new way of playing in the longer term.

It is noteworthy that this was not caused by exceptionally highly rated room acoustics but rather room acoustical conditions – great sound density and clarity – not experienced before.
The emotional state of the cellist was determined by many different aspects. In some cases, he was positively affected by certain factors (room acoustics, audience, atmosphere), in other cases they rather disappointed him (room acoustics, instrument). As the table shows, the external circumstances were also quite relevant for his emotional and physical form. Moreover, the climatic conditions became important in one instance because of a very high humidity and temperature, which not only affected the physical state of the musician, as observed by the author, but also the instrument and the room acoustics, as stated by the performer (table 5.10).
The audience is one of the situational factors of a performance that is often mentioned in literature and that was addressed directly in the interviews. As the performer stated, there is rarely a direct effect on his playing, but the table shows that there was a quite frequent relation between the audience and the emotional state. In one concert, the performer also noted a difference in the room acoustics when the hall was occupied by the audience in comparison with the empty room during the rehearsal (table 5.10). Perhaps not very surprisingly, the audience was also reported to have an effect on the atmosphere, just like the lighting and the room dimensions. The lighting conditions were mentioned in a few more instances, but without a particular influence on the other factors. Interestingly, the cellist remarked in the last interview that he usually paid little attention to the lighting, but had realised during the conversations how important it was for him in concerts.

## 5.5 Conclusions

The field study investigated the influence of room acoustical parameters on the performances of a renowned solo cellist under real-world concert conditions. Both the way of playing of the musician and the room acoustical properties of the investigated halls were measured and entered as variables into the statistical analysis. Regarding the room acoustics, a focus lay on determining the exact conditions the performer experienced during his performances, so the directivity of the instrument and the presence of the audience were restored in computer models of the concert spaces before conducting simulated room acoustical measurements.

Despite the many influential factors in a real-world performance situation, the statistical analysis presented in section 5.3 showed a clear and significant influence of the room acoustical environments on the performances of the cellist. A hierarchical linear model accounting for the effect of 4 room acoustical parameters on 8 performance characteristics of 36 music pieces played in 7 concert halls yielded an explained variance of than 52.55%. Thus, more than half of the variance in the performance characteristics can be explained by the room acoustical properties of the environments, whereas less than half of this variance may be attributed to other influencing factors, which were explored and discussed in section 5.4.

The analysis of the influence of the four room acoustical parameters on the performances of the cellist showed that all of them have a significant effect on at least one of the investigated aspects of music performance. This indicates that they all represent relevant aspects for the musician's perception of the room acoustical environments. Ordering the room acoustical predictors according to the extent of their effect suggested that the cellist mainly adjusted his performances to the reverberation time $RT_{\mathrm{vlc}}$ and the late support $ST_{\mathrm{late\ vlc}}$ of the concert halls. Aspects related to the reverberation as well as the „response from the room" were also mentioned by the musician most frequently when describing the room acoustics of the concert spaces in the interviews.

By comparing the explained variance of different HLMs it was shown that an inverse quadratic function is suitable to approximate the relation between the reverberation time of the rooms and the *tempo* played by the performer, confirming indications in a previous study. Beyond that, (inverse) quadratic functions were also found to predict the relation between other room acoustical parameters and performance characteristics. The influence of $RT^2_{\mathrm{vlc}}$ on *tempo* was examined separately for the different basic tempi of the played pieces, which revealed that the cellist only played the fast movements significantly slower in rooms with long and short reverberation time. The former effect is in line with recommendations made by J. J. Quantz (see section 2.3), who suggested to avoid playing fast pieces in large halls because the tones are blurred by the reverberation. In some of the other music treatises cited in section 2.3 it was clearly advocated to avoid forcing the tone, especially of string instruments, in rooms with short $RT$. While the contrary adjustment strategy was observed in previous studies (negative correlation of dynamic strength and reverberation time), the cellist in this field study indeed consciously reduced his *dynamic strength* in rooms with short $RT_{\mathrm{vlc}}$. Moreover, he also consciously played more piano in rooms with long reverberation time (inverse quadratic function predicting the relation between $RT_{\mathrm{vlc}}$ and *dynamic strength*), which is in turn in line with the previous studies. Interestingly, the strongest effects in the statistical analysis can be observed for the influence of the reverberation time and late support on two of the investigated timbre characteristics of the performances, *timbre (soft – hard)* and *timbre (dark – bright)*. These attributes may also be related to articulation, even though this aspect of performance was not examined directly. Adjustments of the tonal rendition were barely investigated in previous studies, where these results show the necessity to take this aspect into account.

Context-sensitive conditions of a musical performance are usually mentioned in one breath in literature and without referring to any interrelation between the different possible factors of influence. Based on the guided interviews conducted with the performer in this field study, it is possible to differentiate between the factors more clearly and study their effect on each other and especially on the way of playing.

The cellist reported an effect of the room acoustics on his way of playing in most concerts and many of his statements correspond to the results of the statistical analysis. Apparently, there were also unconscious adjustments, though, since he did not mention all the influences of room acoustical conditions that were reported in section 5.3. Furthermore, some of the cellist's descriptions cannot be unequivocally assigned to the quantitative data due to his distinct

vocabulary used to describe the music performances and room acoustics. This was mentioned in section 3.2 as a general challenge when conducting surveys with musicians that involve the verbalisation of room acoustical conditions. As emerged from some of the interview statements, the conscious adjustment of performances can be based on specific strategies to deal with certain room acoustical surroundings, thus forming one aspect of the performance concept described in section 2.2. There was a particularly interesting case of a room acoustical surrounding that inspired the cellist to a new way of playing because of its extraordinary „clarity" and „density" and changed his performance concept of the cello suites by Bach in the longer term.
Apart from the room acoustical environment, in concerts with unusual conditions (e.g. extreme climatic conditions, unfavourable external circumstances) these exceptional variables became dominant and, in one case, influenced the cellist's performance or, more often, his personal form. Interestingly, it is his emotional state that was affected most often by other situational variables, possibly because the emotional involvement in music performance makes this aspect of personal form particularly exposed to external influences. A factor affecting the cellist's emotional state rather often was the audience, which points out that the social interaction in music performance is essential even in Western classical music tradition, where the active involvement of the listeners is usually restricted to the final applause. Nevertheless it is noteworthy that the musician in this field study remarked that generally the audience has no influence on the performance itself.

The question if the findings reported here hold for other performance situations and whether they are mainly due to he specific instrument or rather the individual performer cannot be answered on the basis of the data of the field study. This gap is filled by the laboratory study presented in chapter 6, where the relations between room acoustical parameters and performance characteristics were investigated with different performers, different instruments and a varying musical repertoire.

# 6

# LABORATORY STUDY

The laboratory study of this thesis was conducted with twelve professional solo players of six orchestral instruments in a fully anechoic chamber. The musicians were invited to play two pieces of their choice with differing musical characteristics in concert halls that were simulated with dynamic binaural synthesis. Recordings of the performances were used for the real-time interactive simulations and for later analysis to determine performance qualities and characterise the musicians' way of playing in the rooms. Furthermore, the performers rated the concert spaces regarding different room acoustical aspects in questionnaires and short guided interviews were held with them. A qualitative content analysis of these interviews revealed distinct strategies for dealing with the encountered room acoustical conditions. The binaural simulations were based on computer models of typical concert spaces and these models were also used to determine room acoustical parameters. In both cases, directional sources representing the played instruments were used in order to simulate the room acoustical conditions experienced by performers as precisely as possible. As in the field study, a statistical analysis was employed to gain insight into the effect of certain room acoustical measures on music performance. Furthermore, the effect of instruments and musicians was explored.

In the following sections these points are elaborated, the results of the study are presented and the chapter is concluded with a discussion of the findings.

## 6.1 Performances

So far, few studies have taken into account more than one solo instrument when investigating the influence of room acoustics on music performance. However, the played instrument is likely to have an effect on the way musicians adjust their performance to room acoustical environment. Thus, six standard orchestral instruments were included in the current experiment, covering different registers of strings, woodwind and brass: violin, cello, clarinet, bassoon, trumpet and trombone. Two professional performers of each of these instruments were asked to play excerpts of about 1 min of two pieces of their choice with calm and lively characters, respectively. Additionally, the played pieces were required to vary in dynamics, articulation and range and to be well known to the performers. As explained in section 4.1, the pieces were classified into ‚slow' and ‚fast' a categorization that was meant to enable a comparison between pieces of different tempo, even though the musicians did not play exactly the same music. This approach was favoured over the option to have all performers play the same piece (as done by Ueno et al., 2010), which was considered to be too far from reality and would have inevitably reduced the technical level of the performances. Table 6.1 shows the compositions and excerpts played by the performers.

In contrast to the field study, the recording microphone could be mounted directly on the instrument in the laboratory experiment, so a Sennheiser MKE 1 miniature microphone on a flexible mounting was attached to each instrument, as shown in figure 6.2. In this way, a constant distance between the microphone and the instruments was ensured and sound level fluctuations caused by instrument movements were prevented. The recordings were used as input signal for the binaural simulation of the room models (see section 6.3) and stored for later analysis. The instrumental directivities of the sources used in the room models are defined as level differences with respect to a reference orientation. Thus, this orientation was followed when recording the input signal – even though the directivities of the instruments apply to the far field – to ensure a consistent frequency-dependent directional characteristic of the input and output signal in

| Instrument | Piece | Composer | Bars | Tempo |
|---|---|---|---|---|
| Violin 1 | Concert for violin No. 5 KV 219, 1st movement | W. A. Mozart | 46-88 | fast |
| | Concert for violin op. 35, 1st movement | P. I. Tchaikovsky | 23-50 | slow |
| Violin 2 | Sonata for violin solo No. 6 op. 27, 1st movement | E. Ysaye | 1-40 | fast |
| | Sonata for violin solo BWV 1005 | J. S. Bach | 1-8 | slow |
| Cello 1 | Suite No. 5 for violoncello solo BWV 1011, gigue | J. S. Bach | 1-72 | fast |
| | Suite No. 5 for violoncello solo BWV 1011, sarabande | J. S. Bach | 1-20 | slow |
| Cello 2 | Suite No. 1 for violoncello solo BWV 1007, prélude | J. S. Bach | 1-22 | fast |
| | Suite No. 1 for Violoncello solo BWV 1007, sarabande | J. S. Bach | 1-15 | slow |
| Clarinet 1 | Sonata for clarinet and piano, 3rd movement | F. Poulenc | 1-33 | fast |
| | Concert for clarinet (Darmstädter), 1st movement | K. Stamitz | 1-20 | slow |
| Clarinet 2 | Three pieces for clarinet solo, 2nd movement | I. Stravinsky | 1-14 | fast |
| | Three pieces for clarinet solo, 1st movement | I. Stravinsky | 1-19 | slow |
| Bassoon 1 | Concert for bassoon KV 191, 1st movement | W. A. Mozart | 35-71 | fast |
| | Concert for bassoon KV 191, 2nd movement | W. A. Mozart | 1-18 | slow |
| Bassoon 2 | Fantasia No. 8 for bassoon solo | B. de Selma | 1-31 | fast |
| | Fantasia No. 7 for violin solo, 1st movement | G. Ph. Telemann | 1-11 | slow |
| Trumpet 1 | Suite No. 1 for violoncello solo BWV 1007, gigue | J. S. Bach | 1-20 | fast |
| | Suite No. 2 for violoncello solo BWV 1008, sarabande | J. S. Bach | 1-20 | slow |
| Trumpet 2 | Trumpet voluntary | J. Clarke | 9-16/25-32/41-56 | fast |
| | Pavane op. 5 | G. Fauré | 1-16 | slow |
| Trombone 1 | Morceau Symphonique op. 88 | A. Guilmant | 43-80 | fast |
| | Romance | C. M. von Weber | 30-58 | slow |
| Trombone 1 | Concertino Petite | J. Cimera | 6-24 | fast |
| | Vocalise #1 | M. Bordogni | 4-28 | slow |

**Table 6.1.** – Pieces chosen and excerpts played by the musicians in the laboratory experiment.

the simulation. Since the experiment took place in a fully anechoic chamber, the recordings were free of room acoustical influence.
The 336 recorded audio signals with an average number of 171 notes and 24 bars had an average length of 67 s (see table A.2, appendix A). This data was used for the audio feature extraction and computation of performance characteristics described in section 4.3.

## 6.2 Room acoustics

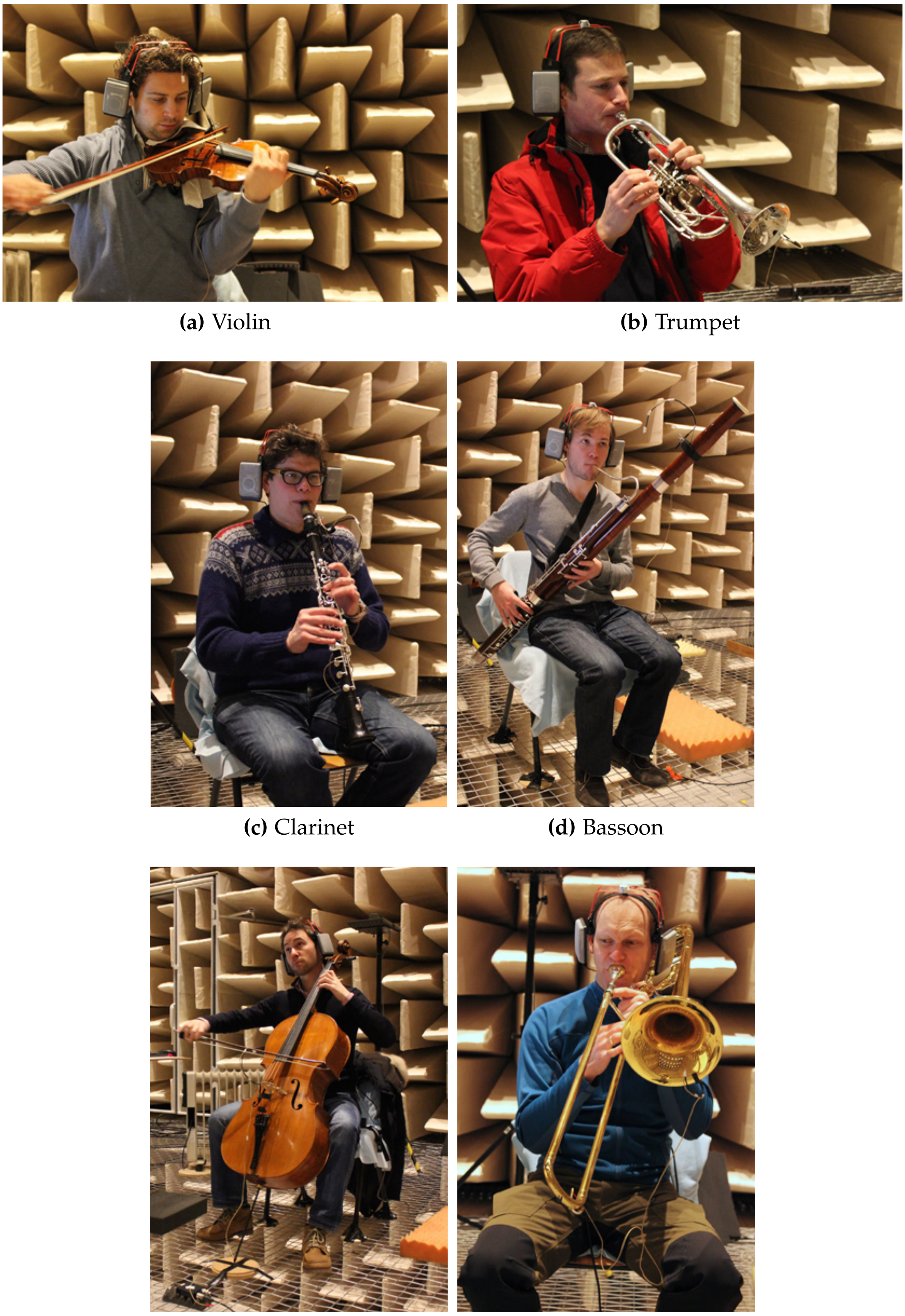
### 6.2.1 Room acoustical models

The concert halls simulated in the laboratory experiment were based on computer models generated with EASE 4.3, as explained in section 4.2. In order to simulate typical concert spaces covering a broad range of room acoustical properties, appropriate halls were chosen as prototypes for the computer models. For this purpose, measurement data of $EDT$, $RT$, $C_{80}$ and $G$ of 36 European performance spaces (Beranek, 2004; Hidaka & Nishihara, 2004) was evaluated. Even though available for some rooms, the stage parameter $ST_{\text{early}}$ could not be considered because there were too many missing values.

| | $RT$ | $EDT$ | $C_{80}$ | $G$ |
|---|---|---|---|---|
| $RT$ | 1 | | | |
| $EDT$ | 0.86** | 1 | | |
| $C_{80}$ | -0.87** | -0.85** | 1 | |
| $G$ | 0.29 | 0.07 | -0.32* | 1 |

**Table 6.2.** – Pearson correlations between the frequency-averaged room acoustical parameters of 36 European concert halls (Beranek, 2004; Hidaka & Nishihara, 2004). * $p < 0.05$ (two-tailed); ** $p < 0.01$ (two-tailed)

To reveal categories of typical performance spaces, a cluster analysis was performed with the parameters. In view of the high correlations between the variables (see table 6.2), a method recommended by Bortz (2005, p. 569) was followed: First, a principle component analysis (PCA) with varimax rotation was performed with all the parameters and then only the two meaningfully interpretable components (see table 6.3) were used as variables in the cluster analysis

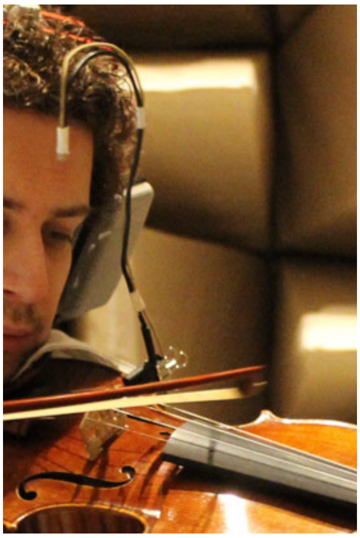


(a) Violin (b) Trumpet

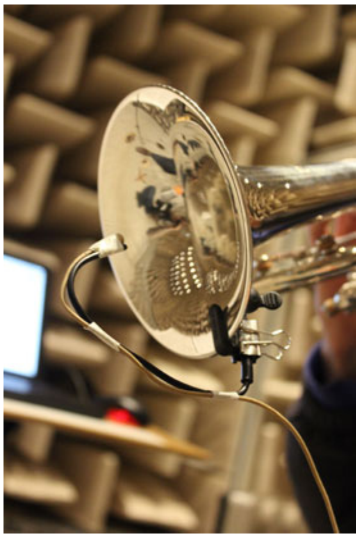
(c) Clarinet (d) Bassoon

(e) Cello (f) Trombone

**Figure 6.1.** – Musicians playing their instrument in the experimental setup.

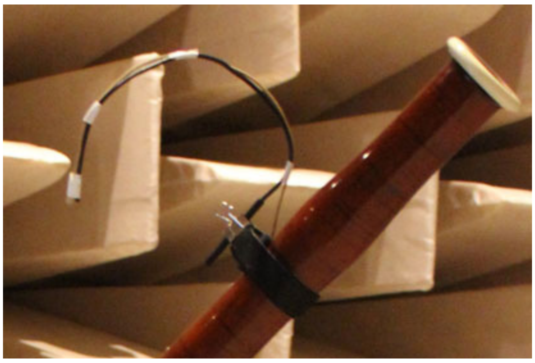


(a) Violin



(b) Trumpet

(c) Clarinet



(d) Bassoon

(e) Cello

(f) Trombone

**Figure 6.2.** – Recording microphone (Sennheiser MKE 1) attached to the instruments played in the experiment.

| | Components | |
|---|---|---|
| Parameters | 1 | 2 |
| $RT$ | **0.965** | -0.046 |
| $EDT$ | **0.953** | 0.209 |
| $C_{80}$ | **-0.904** | -0.231 |
| $G$ | 0.103 | **0.992** |
| Expl. var. [%] | 66.72 | 27.08 |

**Table 6.3.** – Loadings and explained variance for components resulting from a PCA with varimax rotation conducted with 4 room acoustical parameters measured in 36 European concert halls. Factor loadings $> |0.5|$ are marked bold.

using Euclidean distances and the average linkage fusion criterion. Figure 6.3 shows a strong increase of the linkage distance $\Delta d$ between the generation of four and five clusters, so a number of five clusters was considered as appropriate. A non-hierarchical cluster analysis with Euclidean distances using the k-means method was employed, whereby the initial cluster centroid positions were determined with a hierarchical analysis (Euclidean distances, average linkage). The result of this analysis and the rooms selected as prototypes from each cluster are depicted in figure 6.4. Thus, the simulated rooms included an opera (no. 22), a non-reverberant chamber hall (no. 8), a reverberant chamber hall (no. 31), a shoebox-shaped concert hall with high sound strength (no. 5) and a vineyard-type concert hall with low sound strength (no. 26). As a further typical performance space for Western classical music, a baroque church was simulated, using the St. Stephen's cathedral in Passau as prototype for the computer model.

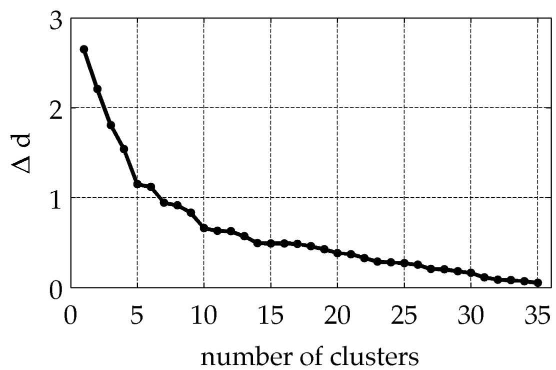
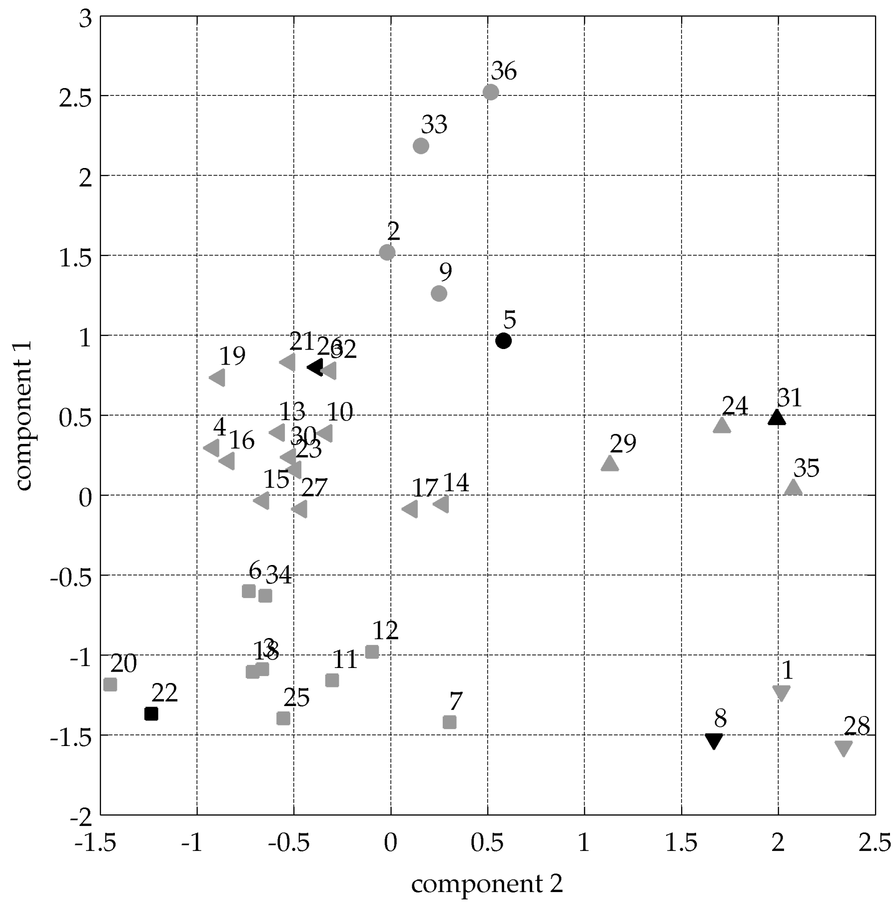



**Figure 6.3.** – Linkage distance $\Delta d$ for different numbers of clusters resulting from a cluster analysis (Euclidean distances, average linkage) with the two PCA components shown in table 6.3.




| | |
|---|---|
| 1 -Concertgebouw, Chamber Hall, Amsterdam | 19 -Philharmonie am Gasteig, Munich |
| 2 -Concertgebouw, Main Hall, Amsterdam | 20 -Teatro alla Scala, Milan |
| 3 -Music Theater, Amsterdam | 21 -Koncerthus Nielsen Hall, Odense |
| 4 -Festspielhaus, Baden-Baden | 22 -Opera Garnier, Paris |
| 5 -Stadtcasiono, Basel | 23 -Salle Pleyel, Paris |
| 6 -Deutsche Oper, Berlin | 24 -Martine Hall, Prague |
| 7 -Komische Oper, Berlin | 25 -State Opera, Prague |
| 8 -Konzerthaus, Chamber Hall, Berlin | 26 -De Doelen Concertgewouw, Rotterdam |
| 9 -Konzerthaus, Main Hall, Berlin | 27 -Festspielhaus, Salzburg |
| 10 -Philharmonie, Main Hall, Berlin | 28 -Mozarteum, Wiener Saal, Salzburg |
| 11 -Erkel Theatre, Budapest | 29 -Mozarteum, Main Hall, Salzburg |
| 12 -Staatsoper, Budapest | 30 -Liederhalle, Main Hall, Stuttgart |
| 13 -St. David's Hall, Cardiff | 31 -Brahmssaal, Vienna |
| 14 -Radiohuset Studio 1, Copenhagen | 32 -Konzerthaus, Main Hall, Vienna |
| 15 -Semper Oper, Dresden | 33 -Musikvereinssaal, Main Hall, Vienna |
| 16 -Royal Concert Hall, Glasgow | 34 -Staatsoper, Vienna |
| 17 -Konserthus, Goeteborg | 35 -Tonhalle, Chamber Hall, Zurich |
| 18 -Staatsoper, Hamburg | 36 -Tonhalle, Main Hall, Zurich |

**Figure 6.4.** – Five clusters (denoted by ■, ▼, ▲, ◀) resulting from a non-hierarchical cluster analysis with the k-means method and Euclidean distances. The halls chosen as prototypes for the computer models generated for the laboratory experiment are marked black.

To increase the number of rooms and the room acoustical diversity, the models of the reverberant chamber hall, the vineyard-type concert hall and the church were used in two versions with different absorption properties, that is frequency dependent reverberation times. Furthermore, four room models of the field study (ANC, GGA, TJV, WMH) as well as the model of a historical concert space, the Eroica hall (Palais Lobkowitz) in Vienna (Weinzierl, 2002), were included. Table 6.4 lists the purpose and dimensions, figure 6.5 shows the models of the 14 halls used for the room acoustical simulations in the laboratory experiment.
The computer models were generated on the basis of floor plans (Beranek, 2004; Hidaka & Nishihara, 2004) and existing models (Weinzierl, 2002; section 5.2.3). The absorption coefficients for the side walls of the models were treated as residual absorption, while reasonable materials were assigned to the other surfaces and provided with typical absorption properties (Beranek, 2004; Egan, 1988; Fasold et al., 1987; Long, 2006; Moore, 1978; Templeton, 1997). Instead of using the same scattering properties for the materials as in the field study (shown in figure 5.8), a frequency-independent default value was used here (the simulation parameters used for each room are given in appendix B.2), since the room models were also used for auralisations, which by experience sounded more natural in this way (see also Schneider, 2011).

| **Abbr.** | **Purpose** | $V$ **[m$^3$]** | $A_{\text{stage}}$ **[m$^2$]** |
|---|---|---|---|
| CHA1 | Chamber hall | 2300 | 56 |
| CHA2 a/b | Chamber hall | 3200 | 85 |
| CHU a/b | Baroque church | 12500 | 55 |
| CON1 a/b | Concert hall | 21700 | 109 |
| CON2 | Concert hall | 10300 | 186 |
| OPR | Opera | 14900 | 97 |
| ANC | Chamber hall | 5700 | 83 |
| GGA | Concert hall | 12600 | 108 |
| PLE | Historical concert hall | 900 | 29 |
| TJV | Theatre | 11200 | 67 |
| WMH | Chamber hall | 2800 | 32 |

**Table 6.4.** – Abbreviation, purpose, volume and stage area of the simulated concert spaces. The affix „a/b“ denotes the halls generated with two different versions of absorption properties.

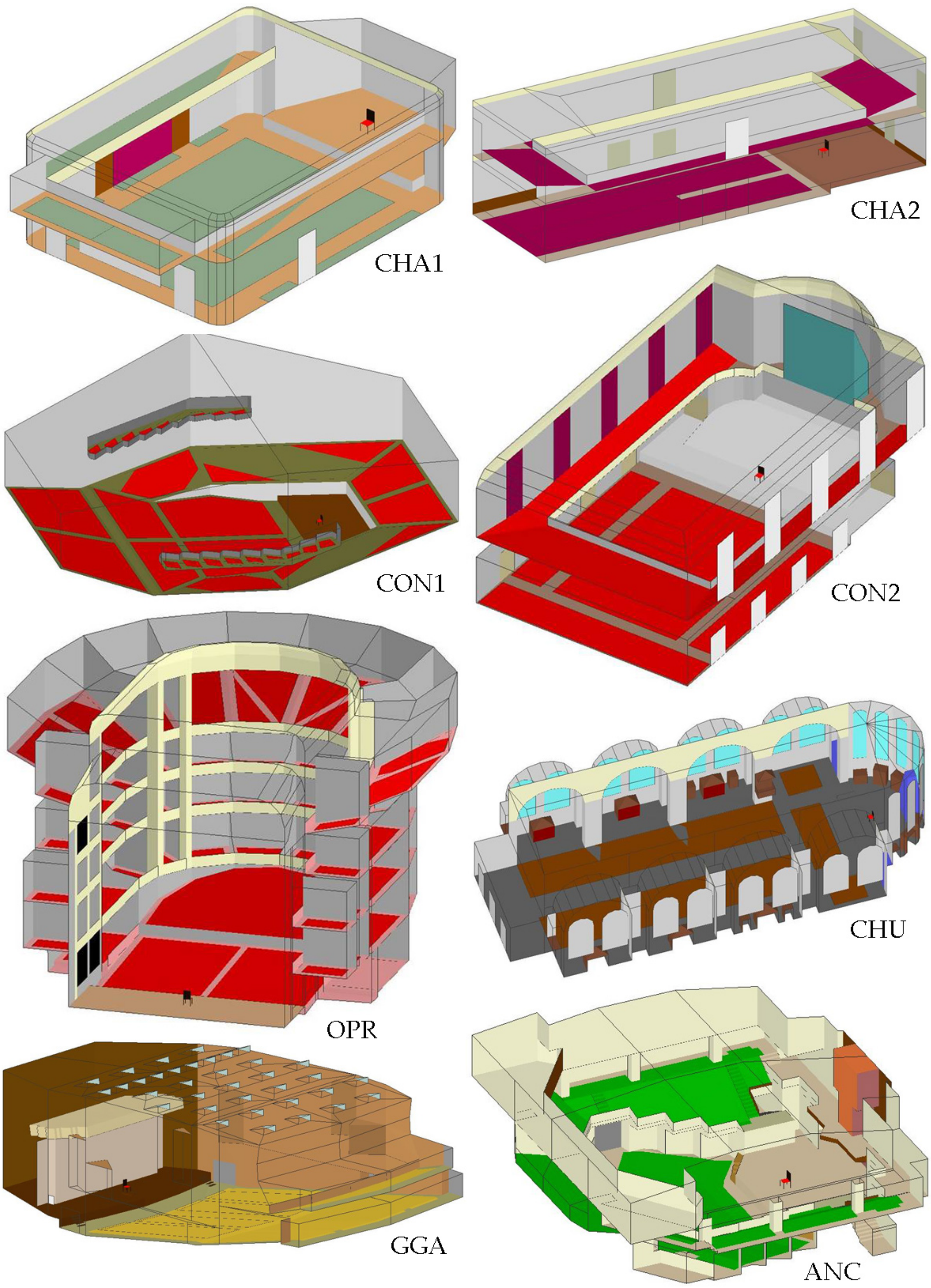



**Figure 6.5.** – Room models of the laboratory study (not to scale)

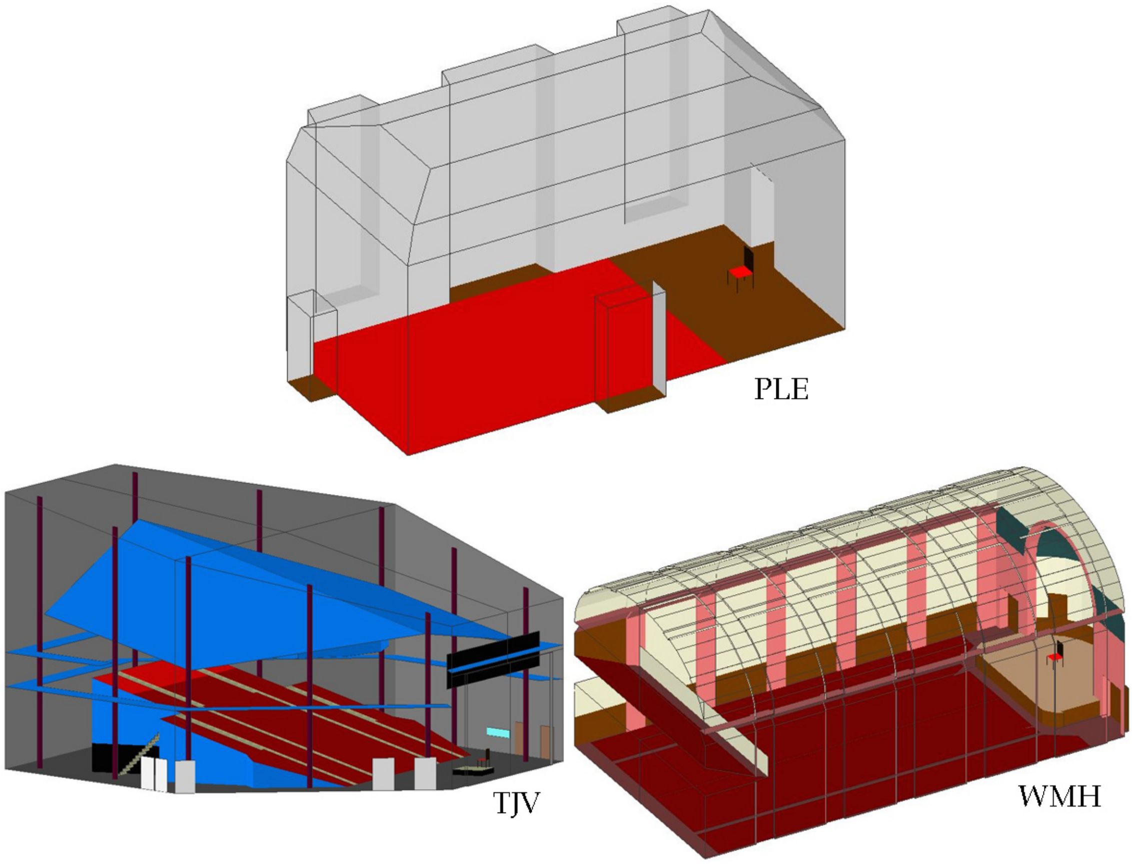



**Figure 6.5.** – (Continued) Room models of the laboratory study (not to scale)

### 6.2.2 Room acoustical measurements

For an overview of the room acoustical conditions the musicians encountered during the experiment, simulated measurements were carried out in the room models with the simulation parameters shown in appendix B.2. The omnidirectional source and the receiver were 1 m apart, both at a height of 1 m, located in the centre of each stage with the source placed 1.5 m from the stage edge. The parameters measured with this source-receiver setup are denoted by the subscript *solo* in the following to discriminate them from spatially averaged parameters determined with a greater source-receiver distance. In each model, the following room acoustical parameters were calculated in octave bands with EASERA 1.2 and Matlab R2012a: $EDT_{\mathrm{solo}}$, $RT_{\mathrm{solo}}$, $C_{80\ \mathrm{solo}}$, $G_{\mathrm{solo}}$, $ST_{\mathrm{early\ solo}}$, $ST_{\mathrm{late\ solo}}$, $G_{\mathrm{e\ solo}}$ , $G_{\mathrm{l\ solo}}$, $BR_{\mathrm{solo}}$ and $G_{125\ \mathrm{solo}}$ (see sections 3.2 and 4.1). Figure 6.6 (solid lines) shows these room acoustical measures frequency averaged according to ISO 3382-1 (2009). The only parameters that show little variation are $G_{\mathrm{solo}}$, $G_{\mathrm{e\ solo}}$ and $G_{125\ \mathrm{solo}}$, due to the dominance of the direct sound in the measurements at this short distance between source and receiver. The correlations between the frequency-averaged parameters are given in table 6.5.

For the statistical analysis of the relationship between room acoustical conditions and music performance, the room acoustical parameters were determined with directional sources representing the played instruments (section 4.1). For these measurements, the receiver was defined in the centre of each stage, 2.5 m behind the stage edge and at a height of 1.2 m, which was assumed as the typical ear height of a seated person. The positions of the directional sources in relation to the receiver point were established by estimating the typical distance between the acoustical centre of the respective instrument and the performers' ears (see table 4.3). In the following, the room acoustical parameters determined with these source-receiver configurations are denoted by a subscript referring to the respective instrument if a specific source directivity is meant and by the subscript *ins* if a general reference is made to a parameter measured with a directional source. Figure 6.6 shows the frequency-averaged room acoustical parameters of each room model and instrument.

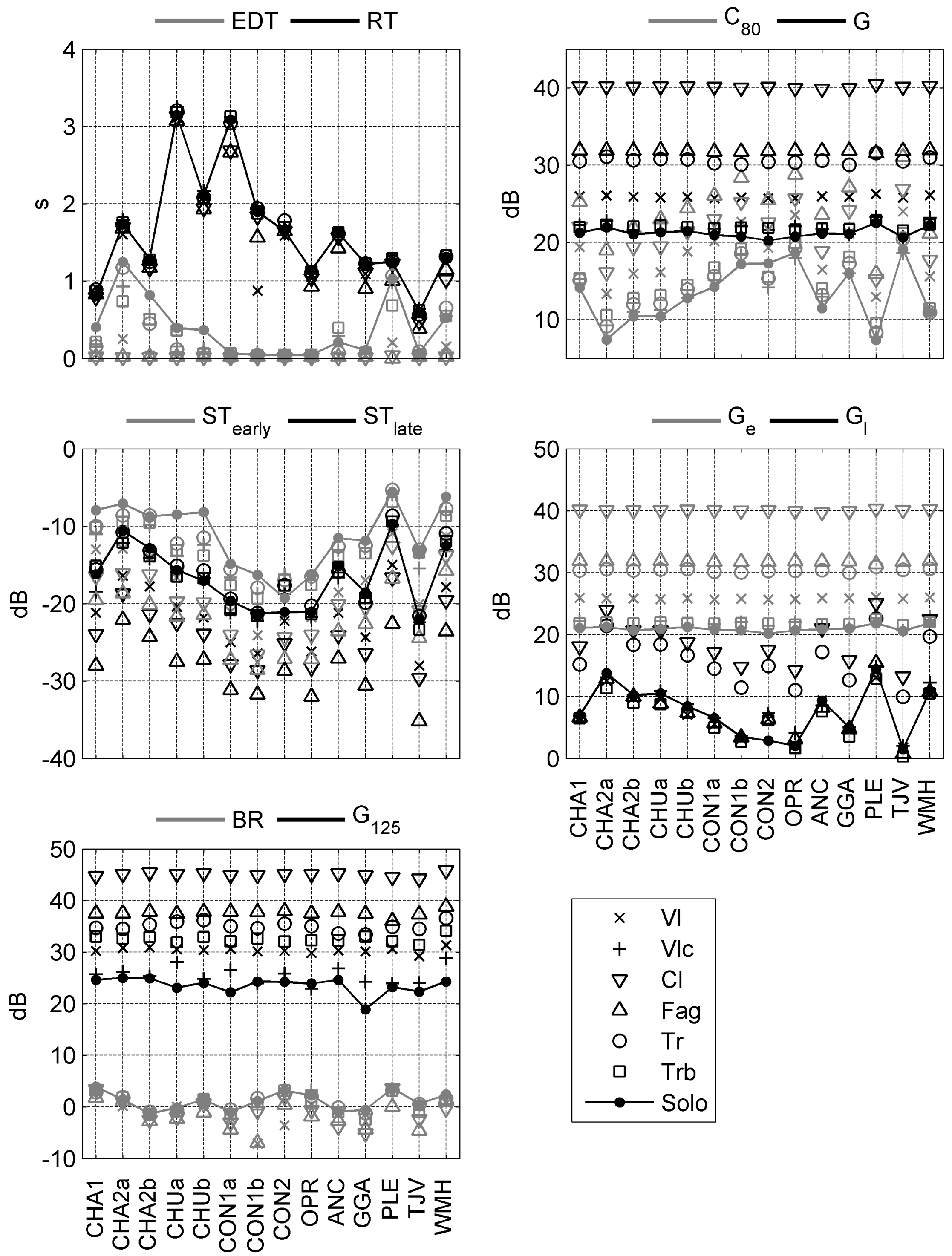



**Figure 6.6.** – Frequency-averaged room acoustical parameters (gray and black) measured on the stages of the room models using an omni-directional source (solid line) as well as sources with the directivity of the investigated instruments.

| | $EDT_{solo}$ | $RT_{solo}$ | $C_{80\ solo}$ | $G_{solo}$ | $ST_{early\ solo}$ | $ST_{late\ solo}$ | $G_{e\ solo}$ | $G_{l\ solo}$ | $BR_{solo}$ | $G_{125\ solo}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| $EDT_{solo}$ | 1 | | | | | | | | | |
| $RT_{solo}$ | -0.08 | 1 | | | | | | | | |
| $C_{80\ solo}$ | -0.88** | -0.24 | 1 | | | | | | | |
| $G_{solo}$ | 0.78** | -0.02 | -0.83** | 1 | | | | | | |
| $ST_{early\ solo}$ | 0.78** | -0.08 | -0.82** | 0.87** | 1 | | | | | |
| $ST_{late\ solo}$ | 0.92** | -0.03 | -0.96** | 0.88** | 0.87** | 1 | | | | |
| $G_{e\ solo}$ | 0.61* | -0.08 | -0.67** | 0.96** | 0.83** | 0.75** | 1 | | | |
| $G_{l\ solo}$ | 0.88** | 0.21 | -0.99** | 0.87** | 0.84** | 0.97** | 0.73** | 1 | | |
| $BR_{solo}$ | 0.18 | -0.40 | 0.02 | 0.27 | 0.11 | 0.11 | 0.32 | 0.02 | 1 | |
| $G_{125\ solo}$ | 0.37 | -0.03 | -0.32 | 0.12 | 0.15 | 0.32 | 0.02 | 0.29 | 0.32 | 1 |

**Table 6.5.** – Pearson correlations between the frequency-averaged room acoustical parameters measured on the stages of the computer models with 1 m distance between omni-directional source and receiver, both at 1 m height. * $p < 0.05$ (two-tailed); ** $p < 0.01$ (two-tailed)

## 6.3 Technical setup and experimental procedure

The experiment took place in the fully anechoic chamber of the Technical University of Berlin ($V = 1850\,\mathrm{m}^3$, $f_c = 63\,\mathrm{Hz}$) with 12 professional solo performers (10 males, 2 females) aged between 21 and 48 years (average: 32 years). They had between 5 and 30 years of experience in performing on concert hall stages (average: 20 years) and were thus acquainted with varying room acoustical conditions.

As explained in section 4.2.3, binaural room impulse responses were acquired from the computer room models described above for their auralisation. Since the musicians actively participated in the simulation by producing the sound to be recorded and used for the simulation, only the response of the room was simulated and not the direct signal of the instruments (see figure 6.7) A head-tracker (Polhemus Patriot) registered the musician's head movements and determined the appropriate binaural room impulse response which was convolved with the anechoic input signal in real-time. The latency between the input of the audio interface and the output of the convolution computer (see figure 6.7) was approximately 25 ms. This appears as a high value when compared to the delay of

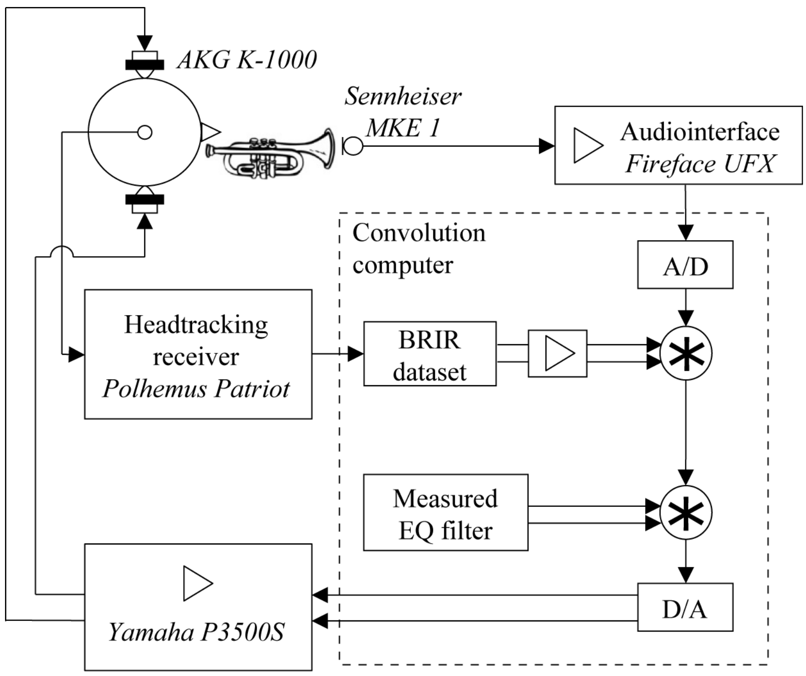



**Figure 6.7.** – Technical setup of the laboratory experiment.

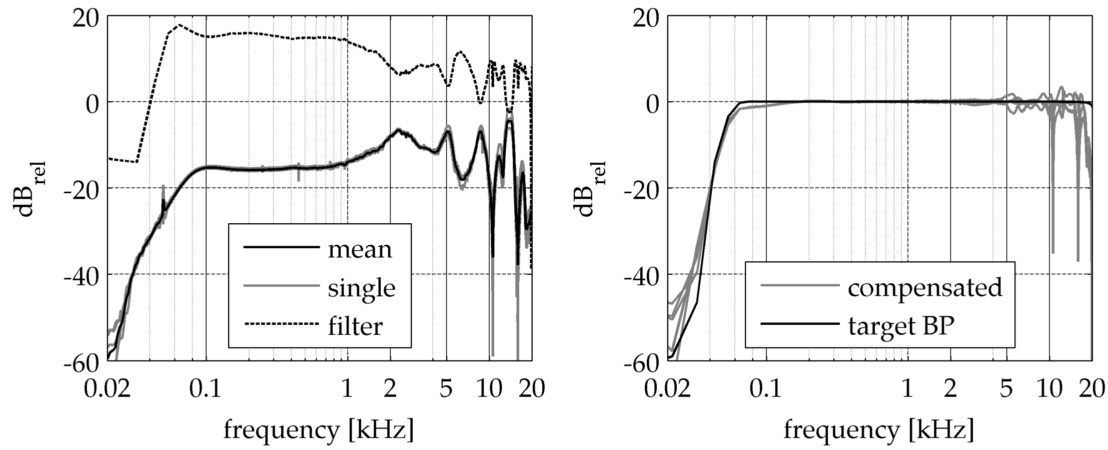



**Figure 6.8.** – Left: Example of a headphone transfer function measurement (left ear) conducted with the participants of the experiment. The grey solid lines show five single measurements with re-placement of the headphones in between. The black solid line is the average of the single measurements, the black dotted line shows the compensation filter used for equalisation. Right: Equalisation result using the measurements and filter shown on the left. The grey lines show the compensated single measurements, the black line shows the bandpass used as target function for the equalisation.

the first (floor) reflection (6 ms for approximately 2 m runtime), which marked the starting point of the simulated room response. However, the latency was not perceived as perceptually disturbing and it was furthermore constant for all rooms in the experiment. The convolution result was presented to the performers with headphones (AKG K-1000) that almost perfectly met the requirement of free air equivalent coupling (Møller, 1992) and barely impeded the path of the instrument's direct sound to the performer's ears. The frequency responses of the recording microphone and the headphones were compensated, whereby the latter were equalised with filters calculated from individually measured headphone transfer functions (Schärer & Lindau, 2009; Lindau & Brinkmann, 2012). The performers attended the experiment in two sessions with seven rooms each. Before the actual experiment, the measurement of the individual headphone transfer function needed for the headphone compensation was carried out. This was done by placing the headphones on the performer's head five times with an individual measurement each time. The compensation filter was then calculated from the average of the multiple measurements by employing the least squares equalisation method with high-pass shelve regularisation. An example for five measurements, the corresponding filter and the compensation result can be seen in figure 6.8.

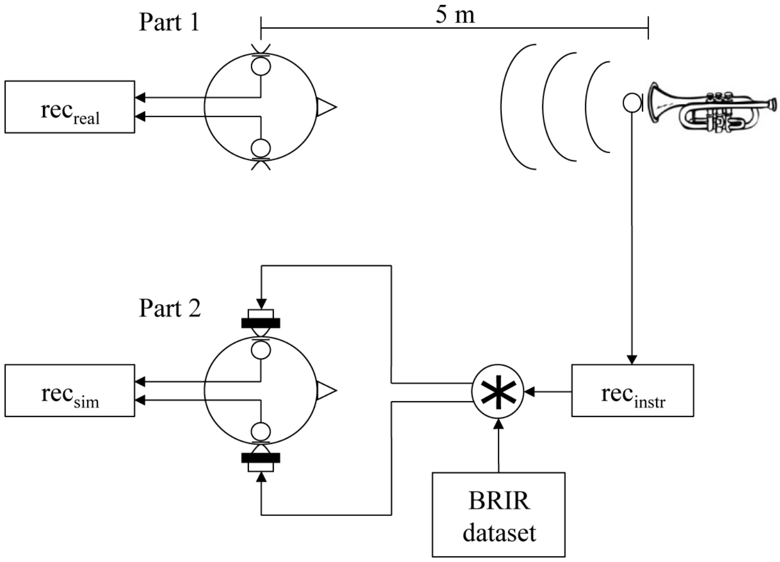



**Figure 6.9.** – Technical setup of the sound level calibration. Part 1 shows the recording of a sound event from the instrument with a dummy head at 5 m and with a microphone attached to the instrument. Part 2 shows the dummy head recording of the sound event in a simulated anechoic environment played back through head phones on the dummy head.

A sound level calibration of the simulation was performed because although the level between the individual rooms was correct due to an identical sound power of the sources in all computer models, the level of the simulations relative to the direct sound needed to be determined. For this purpose, a single sound event of each instrument was recorded with both the instrument microphone and a dummy head (Neumann KU 81i) located at 5 m distance from the musician (part 1 in figure 6.9). Then, the headphones were placed on the dummy head and the sound event previously recorded at the instrument (rec$_{instr}$ in figure 6.9) was played through a binaural simulation of an anechoic chamber – that is an auralised EASE computer model – with a directional source corresponding to the involved instrument and a receiver at a distance of 5 m. This simulation was again recorded with the dummy head (part 2 in figure 6.9) and the RMS level difference of both dummy head recordings (rec$_{sim}$ and rec$_{real}$ in figure 6.9) yielded a scaling factor for the binaural simulations of the concert halls.

Prior to the recording session in the experiment, the performers were given 10 minutes to become familiar with each virtual room. Then, they were recorded playing excerpts of two music pieces (see table 6.1). After the recording, the players rated the previously encountered concert hall regarding 20 perceptual room acoustical attributes (see appendix C.2). These were the result of a qualitative study conducted with solo performers to elicit an appropriate terminology describing the perception of room acoustics by musicians (Stahnke, 2013). Furthermore, the participants of the laboratory experiment were interviewed about their way of playing and their impression of the room acoustics (see section 6.5). The warm-up, recording, rating and interview were repeated in each of the randomly presented virtual rooms. One experimental session lasted between three and four hours with a longer break in the middle of a session and additional pauses whenever necessary.

## 6.4 Statistical analysis

The statistical analysis of the experiment was to reveal the effect of ten room acoustical parameters – measured individually with the source-directivity of six instruments – on eight performance qualities determined from recordings of twelve musicians playing two pieces each. For this purpose, a multivariate hierarchical linear model was employed.

### 6.4.1 Predictor variables

In the HLM, the room acoustical parameters measured with directional sources were to be used as predictors. However, as shown in table 6.5 for the room acoustical parameters measured with an omni-directional source, there are high correlations between several of the measures. In order to avoid multicollinearity, the number of predictors needed to be reduced, so a principle component analyses was performed with the room acoustical parameters measured for each source directivity, respectively. The criterion for the number of components to be extracted was set to a minimum of 95 % cumulative proportion of explained variance. After varimax rotation all six PCAs yielded five components explaining between 97.26 % (clarinet) and 98.70 % (cello) of the acoustical variance measured in the modelled concert spaces. In contrast to the field study, the

| | Components | | | | |
|---|---|---|---|---|---|
| Parameters | 1 | 2 | 3 | 4 | 5 |
| $ST_{\text{late vlc}}$ | **0.96** | 0.22 | 0.00 | 0.15 | 0.07 |
| $C_{80\text{ vlc}}$ | **-0.94** | -0.18 | -0.19 | -0.22 | -0.06 |
| $ST_{\text{early vlc}}$ | **0.90** | 0.18 | -0.30 | 0.12 | 0.02 |
| $G_{\text{l vlc}}$ | **0.90** | 0.30 | 0.19 | 0.22 | 0.09 |
| $EDT_{\text{vlc}}$ | **0.89** | 0.34 | -0.16 | -0.11 | -0.04 |
| $G_{\text{e vlc}}$ | 0.33 | **0.89** | 0.10 | 0.16 | 0.25 |
| $G_{\text{vlc}}$ | 0.50 | **0.81** | 0.11 | 0.13 | 0.24 |
| $RT_{\text{vlc}}$ | -0.05 | 0.12 | **0.94** | 0.21 | -0.20 |
| $G_{125\text{ vlc}}$ | 0.23 | 0.17 | 0.22 | **0.92** | -0.13 |
| $BR_{\text{vlc}}$ | 0.05 | 0.37 | -0.24 | -0.15 | **0.88** |
| Expl. var. [%] | 46.32 | 19.52 | 12.13 | 11.04 | 9.69 |

**Table 6.6.** – Loadings and explained variance for components resulting from a PCA with varimax rotation conducted with 10 room acoustical parameters measured with the source directivity of a cello. Factor loadings $> |0.5|$ are marked bold, highest loadings are underlined.

parameters $G_{125\text{ ins}}$ and $BR_{\text{ins}}$ interestingly loaded on two separate components here. Table 6.6 shows the loadings on the five components for the PCA carried out with the parameters for cello directivity. The component structures resulting from the PCAs for the other instruments (except the violin) were highly similar and are shown in appendix B.3, tables B.3 to B.7.

Following the same procedure as in the field study, two different sets of predictors were chosen for two HLMs on the basis of the PCAs: On the one hand, the components of the PCAs were used as predictors for a hierarchical model denoted as $\text{HLM}_{\text{comp}}$. The five components were interpreted as *late energy*, *early energy*, *duration of reverberation*, *bass strength* and *bass ratio*. On the other hand the room acoustical parameters with the highest loading on each of the five components were selected as predictors for a hierarchical model named $\text{HLM}_{\text{par}}$: $ST_{\text{late ins}}$, $G_{\text{e ins}}$, $RT_{\text{ins}}$, $BR_{\text{ins}}$ and $G_{125\text{ ins}}$. In the case of the first component, some of the PCAs yielded $C_{80\text{ ins}}$ or $EDT_{\text{ins}}$ as the highest loading variable. Because of the high correlation between $ST_{\text{late ins}}$ and these measures (see table 6.5), $ST_{\text{late ins}}$ was selected for all instruments, which also enabled a better comparison with the field study. Hence, the ten possible room acoustical predictors were reduced to two sets of five salient predictors each that were entered as explanatory variables into two multilevel analyses ($\text{HLM}_{\text{comp}}$ and $\text{HLM}_{\text{par}}$).

| Response Variables | Predictors | | | | |
|---|---|---|---|---|---|
| | $RT_{\mathrm{ins}}$ | $ST_{\mathrm{late\ ins}}$ | $G_{\mathrm{e\ ins}}$ | $BR_{\mathrm{ins}}$ | $G_{125\ \mathrm{ins}}$ |
| *Tempo* | lin | lin | lin | lin | lin |
| *Agogic* | qdr | qdr | lin | qdr | qdr |
| *Dynamic strength* | lin | lin | qdr | qdr | lin |
| *Dynamic bandwidth* | qdr | lin | qdr | lin | qdr |
| *Timbre (soft – hard)* | lin | qdr | qdr | qdr | qdr |
| *Timbre (dark – bright)* | qdr | lin | qdr | qdr | qdr |
| *Timbre (lean – full)* | qdr | lin | qdr | qdr | qdr |
| *Timbral bandwidth* | lin | qdr | lin | qdr | qdr |

**Table 6.7.** – $\mathrm{HLM}_{\mathrm{par}}$: The columns show the optimum combination of functions (qdr: quadratic; lin: linear) describing the relation between the performance characteristics and each room acoustical predictor in models with the other four predictors being used as linear variables. The final full $\mathrm{HLM}_{\mathrm{par}}$ was calculated with those functions shown in the table.

All of these predictors varied on the musician level of the HLMs since the room acoustical parameters were individually measured for the instruments. However, the absolute difference between the parameters for the six instruments was not of interest. The focus rather lay on the differences among the acoustical properties of the performance venues experienced by the performers, so in the case of the $\mathrm{HLM}_{\mathrm{par}}$ all room acoustical parameters were z-transformed within the measurements for the individual instruments. In the case of $\mathrm{HLM}_{\mathrm{comp}}$ this was not necessary since the components were already z-transformed.

It was already elaborated in the context of the field study (section 5.3.1) that the possibility of using a quadratic function to approximate the relation between some of the predictors and some of the performance characteristics needed to be explored. As explained in that section, this was accomplished by comparing the pseudo-$R^2$ (equation 4.12) of $2^8$ HLMs with all possible combinations of the linear and quadratic version of one predictor each, while the other four predictors were entered as linear regressors. This was done for all five predictors, resulting in five models representing the most suitable function (linear/quadratic) between that particular predictor and each performance quality. For the two final HLMs ($\mathrm{HLM}_{\mathrm{comp}}$ and $\mathrm{HLM}_{\mathrm{par}}$), these five linear/quadratic-combinations were merged into one model. Tables 6.7 and 6.8 show the functions for the predictors and response variables for $\mathrm{HLM}_{\mathrm{par}}$ and $\mathrm{HLM}_{\mathrm{comp}}$, respectively.

| Response Variables | Predictors | | | | |
|---|---|---|---|---|---|
| | *Reverberance* | *Late energy* | *Early energy* | *Bass ratio* | *Bass strength* |
| *Tempo* | lin | qdr | lin | lin | lin |
| *Agogic* | lin | qdr | lin | qdr | lin |
| *Dynamic strength* | lin | lin | qdr | qdr | qdr |
| *Dynamic bandwidth* | lin | lin | qdr | lin | qdr |
| *Timbre (soft – hard)* | lin | qdr | qdr | qdr | qdr |
| *Timbre (dark – bright)* | lin | lin | lin | lin | lin |
| *Timbre (lean – full)* | lin | lin | lin | qdr | lin |
| *Timbral bandwidth* | qdr | qdr | lin | lin | qdr |

**Table 6.8.** – $\text{HLM}_{\text{comp}}$: The columns show the optimum combination of functions (qdr: quadratic; lin: linear) describing the relation between the performance characteristics and each room acoustical predictor in models with the other four predictors being used as linear variables. The final full $\text{HLM}_{\text{comp}}$ was calculated with those functions shown in the table.

## 6.4.2 Data structure

The HLMs calculated for the analysis of the data were based on the assumption that the adjustments of the way of playing adopted by the players in one room were similar for all pieces and also for all performers. This means the performance characteristics calculated for all the 336 played pieces were expected to be grouped according to the rooms they had been performed in and the musicians that had played them. Thus, three-level HLMs were calculated with the pieces constituting the first, the musicians the second and the rooms the third level.

To verify this assumption, the proportion of variance in the response data at the different levels was compared for each of the eight response variables. For this purpose, the variances on room, musician and piece level , $\sigma^2_{v|\text{room}}$, $\sigma^2_{v|\text{musician}}$ and $\sigma^2_{v|\text{res}}$, were estimated in univariate 3-level intercept-only HLMs – that is in models with no regressors that only consider the grouping structure – for each performance quality. The results showed that $\sigma^2_{v|\text{room}}$ was very small compared to the variance on the other levels for all response variables, in some cases (*agogic, timbre (soft – hard), timbre (dark – bright), timbral bandwidth*) it was even too small to be estimated. In the 3-level model with the level hierarchy described above, $\sigma^2_{v|\text{room}}$ indicates the variance across rooms when the respective performance quality is averaged across musicians and pieces. $\sigma^2_{v|\text{musician}}$, on the other hand, is to be understood as the variance across musicians within rooms. If

| Response variable $v$ | $\sigma^2_{v\|\text{musician}}$ | $\sigma^2_{v\|\text{res}}$ | $\rho_v$ |
|---|---|---|---|
| *Tempo* | 0.14 | 0.86 | **0.14** |
| *Agogic* | 0.21 | 0.79 | **0.21** |
| *Dynamic strength* | 0.27 | 0.73 | **0.27** |
| *Dynamic bandwidth* | 0.21 | 0.79 | **0.21** |
| *Timbre (soft – hard)* | 0.37 | 0.63 | **0.37** |
| *Timbre (dark – bright)* | 0.19 | 0.82 | **0.19** |
| *Timbre (lean – full)* | 0.11 | 0.89 | **0.11** |
| *Timbral bandwidth* | 0.22 | 0.78 | **0.22** |

**Table 6.9.** – Variance on musician level $\sigma^2_{v|\text{musician}}$, residual variance $\sigma^2_{v|\text{res}}$ and intraclass correlation coefficients $\rho_v$ for the eight response variables.

$\sigma^2_{v|\text{room}} \ll \sigma^2_{v|\text{musician}}$, this thus implies that the variance of the musicians' individual adjustments to the room acoustics was greater than the variance of their averaged adjustments, that is that the players' reaction patterns to the room acoustical environment were highly individual. Since $\sigma^2_{v|\text{room}}$ was so small for all performance characteristics, indicating that the room level was not relevant in the hierarchical structure, so this level was omitted in the further analysis, as suggested by Hox (2010, p. 18). Table 6.9 shows the musician level and residual variances as well as the ICC $\rho$ to assess the correlation of the pieces within one musician. Even though the resulting ICCs are lower than the ones shown in table 5.6, they indicated a group structure on the musician level in the data and thus support the use of a multilevel analysis.
In a next step, multivariate intercept-only models were calculated by adding a variable level (see section 4.4) below the piece and musician levels. In contrast to the field study data, here the variance on all levels was $> 0$, so the further multivariate analysis was conducted with a three-level structure: variables on the first, pieces on the second and musicians on the third level.

### 6.4.3 Results

The explanatory power of the two three-level models, $\text{HLM}_{\text{par}}$ and $\text{HLM}_{\text{comp}}$, using the predictors described above was evaluated by calculating the pseudo-$R^2$ according to equation 4.12. This resulted in 1.70% for $\text{HLM}_{\text{par}}$ and 4.15% for $\text{HLM}_{\text{comp}}$. Compared to the results of the field study, it is noticeable that the PCA components have a considerably higher explanatory power than the room acoustical parameters. Furthermore, the pseudo-$R^2$ are as a whole much lower than in the field study. However, it needs to be considered that the musicians in the laboratory study used very individual strategies to adjust their way of playing to the room acoustical environments, as was shown in section 6.4.2 above. Thus, to obtain models comparable to the field study, the pseudo-$R^2$ were calculated using the musician index as factor, estimating regression coefficients for the interaction between each individual musician and the room acoustical predictors. The variance explained by these models was 12.78% for $\mathrm{HLM}_{\mathrm{par}}$ and 19.42% for $\mathrm{HLM}_{\mathrm{comp}}$.

The parameters of these HLMs were calculated with the restricted maximum likelihood method with standardised explanatory and response variables. The standardised regression coefficients with 95% confidence intervals for each explanatory and response variable of $\mathrm{HLM}_{\mathrm{par}}$ and $\mathrm{HLM}_{\mathrm{comp}}$ are shown in figures 6.10 and 6.11 (black $*$), respectively. They illustrate the extent and significance of the effect of each room acoustical predictor on the response variables. It is evident that the regression coefficients for the two sets of predictors are very similar in most cases. Even though the explanatory power of $\mathrm{HLM}_{\mathrm{comp}}$ was higher, the following discussion of the results focusses on $\mathrm{HLM}_{\mathrm{par}}$ to enable a more direct comparison with the results of the field study.

To explore the influence of the basic tempo of the pieces as well as the played instruments, these two factors were separately entered into two $\mathrm{HLMs}_{\mathrm{par}}$ (see table 4.1 for factor levels). In the first case, the resulting model yielded no significant difference between the two factor levels for any performance quality and room acoustical predictor. Nevertheless, figure 6.10 (grey $-$ and $\times$) shows some interactions between the basic tempo and the room acoustical parameters that indicate a strong tendency for a difference between both categories. The effect of the played instrument was not significant for all interactions, but as figure 6.12 shows, there were large differences between some of the instruments for all performance characteristics.

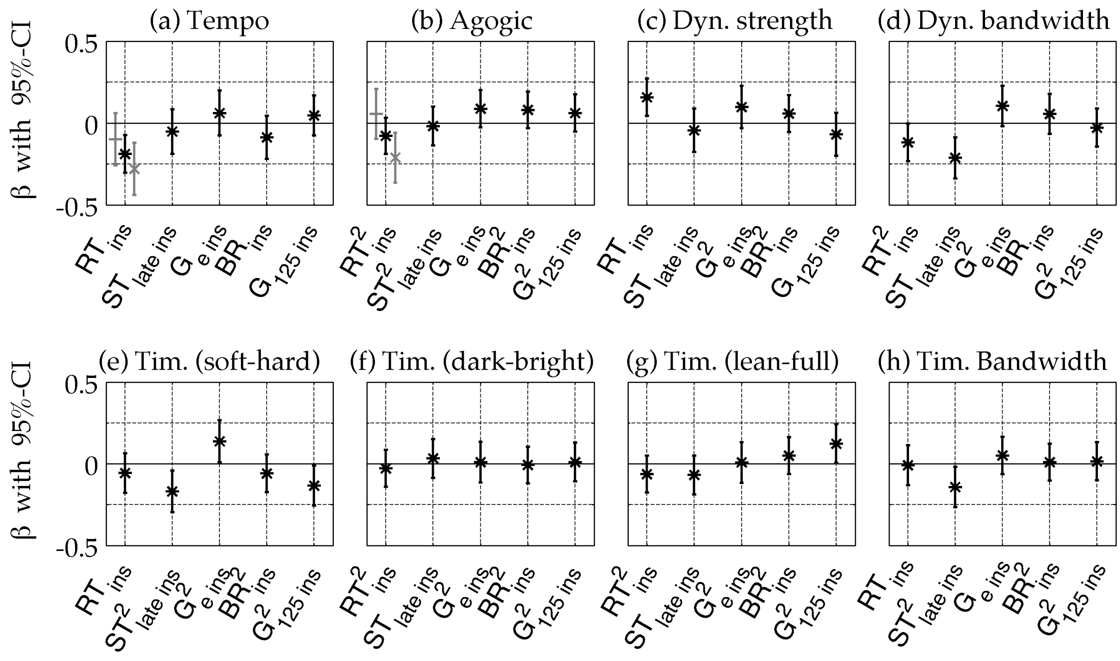



**Figure 6.10.** – $HLM_{par}$: Standardised regression coefficients with 95% confidence intervals (CIs) for the five room acoustical parameters (x-axes) predicting the eight performance characteristics (a-h). The coefficients of the HLM with room acoustical predictors only are shown in black, selected coefficients of an HLM with ‚basic tempo' as additional factor are shown in grey ($-$: ‚fast'; $\times$: ‚slow'). CIs not crossing the zero-line indicate significant coefficients ($p < 0.05$).

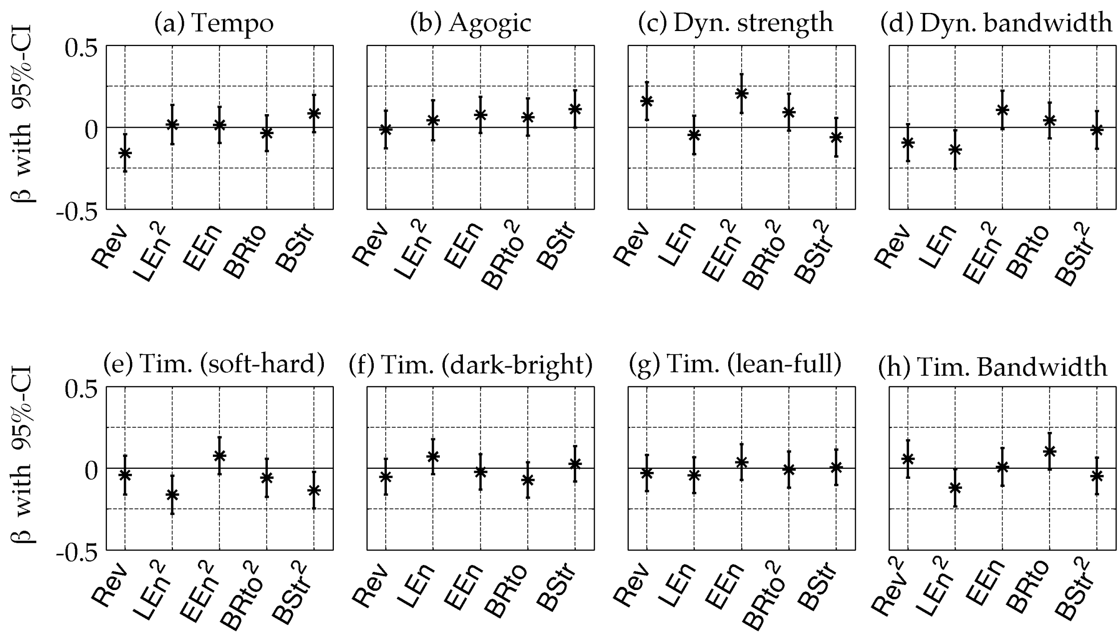



**Figure 6.11.** – $HLM_{comp}$: Standardised regression coefficients with 95% CIs for the five room acoustical parameters (x-axes) predicting the eight performance characteristics (a-h). CIs not crossing the zero-line indicate significant coefficients ($p < 0.05$). Rev: *duration of reverberation*; LEn: *late energy*; EEn: *early energy*; BRto: *bass ratio*; BStr: *bass strength*.

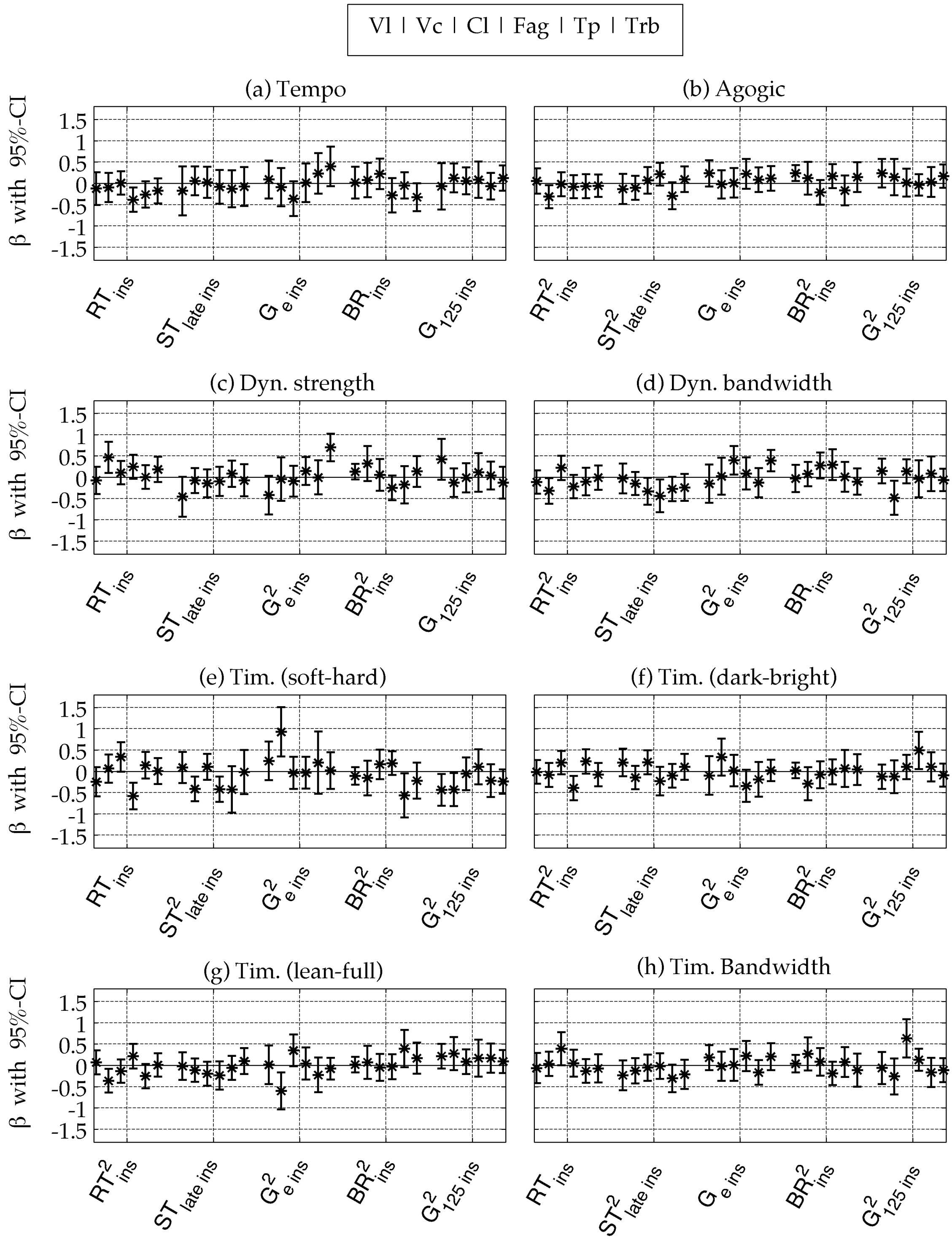



**Figure 6.12.** – $HLM_{par}$: Standardised regression coefficients with 95% CIs for the five room acoustical parameters (x-axes) separately predicting the instruments' performance attributes (a–h). Coefficients for each predictor from left to right: violin (Vl), cello (Vlc), clarinet (Cl), bassoon (Fag), trumpet (Tp), trombone (Trb). CIs not crossing the zero-line indicate significant coefficients ($p < 0.05$).

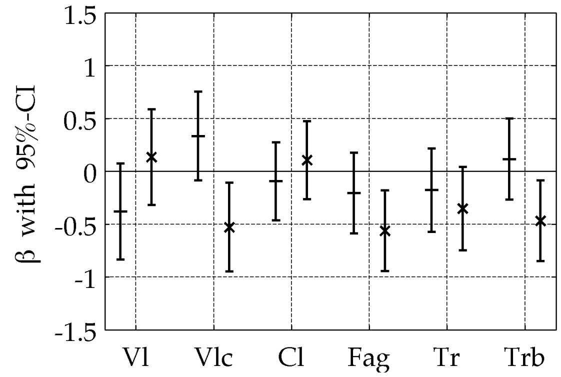



**Figure 6.13.** – $\mathrm{HLM}_{\mathrm{par}}$: Standardised regression coefficients with 95% CIs for $RT_{\mathrm{ins}}$ separately predicting the tempo of each instrument (x-axes) and each basic tempo ($-$: ‚fast'; $\times$: ‚slow'). CIs not crossing the zero-line indicate significant coefficients ($p < 0.05$).

**Tempo** Averaged over musicians and pieces, the *tempo* chosen by the players was significantly influenced by the reverberation time of the concert spaces (figure 6.10a, black $*$) but here the relation was better described by a linear function and not a quadratic one as in section 5.3.3. The musicians played slower in rooms with long reverberation time, presumably to maintain the intelligibility of tone and chord sequences. This is supported by the interviews held with the participants of the experiment (see section 6.5). Some performers also mentioned the prolongation of pauses as an adjustment strategy for rooms with long reverberation time, which of course also reduces the playing tempo.

When looking at the difference between the basic tempo of the pieces (figure 6.10a, grey $-$ and $\times$), it is interesting to see that, unlike the results of the field study, it was mainly the slow piece that was played with reduced *tempo* in rooms with long reverberation time. The interviews indicated that many of the musicians focused on playing shorter notes when performing fast pieces in reverberant rooms rather than adjusting the tempo. In the case of the cellos, this articulation was even accompanied by an increase in *tempo*, as can be seen in figure 6.13, where the interactions between the factor ‚basic tempo' and the room acoustical predictors with regard to *tempo* are shown separately for the instruments. Figure 6.13 also demonstrates that the violins reacted similarly to the cellist in the field study by decreasing the *tempo* of the fast piece with increasing reverberation time while the *tempo* of the slow piece was not adjusted.

**Agogic** As can be seen in figure 6.10b (black $*$), the *agogic* averaged over musicians and pieces was not significantly affected by any of the room acoustical parameters. When looking at the results of $\mathrm{HLM}_{\mathrm{comp}}$ in figure 6.11b, there was a strong tendency ($p = 0.058$) for the PCA component *bass strength* to influence the average *agogic*, indicating more tempo modulations with increasing warmth. Differentiating between the two pieces in $\mathrm{HLM}_{\mathrm{par}}$ (figure 6.10b, grey $-$ and $\times$) reveals that there was a significant effect of the reverberation time on *agogic* that was related to the slow pieces only. These were played with less tempo modulations in rooms with long and short reverberation time, which is the same interaction that was found in the field study for all pieces.
Figure 6.12b shows that there were furthermore strong tendencies or significant effects of $ST^2_{\mathrm{late\ ins}}$ and $BR^2_{\mathrm{ins}}$ regarding some instruments but the response strategies were very individual here.

**Dynamic strength** As the cellist in the field study, the musicians of the laboratory study on average played significantly more *piano* with decreasing $RT_{\mathrm{ins}}$, which is in line with the recommendations found in the music treatises cited in section 2.3. Regarding rooms with long $RT_{\mathrm{ins}}$, the *dynamic strength* was not reduced as in the field study but rather increased (see figure 6.10c). Since playing louder in rooms with less sound enhancement appears as an intuitive reaction and was described by all of the wind instruments in the interviews, it is surprising that $G^2_{\mathrm{e\ ins}}$ did not have a significant effect on *dynamic strength*. However, figure 6.11c shows that low and high values of the PCA component *early energy* were accompanied by significantly louder playing by the musicians. While the first part of this effect is explained by the interview statements of the wind instruments mentioned above, the second part (playing louder in acoustically enhanced rooms) could be due to the attempt to drown out the sound of the room if the own instrument cannot be heard well enough.
As can be seen in figure 6.12c, some of the instruments were significantly influenced by $ST_{\mathrm{late\ ins}}$ and $G^2_{\mathrm{e\ ins}}$: The violins used more dynamic strength in rooms with low late support, while the trombones strongly reacted to the early sound

strength in the same way that was described above for the influence of the PCA component *early energy* on the *dynamic strength* of all instruments.

**Dynamic bandwidth** On average, the *dynamic bandwidth* of the musicians was low in rooms with short and long reverberation time as well as in concert spaces with high late support. A long and strong response of the room causing low *dynamic bandwidth* could be due to the fact that especially loud sections of the music pieces were reduced in dynamic strength under these room acoustic conditions (see section 6.5.2). It seems that too much reverberant energy is detrimental to the use of the full instrumental dynamic range.
Looking at figure 6.12d reveals that the *dynamic bandwidth* of the clarinets and trombones was also significantly increased with low and high early sound strength.

**Timbre characteristics** Figure 6.10e shows that the influence of $ST^2_{\text{late ins}}$, $G^2_{125\text{ ins}}$ and $G^2_{\text{e ins}}$ on *timbre (soft – hard)* was quite consistent among the performers: they played significantly *softer* in rooms with low and high late support and bass strength and significantly *harder* in rooms with low and high early sound strength. As already mentioned in section 5.3.3, a *soft* tone production might also be related to a „held back sound“, which is a way of playing described by most musicians in the interviews for rooms with a lot of reverberant energy. On average, the players furthermore used a significantly *fuller* tonal rendition in rooms with low and high bass strength (figure 6.10g). The average timbral bandwidth was significantly lower in rooms with low and high late support (figure 6.10h).
Beyond these average, largely consistent reactions, figures 6.12e-h reveal large and significant differences among the instruments in the way their timbre was adjusted to rooms with varying reverberation time: The clarinets played *harder* and *brighter* with increasing $RT_{\text{ins}}$, while the opposite can be seen for the bassoons. Furthermore, the celli and trumpets were encouraged to us a more *lean* tonal rendition in rooms with long and short $RT_{\text{ins}}$ but the bassoons reacted contrarily. With respect to the timbre of the rooms, a low and high bass strength influenced the strings and trombones to play *softer* (figure 6.12e), while the bas-

| *Tempo* | | *Agogic* | | *Dyn. strength* | | *Dyn. bandwidth* | |
|---|---|---|---|---|---|---|---|
| Pred. | $\lvert\beta\rvert_{\mathrm{mean}}$ | Pred. | $\lvert\beta\rvert_{\mathrm{mean}}$ | Pred. | $\lvert\beta\rvert_{\mathrm{mean}}$ | Pred. | $\lvert\beta\rvert_{\mathrm{mean}}$ |
| $G_{\mathrm{e\ ins}}$ | 0.28 | $RT^{2}_{\mathrm{ins}}{}^{**}$ | 0.22 | $ST_{\mathrm{late\ ins}}$ | 0.28 | $G^{2}_{\mathrm{e\ ins}}{}^{**}$ | 0.28 |
| $RT_{\mathrm{ins}}$ | 0.21 | $G^{2}_{125\ \mathrm{ins}}$ | 0.18 | $G^{2}_{\mathrm{e\ ins}}{}^{**}$ | 0.28 | $ST_{\mathrm{late\ ins}}$ | 0.26 |
| $ST_{\mathrm{late\ ins}}$ | 0.20 | $BR^{2}_{\mathrm{ins}}$ | 0.17 | $RT_{\mathrm{ins}}{}^{**}$ | 0.26 | $G^{2}_{125\ \mathrm{ins}}$ | 0.25 |
| $BR_{\mathrm{ins}}$ | 0.20 | $ST^{2}_{\mathrm{late\ ins}}$ | 0.17 | $BR^{2}_{\mathrm{ins}}$ | 0.23 | $RT^{2}_{\mathrm{ins}}{}^{*}$ | 0.23 |
| $G_{125\ \mathrm{ins}}$ | 0.14 | $G_{\mathrm{e\ ins}}$ | 0.14 | $G_{125\ \mathrm{ins}}$ | 0.20 | $BR_{\mathrm{ins}}$ | 0.18 |

| *Tim. (soft – hard)* | | *Tim. (dark – bright)* | | *Tim. (lean – full)* | | *Tim. bandwidth* | |
|---|---|---|---|---|---|---|---|
| Pred. | $\lvert\beta\rvert_{\mathrm{mean}}$ | Pred. | $\lvert\beta\rvert_{\mathrm{mean}}$ | Pred. | $\lvert\beta\rvert_{\mathrm{mean}}$ | Pred. | $\lvert\beta\rvert_{\mathrm{mean}}$ |
| $G^{2}_{\mathrm{e\ ins}}$ | 0.40 | $RT^{2}_{\mathrm{ins}}{}^{*}$ | 0.25 | $G^{2}_{\mathrm{e\ ins}}$ | 0.23 | $BR^{2}_{\mathrm{ins}}$ | 0.23 |
| $G^{2}_{125\ \mathrm{ins}}{}^{*}$ | 0.31 | $ST_{\mathrm{late\ ins}}$ | 0.23 | $G^{2}_{125\ \mathrm{ins}}$ | 0.20 | $G^{2}_{125\ \mathrm{ins}}$ | 0.20 |
| $ST^{2}_{\mathrm{late\ ins}}{}^{**}$ | 0.29 | $G^{2}_{\mathrm{e\ ins}}$ | 0.21 | $ST_{\mathrm{late\ ins}}$ | 0.20 | $G_{\mathrm{e\ ins}}$ | 0.20 |
| $RT_{\mathrm{ins}}{}^{*}$ | 0.26 | $G^{2}_{125\ \mathrm{ins}}$ | 0.19 | $RT^{2}_{\mathrm{ins}}{}^{*}$ | 0.20 | $ST^{2}_{\mathrm{late\ ins}}$ | 0.19 |
| $BR^{2}_{\mathrm{ins}}$ | 0.25 | $BR^{2}_{\mathrm{ins}}$ | 0.18 | $BR^{2}_{\mathrm{ins}}$ | 0.16 | $RT_{\mathrm{ins}}$ | 0.18 |

**Table 6.10.** – Absolute, averaged regression coefficients ($\lvert\beta\rvert_{\mathrm{mean}}$) of the room acoustical predictors. The regression coefficients were calculated separately for the individual musicians in an HLM with the factor ‚musician' and then averaged as absolute values. The predictors are ordered according to their influence on each performance attribute. Significant interactions between the factor ‚musician' and the predictors are highlighted (*: $p < 0.05$, **: $p < 0.01$).

soons played significantly *brighter* under these conditions (figure 6.12f). Regarding the *timbral bandwidth*, figure 6.12h shows that for the clarinets there was also a significant positive influence of $RT^{2}_{\mathrm{ins}}$ and $BR^{2}_{\mathrm{ins}}$.

To explore the importance of the five room acoustical predictors for the individual performative adjustments, the absolute regression coefficients calculated for the interaction between each individual musician and the predictors ($\mathrm{HLM}_{\mathrm{par}}$ with factor ‚musician') were averaged for each room acoustical parameter and performance quality. Table 6.10 shows the predictors ordered by their average impact on the respective performance characteristic. Each of the investigated room acoustical parameters except $BR_{\mathrm{ins}}$ had a significant influence on at least one performance quality. However, the importance of the stage parameters (especially $G_{\mathrm{e\ ins}}$) is emphasised, as they had the greatest influence in almost all cases. Again, $BR_{\mathrm{ins}}$ seems to be of minor importance, while $G_{125\ \mathrm{ins}}$ had a rather strong influence on many of the performance characteristics, indicating that this parameter might be a better predictor to characterise the timbre properties of a room, at least for musicians on stage. Comparing the averaged absolute regression coefficients $|\beta|_{\mathrm{mean}}$ among each other shows that the highest value resulted for the influence of $G^2_{\mathrm{e\,ins}}$ on *timbre (soft – hard)*. So, as in the field study, this performance characteristic was affected most strongly by the room acoustical surroundings.

### 6.4.4 Influence of subjective room acoustical quality

As explained in section 6.3, the participants of the experiment rated the virtual rooms in a questionnaire with 20 attributes relating to perceptual aspects of room acoustics. Of course, all of these attributes were possible predictors in HLMs designed to investigate how the perception of room acoustics (as opposed to measurable room acoustical parameters) influences the performance of musicians. It was beyond the scope of this thesis to examine the effect of all 20 attributes, but one of them seemed to be of special interest: In the interviews, many of the players mentioned that good acoustics inspired them to play more freely regarding their tempo and dynamics. This statement raised the question if the perceived quality of the room acoustical surrounding had an influence on their way of playing. The aspect of quality was represented by the bipolar attribute „bad acoustics – good acoustics“ in the questionnaire. Figure 6.14 shows the ratings given by each musician for the 14 simulated concert spaces and it is apparent that the perception of the room acoustical quality was very diverse among the performers.

To investigate the effect of the room acoustical quality on the performance characteristics, a multivariate HLM with three levels (variables, pieces, musicians) was calculated using the z-standardised quality ratings as predictors. The variance explained by an HLM with just the quality predictors amounted to 5.85%, while the pseudo-$R^2$ for a model with the musician index as additional factor yielded 7.49%. When using the instruments instead of the musicians as factor, the explained variance was even 8.43%. This means, the adjustment of perfor-

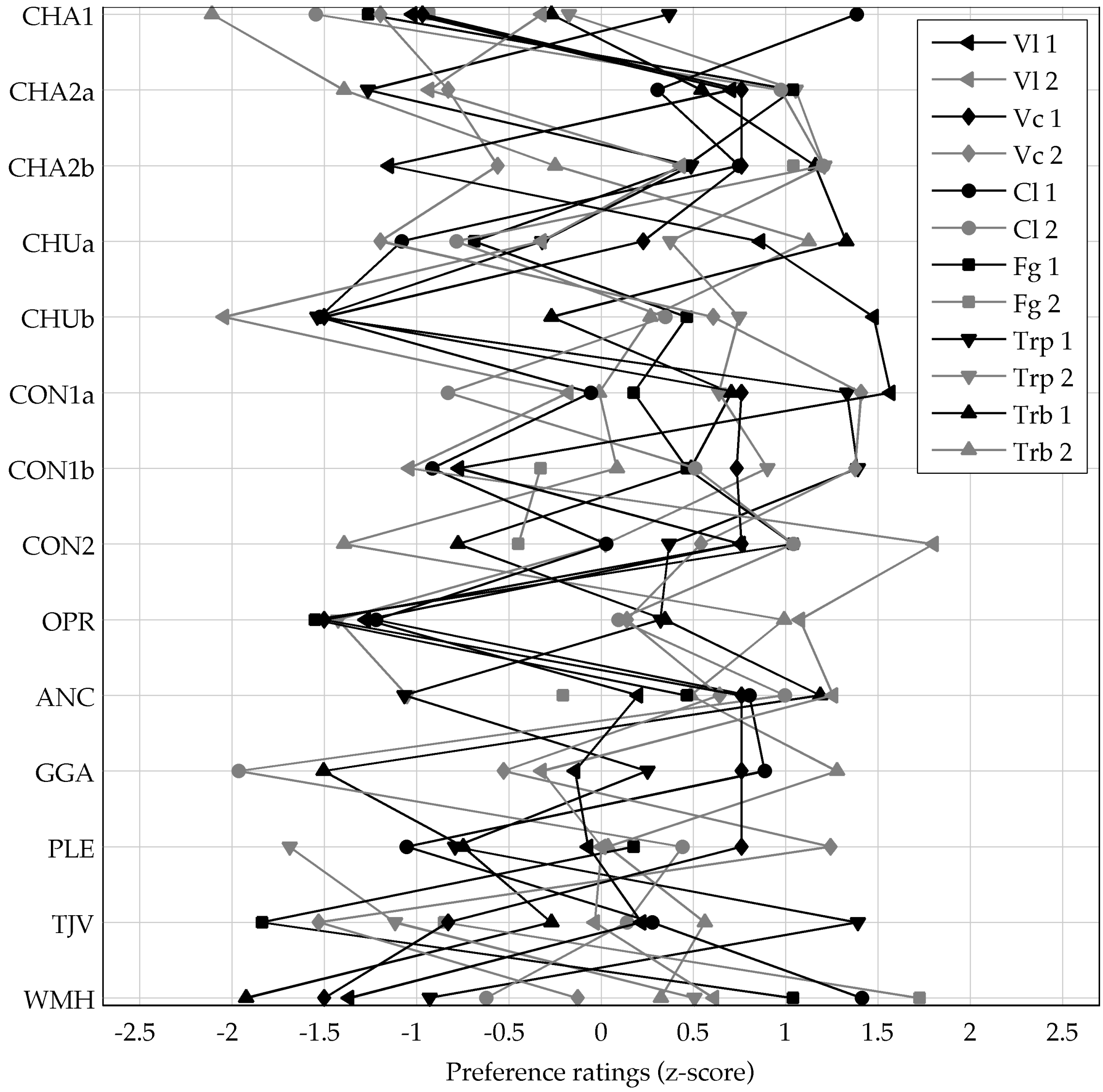



**Figure 6.14.** – Individual quality ratings of the musicians for each simulated concert space. The negative end of the scale in the questionnaire was „bad acoustics“, the positive end was „good acoustics“. Ratings are z-standardised within each musician. Because of technical problems the data of the ratings could not be acquired in three instances. Furthermore, Fg 2 used only the extreme ends of the attribute poles in the first experimental session because of a misunderstanding. All these cases (Fg 1/Trp 2: GGA; Fg 2: CHA2a, CHUa, CHUb, CON1a, OPR, GGA, PLE) were treated as missing values here.

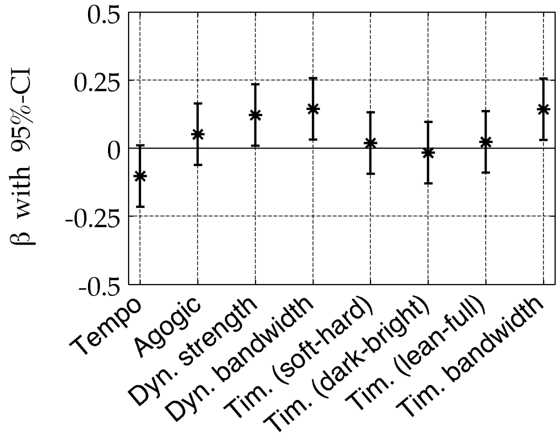



**Figure 6.15.** – Standardised regression coefficients with 95% confidence intervals (CIs) for the quality ratings predicting the eight performance characteristics (x-axes). CIs not crossing the zero-line indicate significant coefficients ($p < 0.05$).

mance characteristics with respect to the perceived quality of the room acoustical surrounding was quite consistent among instruments while differentiating the individual adjustments introduced additional variance.

Figure 6.15 shows the regression coefficients and confidence intervals of the individual quality ratings for each performance characteristic. Evidently, the musicians played significantly more *forte* and with more dynamic and timbral bandwidth in rooms with „good acoustics". Furthermore, there was a tendency ($p = 0.074$) to play slower under pleasant room acoustical conditions. The increase of dynamic bandwidth presumably reflects what was meant by „the free use of dynamics" addressed by the players as mentioned above. At the same time, „the free use of tempo" was apparently not connected to tempo modulations as described by *agogic*, since this performance characteristic was not significantly influenced by the quality ratings. The negative correlation between *tempo* and the quality ratings can be explained by the notion to prolong pauses and play slower under favourable conditions and to play faster in the opposite case. These adjustments were reported by the musicians in the interviews described in the next section.

## 6.5 Guided interviews

The guided interviews carried out in the field study had proven to be a valuable instrument to understand the performance strategies of the cellist as well as his perception of the specific performance situations. Similarly, guided interviews were held with the musicians of the laboratory experiment to find out about conscious adjustments to the room acoustical environments as well as their perception of the room acoustics. In this study, the situational factors of the individual performances were assumed to be constant, but the interviews were furthermore intended to reveal influences of the experimental situation or other artefacts.

### 6.5.1 Methods

The interview guide was made up of the following questions:

- Please describe your performance regarding tempo, dynamic strength, timbre or other characteristics. Were there any peculiarities? If yes, what do you ascribe them to?

- Did the acoustics of this hall influence your way of playing?

- Apart from the acoustics, were there any other factors that influenced you?

The interviews were conducted directly after the recording in each of the virtual rooms. They were held in German, which all the performers were fluent in (nine natives speakers) and lasted about 5 minutes each. The conversations were recorded and transcribed for the analysis.

The analysis was carried out by using the method described in section 4.5 (qualitative content analysis with the content-related structuring technique). This entailed categorising meaningful elements in all the interviews, paraphrasing them and then summarising the text elements with similar content. The categorisation system comprised of one main category and four subcategories, which are

| Main category | Subcategory | Definition |
|---|---|---|
| Instrument | Performance concept | General rules or views concerning performance conditions or the performance of the chosen pieces |
| | Room acoustics | Room acoustical conditions in the concert halls |
| | Performative adjustment | Specific way of playing resulting from room acoustical conditions |
| | Artefact | Technical artefact or influence of the experimental situation |

**Table 6.11.** – Definition of categories and subcategories used in the qualitative content analysis of the interviews held with the performers.

shown in table 6.11. The coding rules and examples are given in table C.1, appendix C.1. Initially, the first two subcategories in table 6.11 were summarised across musicians within one room, that is all interviews regarding one performance space were analysed together. Subsequently, the two subcategories were further summarised across rooms in order to investigate 1. the aspects that were relevant for the musicians when describing the room acoustics and 2. similarities and differences among the musicians' strategies of adjustments to the room acoustical environments. The last two subcategories in table 6.11 were summarised across musicians and rooms in the first place since they were regarded to be independent of a specific room acoustical surrounding. The results of the qualitative content analysis are shown in the next section.

### 6.5.2 Results

To begin with, table 6.12 shows the descriptions categorised as ‚performance concept' in the interviews and gives an overview of the general adjustment strategies of some of the musicians. Interestingly, a few players seem to object to (conscious) performative adjustments, at least regarding the tempo, a notion that was already found in section 2.3.

At the end of each interview the musicians were asked to name salient or disturbing things that had occurred to them while playing. In the majority of interviews, the players had nothing to add to this point but as table 6.13 shows, there were a few artefacts. The first point is a good summary of the drawbacks of the laboratory experiment and it must be borne in mind that this possibly caused the musicians to react less clearly or less reliably to the room acoustical surround-

| Description | Instrument |
|---|---|
| Not much performative adjustment in experimental situation, rather in real concert situation<br>Tempo is generally not varied<br>*Staccato* is played shorter in reverberant rooms, but *legato* cannot be varied | Clarinet |
| Concert for bassoon by Mozart has one tempo that should not be varied | Bassoon |
| Dark sound of instrument if sound of room is sharp<br>Musically important passages are slightly slowed down if the has a certain amount of reverberation<br>Less clear articulation if a room is sustainable<br>Clear articulation if a room is not clear<br>Notes are prolonged if one feels comfortable | Trumpet |

**Table 6.12.** – General performance concepts described by the musicians in the interviews

ings (see also first point in table 6.12). The second point in table 6.13 is obviously related to the rather long experimental sessions and the numerous repetition of the same two musical excerpts. Since the presentation of virtual rooms was randomised in all sessions, the influence of this factor on the results of the study can be neglected, though. The cold temperature in the anechoic chamber was rather unfavourable for performing musicians, but it was only the violins that mentioned it as slightly disturbing. The next three points were hardly avoidable and owed to the extensive technical setup of the experiment. Both violin players repeatedly mentioned that the rooms sounded brazen to them. This could be due to the fact that the directivity of the violin used in the computer models of the concert spaces did not correspond to the directivity of the players' instruments. The modelled directivity acted as a filter on the signal that was recorded from the instruments and entered into the binaural simulations (see figure 6.7), and in the case of a strong mismatch to the real instrument it might be the reason for an audible sound colouration of the simulated rooms. At least, this was an artefact constantly perceived in all rooms making it negligible for the results of the experiment. The last three points in table 6.13 are possibly related to a too low number of rays used for the ray tracing algorithm of the simulation software (see appendix B.2).

In the following tables 6.14 to 6.27, the descriptions regarding the categories ‚room acoustics' and ‚performative adjustment' are shown separately for each of the 14 concert halls presented to the musicians. With respect to the former category, it can be seen that the perception of the room acoustical surroundings

| Description | Instrument |
|---|---|
| Anechoic chamber and experimental situation are very different from a concert situation | Trombone |
| Fatigue, lapse of concentration | Cello, trumpet, trombone |
| Cold temperature | Violin |
| Slightly disturbing cables and headphones | Violin, cello, clarinet |
| Unaccustomed to playing while seated and instability of floor (grid of steel ropes in anechoic chamber) | Violin, cello |
| Tapping on the instrument and blasts (clarinet) are picked up by the microphone | Violin, clarinet |
| Brazen sound of all rooms | Violin |
| Rattling sound, fluttering reverberation when playing resonant tones in some rooms | Cello, clarinet, trumpet |
| Reverberation is cut off in some rooms | Trombone |
| Later echo in one room | Trombone |

**Table 6.13.** – Artefacts of the technical setup or experimental situation named by the musicians in the interviews.

was very disparate in some cases, most obviously in OPR but, for example, also in CON2 regarding the reverberation and in many rooms regarding their timbre (CHA1, CON2, ANC, PLE, WMH). Overall impressions such as „good“ or „unpleasant“ were contradictory in almost all rooms. On the one hand, these conflicts are probably due to the differences among the room acoustical properties of the virtual halls which were caused by the room excitation with varying sound sources and which are exemplified by the differences between the parameters of each instrument shown in figure 6.6. On the other hand, the contradictions are likely to be due to the individual preferences of the musicians and instruments. Tables 6.14 to 6.27 also illustrate the language used by musicians to describe room acoustics and the aspects that are relevant for their perception of performance spaces. To get an impression of the importance of the qualities named by the performers, the descriptions of the room acoustics given for the individual concert halls are summarised in table 6.28. As can be seen, all rooms except one received an overall assessment such as „good“, „beautiful“, „unpleasant“ or „bad“. Furthermore, timbre characteristics relating to darkness/brightness or similar aspects were mentioned in almost all of the halls. Aspects regarding the reverberation were also frequently named and it is interesting to see that the performers evidently made a difference between its amount, duration and timbre without specifically being pointed to this distinction by the examiner. Another aspect that was mentioned very often is the sustainability of the concert spaces, which is possibly especially important for solo musicians who need to reach all listeners with their own instrument only.

The performative adjustments presented in tables 6.14 to 6.27 are summarised across rooms in table 6.29 and it can be seen what was already found in the statistical analysis: many of the adjustments seem to be specific for individual instruments,[1] but a few were very consistent among the performers. Slow playing and prolonged pauses as well as precise playing and short articulation were reactions to long reverberation times that were named by all instruments and that were also found in the quantitative analysis in section 6.4.3. All of the instruments except the trombones reported to play more quiet in rooms with much reverberation, a reaction that was empirically found only for the violins. Hence it is possible that the quiet playing due to a lot of reverberant energy described by the performers was mainly related to *forte* passages, which would explain the reduced *dynamic bandwidth* that was found in the statistical analysis. Loud playing in quiet rooms was a strategy named by all wind instruments and corresponding to the significant effect of the PCA component *early energy* on the *dynamic strength* of the performers. „Free playing" because of „good acoustics" and fast playing because of „bad acoustics" are reactions named by the string/brass players and string/wind players, respectively, and they were reflected by the results of the statistical analysis carried out with the quality ratings given by the performers for each concert space.

The majority of performative adjustments in table 6.29 that are described by one or two instruments only are related to timbre properties of the concert spaces and timbre characteristics of the performances. This is not surprising for two reasons: Firstly, the timbre characteristics were apparently perceived very disparately by the performers as elaborated above. Irrespective of the differences between the room acoustical parameters of the instruments,[2] it was secondly found in section 6.4.3 that especially the adjustments made by the performers regarding their tonal rendition varied significantly between the instruments.

[1]Since the interview analysis only differentiated between instruments and not individual performers, the following results refer to instrument groups and not musicians.

[2]The room acoustical parameters were z-transformed for the statistical analysis, as explained in section 6.4.1.

| | Description | Instrument |
|---|---|---|
| **Room acoustics** | Dry | Violin, clarinet |
| | Slightly reverberant | Cello, bassoon, trumpet |
| | Sustainable | Trumpet |
| | Not sustainable | Clarinet |
| | Quiet sound of room | Cello, bassoon |
| | Hard | Violin |
| | Dark, warm, muffled | Violin, cello, bassoon |
| | Not fostering | Clarinet, trombone |
| | Pleasant | Violin, clarinet, bassoon, trumpet |
| **Performative adjustment** | Legato articulation because of little reverberation | Trumpet |

**Table 6.14.** – CHA1

| | Description | Instrument |
|---|---|---|
| **Room acoustics** | Reverberant, big sound | Clarinet, bassoon, trumpet, trombone |
| | Loud reverberation | Violin |
| | Reverberation with irregular timbre, brazen, sharp | Violin, clarinet, trombone |
| | Sustainable | Cello |
| | Loud sound of instrument | Clarinet |
| | Supportive | Trombone |
| | Late response of room | Cello |
| | Early response of room | Violin, bassoon |
| | Round | Bassoon |
| | Soft | Trumpet |
| | Balanced | Clarinet |
| | Pleasant, great, beautiful | Violin, cello, clarinet, bassoon, trumpet |
| **Performative adjustment** | Slow playing because of reverberation | Violin, trumpet |
| | Longer pauses because of acoustics | Trumpet |
| | Short articulation because of sustainability and diffusity (fast piece) | Cello, trumpet, bassoon |
| | Quiet playing and no forcing of sound because of reverberation and beautiful sound | Violin, bassoon |
| | Clear playing and clear timbre because of reverberation and diffusity | Violin |
| | Free playing and dynamic bandwidth because of good acoustics and big sound | Trumpet, bassoon |

**Table 6.15.** – CHA2a

| | Description | Instrument |
|---|---|---|
| **Room acoustics** | Reverberation slightly too short | Clarinet |
| | Good length of reverberation | Violin, cello, clarinet, bassoon, trumpet, trombone |
| | Timbre of reverberation changes during playing | Bassoon |
| | Sustainable | Cello |
| | Supportive | Cello, trombone |
| | Open sound | Trombone |
| | Warm | Cello, bassoon |
| | Round | Cello |
| | Balanced | Trumpet |
| | Pleasant, good | Violin, cello, clarinet, bassoon, trumpet, trombone |
| **Performative adjustment** | Slow tempo because of enjoyment of sound | Trumpet |
| | Quiet playing despite quiet sound of room | Bassoon |
| | Full playing because of bright sound | Clarinet |
| | Inspired and expressive playing because of good acoustics | Cello, trombone |

**Table 6.16.** – CHA2b

| | Description | Instrument |
|---|---|---|
| **Room acoustics** | Reverberation lowers pitch of instrument | Clarinet |
| | Very long reverberation | Violin, clarinet, trumpet, trombone |
| | Not clear | Clarinet |
| | Sustainable | Clarinet, bassoon, trombone |
| | Room gave back a lot | Trombone |
| | Late response | Violin |
| | Bright, brazen, sharp | Cello, trumpet |
| | Good for slow piece, not good for fast piece (tones are blurred) | Violin, bassoon, trumpet |
| | Unpleasant, not fostering | Cello, clarinet |
| | Pleasant, easy to play | Violin, bassoon, trumpet, trombone |
| **Performative adjustment** | Slow tempo (slow piece) because of acoustics | Violin, cello, bassoon, trumpet |
| | Slow piece faster, fast piece slower because of acoustics | Trombone |
| | Free tempo because of sustainability and beautiful timbre of room | Bassoon, trumpet |
| | Precise playing and short articulation because of acoustics | Violin, cello, clarinet, trumpet, trombone |
| | Loud playing unnecessary because of sustainability | Clarinet |
| | Dark timbre because of bright sound of room | Trumpet |
| | Use of gestures because of unclarity | Clarinet |
| | Faulty intonation and unclean playing because of unclarity | Clarinet, bassoon |

**Table 6.17.** – CHUa

| | Description | Instrument |
|---|---|---|
| **Room acoustics** | A lot of reverberation (too much for slow piece) | Violin, cello, clarinet, trumpet, trombone |
| | Reverberation gets sharp | Violin |
| | Reverberation gets soft | Clarinet |
| | Diffuse | Clarinet |
| | Not sustainable | Cello |
| | Sound directly from the instrument not from the room | Cello |
| | Dark | Violin |
| | Timbre of room and instrument are different | Trumpet |
| | Balanced | Cello |
| | Unpleasant | Trumpet |
| | Pleasant, beautiful, natural, inspiring, fostering (for slow piece) | Violin, cello, clarinet, bassoon, trumpet |
| **Performative adjustment** | Fast tempo because of lacking sustainability | Cello |
| | Moderate tempo because of much reverberation | Trumpet |
| | Longer pauses because of much reverberation and inspiring acoustics | Clarinet, bassoon |
| | Short and precise articulation because of much reverberation | Clarinet, bassoon |
| | Round articulation and relaxed bow because of sharp sound | Violin |
| | Quiet playing because of diffuse and loud acoustics | Clarinet, bassoon |
| | Free bow movements because of good acoustics | Violin |

**Table 6.18.** – CHUb

| | Description | Instrument |
|---|---|---|
| **Room acoustics** | Much reverberation, church-like | Violin, cello, clarinet, bassoon, trombone |
| | Reverberation gets muffled | Clarinet |
| | Clear | Violin |
| | Sustainable | Clarinet, bassoon |
| | Room supports all registers | Bassoon |
| | Room did not give back much | Cello |
| | Easy to hear oneself | Clarinet, bassoon |
| | Bright | Clarinet |
| | Hard | Bassoon |
| | Sound thinner in upper registers than in lower registers | Violin |
| **Performative adjustment** | Restraint of sound because of reverberation | Clarinet |
| | Clear playing because of thin sound of room | Violin, cello |
| | Slow tempo and longer pauses because of reverberation | Violin, clarinet, bassoon |
| | Free playing and dynamic bandwidth because of good acoustics | Violin, cello |

**Table 6.19.** – CON1a

| | Description | Instrument |
|---|---|---|
| **Room acoustics** | Rather reverberant | Violin, clarinet, bassoon, trombone |
| | Reverberation is cut off | Clarinet, trombone |
| | Sustainable | Clarinet, trumpet |
| | Not too loud | Bassoon |
| | Room swallows dynamics | Clarinet |
| | Easy to hear oneself | Cello |
| | Supportive | Cello |
| | Bright | Cello |
| | Hard | Violin, bassoon |
| | Pleasant, beautiful | Cello, bassoon, trombone |
| **Performative adjustment** | Longer pauses (slow piece) because of long reverberation | Bassoon |
| | Precise articulation because of acoustics | Bassoon |
| | More sound volume because room swallows a lot | Clarinet |
| | Free tempo and inspired playing because of beautiful acoustics | Trumpet |

**Table 6.20.** – CON1b

| | Description | Instrument |
|---|---|---|
| **Room acoustics** | Long reverberation | Clarinet, trumpet, trombone |
| | Rather short reverberation | Violin |
| | Diffuse | Clarinet, bassoon |
| | Clear | Cello, clarinet, bassoon |
| | Sustainable | Violin, clarinet |
| | Easy to hear oneself | Violin, bassoon |
| | Early response of room | Bassoon |
| | Restrictive | Bassoon |
| | Round | Cello, bassoon |
| | Dark | Bassoon |
| | Bright, brazen | Cello, clarinet, trumpet, trombone |
| | Room matches the instrument | Bassoon |
| | Unnatural | Trombone |
| | Pleasant, good, harmonious overall impression | Violin, cello, bassoon, trombone |
| **Performative adjustment** | Slow tempo because of reverberation | Trumpet |
| | Short articulation because of reverberation | Clarinet, bassoon, trumpet |
| | „Holding back“ sound because of reverberation and sustainability | Clarinet, trumpet |
| | Conveying a lot of energy because of acoustics | Clarinet |
| | Free playing and dynamic bandwidth because of good acoustics | Violin, cello, bassoon |

**Table 6.21.** – CON2

| | Description | Instrument |
|---|---|---|
| **Room acoustics** | Long reverberation | Violin, cello, trumpet |
| | Short reverberation | Violin, clarinet, trombone |
| | Reverberation is cut off | Clarinet |
| | Soft reverberation | Bassoon |
| | Sustainable | Violin, trombone |
| | Not sustainable | Cello, clarinet, bassoon |
| | Quiet sound of room | Cello, bassoon, trumpet |
| | Early response of room | Violin |
| | Late response of room | Trombone |
| | Bright, brazen | Violin, clarinet |
| | Dark, muffled | Cello, bassoon, trumpet, trombone |
| | Room matches the instrument | Bassoon |
| | Unpleasant, not fostering | Violin, trumpet, trombone |
| **Performative adjustment** | Longer pauses because of reverberation | Bassoon |
| | Precise articulation because of reverberation | Clarinet, trumpet |
| | More sound volume because of quiet sound of room | Bassoon |
| | Quiet playing because of reverberance | Cello, clarinet |
| | Round sound because of brazen sound of room | Clarinet |
| | Bright playing because of muffled sound of room | Trombone |
| | Free playing because of good acoustics | Violin, trumpet |

**Table 6.22.** – OPR

| | Description | Instrument |
|---|---|---|
| **Room acoustics** | Short reverberation | Clarinet |
| | Much reverberation | Cello, clarinet, bassoon, trumpet, trombone |
| | Reverberation is cut off | Clarinet |
| | Loud, full reverberation | Cello, clarinet |
| | Sustainable | Trombone |
| | Supportive | Clarinet, trombone |
| | Early response of room | Trombone |
| | Sharp, brazen | Violin, trumpet |
| | Hard, stony | Bassoon |
| | Bright | Trumpet |
| | Warm | Bassoon |
| | Soft | Violin, bassoon |
| | Unnatural | Violin |
| | Pleasant, beautiful | Clarinet, bassoon, trombone |
| **Performative adjustment** | Slow tempo (slow piece) because of reverberation | Violin, bassoon |
| | Precise articulation because of sustainability | Trombone |
| | Fluent playing because of dark reverberation | Trumpet |
| | Free and relaxed playing because of pleasant acoustics | Bassoon, trombone |

**Table 6.23.** – ANC

| | Description | Instrument |
|---|---|---|
| **Room acoustics** | Much reverberation | Violin, cello, trumpet, trombone |
| | Not much sound of room | Clarinet |
| | Not supportive | Cello, trombone |
| | Early response of room | Violin |
| | Warm | Cello |
| | Hard | Trumpet |
| | Sharp, brazen | Violin, trumpet |
| | Not pleasant, not good, not beautiful | Violin, trumpet, trombone |
| | Pleasant, good | Cello, trumpet |
| | Rehearsal room | Cello |
| **Performative adjustment** | Fast tempo because of lacking reverberation and lacking enjoyment of sound | Violin, trumpet |
| | Avoiding loud playing because of sharp sound of room | Trumpet |
| | Loud playing because of quiet sound of room and lacking support | Clarinet, trombone |

**Table 6.24.** – GGA

| | Description | Instrument |
|---|---|---|
| **Room acoustics** | Short reverberation | Violin |
| | Diffuse | Clarinet, bassoon, trumpet |
| | Good sound of instrument | Cello |
| | Early response of room | Violin, clarinet, trumpet |
| | During quiet passages room barely audible | Clarinet |
| | Warm, muffled | Violin, trumpet |
| | Hard | Bassoon |
| | Bright, brazen, sharp | Violin, trombone |
| | Broad sound | Violin, bassoon |
| | Pleasant, good | Violin, cello |
| | Not pleasant | Clarinet, trumpet, trombone |
| **Performative adjustment** | Soft articulation because of early response of room | Violin |
| | Short articulation because of ample reverberation | Cello |
| | Loud playing because of lacking support | Trombone |
| | Quiet playing because of loud sound of room | Clarinet, trumpet |
| | Little dynamic bandwidth because of loud sound of room | Clarinet, trumpet |
| | Free playing and dynamic bandwidth because of good acoustics | Violin, bassoon |

**Table 6.25.** – PLE

| | Description | Instrument |
|---|---|---|
| **Room acoustics** | Dry, not much reverberation | Violin, clarinet, bassoon, trumpet, trombone |
| | Clear | Bassoon, trumpet |
| | Quiet sound of room | Bassoon |
| | Not supportive | Clarinet, bassoon, trombone |
| | Early response of room | Violin, bassoon |
| | Bright | Violin, bassoon |
| | Pleasant, beautiful, realistic | Violin, bassoon, trumpet, trombone |
| | Bad | Cello, bassoon |
| | Rehearsal room | Violin, cello, bassoon, trumpet, trombone |
| **Performative adjustment** | Fluent and fast playing because of acoustics | Violin, cello, bassoon, trumpet |
| | Soft articulation because of acoustics | Cello |
| | Loud playing because of quiet sound of room | Bassoon |
| | No „relaxing the reins“ because of lacking support | Clarinet, bassoon |

**Table 6.26.** – TJV

| | Description | Instrument |
|---|---|---|
| **Room acoustics** | Reverberant, big | Violin, clarinet, trombone |
| | Diffuse | Clarinet, bassoon |
| | Clear | Clarinet, bassoon |
| | Supportive | Bassoon |
| | Not supportive | Trombone |
| | Not easy to hear oneself | Trumpet |
| | Late response of room | Violin |
| | Bright, brazen, sharp | Violin, bassoon, trumpet |
| | Hard | Cello, bassoon |
| | Dark | Violin |
| | Bad, unbalanced | Violin, trombone |
| | Good, beautiful | Cello, clarinet, bassoon, trumpet, trombone |
| | Room matches instrument | Bassoon |
| **Performative adjustment** | Fast playing because of bad acoustics | Trombone |

**Table 6.27.** – WMH

| Description | No. of rooms |
|---|---|
| Reverberant / dry | 5 |
| Amount of reverberation | 5 |
| Duration of reverberation | 6 |
| Timbre of reverberation | 5 |
| Reverberation lowers pitch of instrument | 1 |
| Clear / diffuse | 7 |
| Sustainable / not sustainable | 9 |
| Quiet / loud sound of room | 6 |
| Easy to hear oneself | 6 |
| Supportive / not supportive | 7 |
| Room gave back / did not give back | 2 |
| Early / late response of room | 8 |
| Open / restrictive | 2 |
| Broad | 1 |
| Round | 3 |
| Soft / hard | 6 |
| Dark, warm, muffled / bright, brazen, sharp | 12 |
| Timbre of room and instrument match / are different | 4 |
| Balanced / unbalanced | 4 |
| Natural / unnatural | 2 |
| Pleasant, beautiful, good, fostering / unpleasant, bad, not fostering | 13 |
| Rehearsal room | 2 |
| Good sound of instrument | 1 |

**Table 6.28.** – Description of room acoustics summarised from the individual interviews (tables 6.14 to 6.27) and number of rooms with the respective description.

| Description | Instrument |
|---|---|
| Slow playing and longer pauses because of long reverberation (mostly slow pieces) | Violin, cello, clarinet, bassoon, trumpet, trombone |
| Longer pauses and reduced tempo because of good acoustics | Clarinet, bassoon, trumpet |
| Fast playing because of lacking reverberation and bad acoustics | Violin, cello, trumpet, trombone |
| Precise and clear playing and short articulation because of long reverberation and diffuse sound (mostly fast pieces) | Violin, cello, clarinet, bassoon, trumpet, trombone |
| Round and relaxed articulation because of sharp and brazen sound of room | Violin, clarinet |
| Soft articulation because of early response of room | Violin, cello |
| Legato articulation because of little reverberation | Trumpet |
| Quiet playing despite quiet sound of room | Bassoon |
| Avoiding loud playing because of sharp sound of room | Trumpet |
| Quiet playing, „holding back“ because of much reverberation | Violin, cello, clarinet, bassoon, trumpet |
| Reduced dynamics because of loud sound of room | Clarinet, trumpet |
| Loud playing and sound volume because of quiet sound of room and lacking support | Clarinet, bassoon, trumpet, trombone |
| Full playing because of bright sound of room | Clarinet |
| Dark playing because of bright sound of room | Trumpet |
| Bright playing because of muffled sound of room | Trombone |
| Clear playing because of thin sound of room | Violin, cello |
| Fluent playing because of dark reverberation | Trumpet |
| Free playing (tempo, dynamics, use of bow) because of good acoustics | Violin, cello, bassoon, trumpet |
| Expressive playing and inspiration because of good acoustics | Cello, trumpet, trombone |
| Use of much energy because of lacking support | Clarinet, bassoon |
| Use of gestures because of unclarity | Clarinet |
| Unclean playing and faulty intonation because of unclarity | Clarinet, bassoon |

**Table 6.29.** – Performative adjustments summarised from the individual rooms (tables 6.14 to 6.27)

## 6.6 Conclusions

The laboratory study explored the influence of room acoustics on the performances of professional solo players of different instruments by means of a highly plausible simulation of 14 typical concert spaces. As in the field study, the room acoustical parameters used as independent variables in the statistical analysis were measured in computer models by applying sources with instrumental directivities. This allowed for the representation of typical room acoustical conditions experienced by performers. The analysis furthermore considered the played instrument and the musical content as covariates.

A substantial result of the investigation is that the response strategies of musicians regarding their room acoustical environment are highly individual. This is indicated by the amount of variance in the examined performance characteristics explained by room acoustical predictors. If adjustments in the performative rendition of the played pieces are considered on average over all musicians, only 1.78% of this variance is explained by the room acoustical parameters used as regressors. However, if their effect is estimated separately for each individual musician, the explained variance amounts to 12.78%.

A systematic comparison of HLMs with quadratic and linear predictors revealed a higher amount of explained variance if the *tempo* played by the musicians is predicted by the linear reverberation time. Since this differs from the results of the field study, one could assume that a quadratic prediction function might be more suitable for some musicians in the laboratory study, but this could not be investigated in the scope of this thesis. The comparison of HLMs also yielded a better fit of the models when using the quadratic version of other regressors, so a combination of linear and quadratic predictors was entered into the final HLM.

Despite the individual adjustment strategies of the musicians, some patterns of reaction are significant when considering the average performance over all individual players involved. Moreover, most of these relations were addressed in the interviews, pointing to conscious adjustment strategies. A reduced *tempo* was found in rooms with long reverberation time, which was much more pronounced for slow than for fast pieces and is clearly in agreement with the interviews. The conversations furthermore revealed that for fast pieces most performers concentrate on a precise articulation instead of slowing down the tempo, explaining why the effect of $RT_{\text{ins}}$ on *tempo* is only significant for slow pieces. A significantly reduced *dynamic strength* was found in rooms with short reverberation time, replicating the results of the field study. Furthermore, the performers used a significantly increased *dynamic strength* in rooms with low and high *early energy*. This might be explained by the notion to play louder in quiet rooms, which was described by the wind instruments in the interviews, and to predominate the sound of the room if its acoustic enhancement exceeds a certain threshold. A reduced *dynamic bandwidth* was found in rooms with long reverberation time and high late support. The effect of room acoustical properties on this performance characteristic was not addressed directly in the interviews, but all instruments reported to „hold back“ their sound when confronted with much reverberant energy. If this reaction is mainly related to *forte* passages, it could explain the results of the statistical analysis and it would be in line with the adjustments of pianists observed by von Békésy (1968). Regarding the tonal rendition, the musicians in the laboratory study played *soft* and *full* with low and high bass strength, they played *soft* with low and high late support and they played *hard* with low and high early sound strength. While it is not entirely clear if the first effect is related to a compensation of the timbre of the concert spaces, the second effect is probably partly associated with the sound „held back“ in reverberant rooms that was mentioned above. The described use of *hardness* could be connected to the increased *dynamic strength* under the same room acoustic conditions, that is low and high early sound strength. The mentioned influences on *timbre (soft – hard)* are the strongest effects found in the statistical analysis. At the same time, significant differences between the performative adjustments of some instruments especially regarding the timbre characteristics were revealed, and this variance is in agreement with the interviews. It was already concluded from the results of the field study that it is important to consider timbre characteristics when investigating the influence of room acoustics on music performance. The laboratory study additionally showed that an awareness of the played instrument is particularly necessary here.

Comparing the five room acoustical predictors with respect to their impact on each individual musician's performance qualities showed that the stage parameters $G_{\mathrm{e\ ins}}$ and $ST_{\mathrm{late\ ins}}$ have the greatest influence. If the performative adjustment of musicians to specific room acoustical parameters is considered as a criterion for their relevance in the context of stage acoustics, this result emphasises the importance of the above stage parameters. When describing the acoustics of the simulated concert spaces in the interviews, the musicians mainly named aspects regarding the timbre, the reverberation (duration, amount, timbre) and the sustainability. Correlating physical room acoustical parameters with ratings regarding these perceptual aspects was beyond the scope of this study but would contribute to finding suitable parameters for the prediction of musicians' perception of stage environments.

Some of the music scholars cited in section 2.3 as well as the interviews presented in section 6.5 implied that the quality of a room acoustical surrounding might also have an influence on the performance of musicians. This was examined by using the individual quality ratings given to the simulated concert spaces by the performers as independent variables in an HLM predicting the investigated performance characteristics. Calculating the pseudo-$R^2$ of this model by taking into account the individual musicians yielded a respectable amount of 7.49% explained variance. Compared to the pseudo-$R^2$ of 12.78% for a model with five room acoustical predictors, this appears as a very high value. It was shown that on average the musicians played slower, with more *dynamic strength* and with increased *dynamic* and *timbral bandwidth* in rooms they liked. These results are partly backed up by the interviews, in which the performers referred to a reduction of tempo and a free use of dynamics under favourable conditions as well as fast playing in rooms they did not like.

The laboratory study yielded results that are partly similar and partly different to the field study, while some aspects of the room acoustical influence on music performance were further distinguished. In the next section, overall conclusions are drawn by bringing together the findings of the two studies presented in this thesis and by considering the recommendations of music scholars as well as the results of previous investigations.

# 7

# OVERALL DISCUSSION AND CONCLUSIONS

In this thesis, the influence of room acoustics on solo music performances was examined by conducting two empirical studies. The first one was a case study with a renowned cellist playing the Six Suites for Violoncello Solo by J. S. Bach in 7 European performance venues. The second one was an investigation in a laboratory setup with 12 professional solo musicians of 6 standard orchestral instruments playing 2 pieces of different musical character in 14 concert halls simulated by means of dynamic binaural synthesis.

In both investigations, the performers were recorded with microphones positioned closely to or on the instruments. These recordings were processed by a software-based analysis extracting the time series of different temporal, loudness and timbre features. Statistical measures of these technical features were in turn used as independent variables in regression models that were based on a listening test. The regression models predicted 8 performance characteristics that had been previously defined by experts as relevant aspects of music performance. This method for quantifying the music performances ensured that perceptually and musically relevant performance characteristics (as opposed to single technical measures) could be determined from simple audio recordings (as opposed to MIDI data).

The room acoustical properties of the concert halls were determined with impulse response measurements in the field study. In a second step, computer

models of the halls were generated, enabling simulated measurements with the presence of an audience as well as the use of a source with the directivity of a cello for the excitation of the rooms. Similar computer models were used in the laboratory study as a basis for the dynamic binaural synthesis and for the simulated measurement of room acoustical parameters. Existing concert spaces representing typical room acoustical environments for the performance of Western classical music were used as prototypes for these computer models. Here, the directivities of the instruments involved in the experiment were used as sources for both the simulated measurements and the auralisations. This method for determining the room acoustical parameters in the field and laboratory study did not conform to standard measurement procedures that require the use of omnidirectional sources. Instead, the computer models and sources that were employed enabled the investigation of a broad range of room acoustical properties as they are typically experienced by musicians performing on stage.
In summary, the measurement methods for both the dependent (performance characteristics) and the independent (room acoustical parameters) variables of the studies were aimed at an outcome that is perceptually relevant and as close to the real-life experience of performers as possible.

**Can the influence of the room acoustical surrounding on music performance be empirically verified?** This was the main research question posed in the introduction of this thesis and concluding from the findings of the multilevel regression analyses applied in both studies the answer is clearly: Yes.
Regarding the explanatory power of the multilevel regression models, more than half of the variance in the performance characteristics determined from the recordings in the field study is explained by four salient room acoustical parameters. In the laboratory study, a regression model taking into account the adjustments of the individual musicians and using five room acoustical predictors for the performance characteristics yielded only one eighth of explained variance. It seems rather surprising that the room acoustical conditions had such a great impact in the field study, since there are presumably a lot of other factors influencing a performance in a real-world concert situation, the more so when

compared to the laboratory study, where the musicians were supposedly able to concentrate entirely on the room acoustics. Perhaps it is exactly this difference, though, that can elucidate why the explained variance was so much higher in the field study: The room acoustical conditions of real halls (as in the field study) can be expected to covary with other, visually conveyed properties of the room such as the room size, the distance between stage and audience or the stage configuration. Presumably, the entirety of these factors has a stronger influence on the performer than the acoustic modality alone (as in the laboratory study). Furthermore, the musicians confronted with the simulation of concert venues were probably engaged with coping with this unusual situation. The effort to get a clear mental idea of the room and the awareness of the experimental situation was mentioned by the performers in interviews carried out in the experiment, and it might have restricted the amount of performative adjustment no matter how good and plausible the room acoustical simulation was.

When focussing on the perceived quality of the room acoustics instead of room acoustical measures as a possible factor influencing the performance of musicians, the laboratory study revealed that one fifth of the variance in the performance characteristics can be explained by quality ratings of the players. In addition to this empirically confirmed effect on several of the independent variables, the interviews with the musicians implied a more general effect with good acoustics fostering „inspired playing“. This can be seen along the lines of good acoustics increasing a performer's sensitivity and enabling a higher degree of emotional expression as described by Flesch (1928). Furthermore, the qualitative content analysis conducted with the interviews of the field study indicated that the room acoustical conditions have an effect on the emotional state of the cellist in many cases. It remains unclear, though, if this in turn affected the performance itself, as these expressive and emotional aspects of music performance could not be in explored in this thesis.

When it comes to the question if the adjustments made to the room acoustical environment are conscious or not, the outcome of this thesis supports both assumptions. Some of the effects found in the statistical analyses clearly correspond to the interviews and were partly reported by the musicians as acquired concepts of how to react to certain room acoustical conditions. On the other hand, there are several significant effects that do not have a qualitative counterpart, so apparently there are also unconscious adjustments.

**Which aspects of performance are adjusted and in what way? Is the influence of the surrounding room dependent on the played instrument or even the musical content?** All of the eight investigated performance characteristics were affected significantly by the room acoustical conditions. The strongest effects in the statistical analysis were observed for the timbre characteristics in both studies, namely the quality *timbre (soft – hard)*, showing that the tonal rendition is a performance aspect that is readily adjusted to the room acoustical surrounding. While the musical content, represented by the basic tempo of the played pieces, only played a role in isolated cases, significant differences were found between the instruments in the laboratory study. Interestingly, this particularly concerned the adaptation of timbre characteristics, so they were not only clearly but also distinctly adjusted. Moreover, an important conclusion drawn from the laboratory study is that the adjustment strategies of musicians employed in different room acoustical surroundings are very individual, partly even if they play the same instrument. It can generally be inferred from the studies in this thesis that there seem to be specific but not always congruent adjustment strategies to room acoustical conditions among musicians, which shall be illustrated in the following by the results concerning the performance characteristics *dynamic strength* and *tempo*.

Turning to the former quality, it is noteworthy that music scholars recommended special care when playing loud in dry rooms because of potential roughness in tone and forced sound (Spohr, 1833; Galamian, 1962). The results of previous studies, however, imply that this recommendation might not be followed, as the greatest dynamic strength was usually found in rooms with short reverberation time (von Békésy, 1968; Ternström, 1989; Bolzinger et al., 1994). On the other hand, the musicians involved in both studies of this thesis in fact did reduce their *dynamic strength* with decreasing reverberation time and the issue was also touched in the interviews of the field study. Here, the cellist reported that his experience had taught him to adopt this strategy, so the way of adapting the *dynamic strength* to dry rooms might be a matter of practical knowledge. Furthermore, it must be noted that two of the three studies mentioned above investigated piano performances where it is less obvious that loud playing is accompanied by a rough or forced tone, so the instrument is an important factor to be considered here. Thus, two distinct adjustment strategies emerge from these observations and the reason why the one or the other is adopted might depend on experience and the played instrument.

In principle, it appears to be a common and intuitive reaction among musicians to play slower with increasing duration of the reverberation in a room. This was found in both studies of this thesis when looking at all of the played pieces together and it also emerged from the recommendations of music scholars and from previous studies (Quantz, 1752; Galamian, 1962; Blum, 1987; Naylor, 1992; Ueno et al., 2007). Along similar lines, prolonging pauses in reverberant conditions also contributes to a reduced tempo and was described by the musicians in the laboratory study and empirically found by Kato et al. (2015). However, some musicians apparently also use short notes (laboratory study; Ueno et al., 2010) probably connected to *staccato* playing (Naylor, 1992; Kato et al., 2015) and clear articulation (laboratory study; Blum, 1987). By differentiating between the basic tempo of the played pieces, it was shown in the laboratory study that if the latter strategy (short notes) was employed it applied mostly to fast pieces, which in some cases even evoked an increased *tempo*. The cellist of the field study apparently did not make use of this concept, instead it is mainly the fast pieces that he played slower with increasing reverberation time. In dry room acoustical surroundings, the *tempo* of the cellist and some musicians in the study by Ueno et al. (2007) was also decreased, which can be explained by prolonging notes to compensate for the lack of reverberation (Ueno et al., 2010). This quadratic function describing the relation between reverberation time and *tempo* was not observed in the laboratory study, though. Here, some players rather reported to play faster in dry rooms, which went along with the perception of bad room acoustical quality. The interrelation between *tempo* and quality was empirically confirmed in the laboratory study and supports an assumption already noted by Winckel (1962). There are thus at least three different concepts regarding the adjustment of *tempo* to long reverberation times (slowing down in slow pieces, slowing down in fast pieces, short notes in fast pieces) and two different concepts regarding the adjustment of *tempo* to short reverberation times (prolonging notes, playing faster). Even though they are conflicting to some extent, all of these concepts can be explained conclusively. Partly, their choice apparently depends on the musical content, but probably other factors – for example simply the personality of a performer – are at least as important.

**Which room acoustical properties are relevant for the presumed performative adjustments?** The 10 room acoustical parameters that were measured in each concert space in the field and laboratory study underwent a principal component analysis to find suitable predictors for the multilevel regression analyses employed. The resulting components were associated with the duration of reverberation, the late energy, the early energy and the timbre of the reverberation. In the field study, the latter component was determined by the bass ratio $BR_{\text{ins}}$ and the bass strength $G_{125\text{ ins}}$, while these two room acoustical parameters loaded on two separate components in the laboratory study. One salient room acoustical parameter was chosen from each component, so the predictors in the multilevel regression analyses represented the 4 to 5 dimensions of the room acoustical variance of the concert spaces that had an explanatory power of over 97%.
With respect to the question of which room acoustical parameters are important for musicians' perception of stage acoustics, those measures that affect music performance can be viewed as having a certain relevance. It should thus be emphasised that all room acoustical parameters except $BR_{\text{ins}}$ have a significant influence on at least one performance characteristic. The cellist in the field study adjusted his way of playing mostly to the duration of reverberation and the amount of reverberant energy ($RT_{\text{vlc}}$ and $ST_{\text{late vlc}}$), while the musicians in the laboratory study reacted mainly to the acoustical enhancement of the rooms and again the amount of reverberant energy ($G_{\text{e ins}}$ and $ST_{\text{late ins}}$). Hence, it seems that these measures are of special importance for musicians. When looking at the room acoustical qualities named in the interviews to describe the concert spaces,

the cellist in the field study indeed primarily referred to aspects regarding reverberation and late energy. The performers in the laboratory study mentioned timbre qualities, duration and amount of reverberation as well as sustainability most often. Since these qualitative descriptions of room acoustics were not determined quantitatively, no investigations of their correlation with measurable room acoustical parameters could be conducted. This would be especially interesting for those perceptual qualities that were reported in the interviews as having an influence on the music performances.

The statistical analyses employed in this thesis took the possibility into account that certain relations between response and predictor variables might be approximated by quadratic and not linear functions and both investigations did find quadratic functions for several room acoustical predictors and performance characteristics. The quadratic function implied as suitable approximation for the relation between the reverberation time and *tempo* by Kato et al. (2007) was also found in the field study but it could not be confirmed in the laboratory study. This suggests that the functional relation between dependent and independent variables might also be a matter of individuality among performers.

This research project was able to contribute substantially towards a better understanding of how performers react to their room acoustical surrounding. At the same time, some issues that future work could be directed at were raised.

In the case of laboratory setups employing virtual concert spaces, special care should be given to achieve natural and plausible simulated environments. This could involve taking into account the movements of the played instruments, as these were shown to have an audible effect on room acoustical simulations (Steger et al., 2015).

More empirical data is necessary to go into the finding that the musicians adjusted their performances in such an individual way. It might be possible to detect „adjustment profiles“, that is similar reaction patterns among several musicians playing different instruments, that imply related concepts of performative adjustment. This was indicated by the reaction patterns regarding *tempo* and *dynamic strength*, which need to be further elucidated, and it could also hold for other aspects of performance. Furthermore, the results concerning the effects on timbre characteristics call for further investigation, since the tonal rendition seems to be clearly adjusted but the underlying concepts cannot always be easily explained. Another object of future research could be to test the assumption that musicians adapt their performance to reach a certain sound effect in the audience area as opposed to simply reacting to the sound on stage. Finally, this thesis concentrated on solo performers, but the same questions that were raised here can of course be asked with respect to ensembles or orchestras.

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A

# PERFORMANCE DATA

| Suite | Mov. | Bars | Dur.$_{mean}$ [s] | Number of notes |
|---|---|---|---|---|
| I | 1 | 1 - 22 | 74 | 343 |
| | 2 | 1-16 | 134 | 464 |
| | 3 | 1-18 | 57 | 344 |
| | 4 | 1-8 | 73 | 128 |
| | 5 | 9-24 | 160 | 175 |
| | 6 | 13-34 | 55 | 281 |
| II | 1 | 1-48 | 159 | 513 |
| | 2 | 1-12 | 122 | 340 |
| | 3 | 1-16 | 51 | 364 |
| | 4 | 1-12 | 103 | 128 |
| | 5 | 9-24 | 133 | 135 |
| | 6 | 33-76 | 83 | 449 |
| III | 1 | 1-27 | 55 | 307 |
| | 2 | 1-12 | 123 | 456 |
| | 3 | 1-40 | 78 | 466 |
| | 4 | 9-24 | 149 | 247 |
| | 5 | 9-28 | 160 | 273 |
| | 6 | 1-48 | 76 | 412 |
| IV | 1 | 1-49 | 121 | 385 |
| | 2 | 1-16 | 108 | 406 |
| | 3 | 1-26 | 84 | 350 |
| | 4 | 12-32 | 137 | 213 |
| | 5 | 13-48 | 184 | 627 |
| | 6 | 1-10 | 32 | 224 |
| V | 1 | 28-80 | 56 | 270 |
| | 2 | 1-18 | 144 | 344 |
| | 3 | 1-12 | 57 | 210 |
| | 4 | 1-8 | 80 | 80 |
| | 5 | 13-36 | 235 | 321 |
| | 6 | 25-72 | 83 | 289 |
| VI | 1 | 1-22 | 58 | 248 |
| | 2 | 1-8 | 201 | 372 |
| | 3 | 1-28 | 82 | 470 |
| | 4 | 9-32 | 216 | 267 |
| | 5 | 9-28 | 172 | 257 |
| | 6 | 1-28 | 101 | 446 |

**Table A.1.** – Excerpts used in the field study for the software-based analysis of the performances of the Six Suites for Violoncello Solo by J. S. Bach; duration of the excerpts averaged over the recorded performances; number of notes in the excerpts.

| Instrument | Tempo | Dur.$_{mean}$ | Number of notes |
|---|---|---|---|
| Violin 1 | fast | 80 | 296 |
| | slow | 97 | 257 |
| Violin 2 | fast | 65 | 200 |
| | slow | 65 | 102 |
| Cello 1 | fast | 65 | 217 |
| | slow | 94 | 107 |
| Cello 2 | fast | 64 | 342 |
| | slow | 84 | 133 |
| Clarinet 1 | fast | 55 | 215 |
| | slow | 65 | 224 |
| Clarinet 2 | fast | 64 | 247 |
| | slow | 58 | 66 |
| Bassoon 1 | fast | 69 | 240 |
| | slow | 72 | 95 |
| Bassoon 2 | fast | 70 | 259 |
| | slow | 60 | 184 |
| Trumpet 1 | fast | 51 | 186 |
| | slow | 73 | 107 |
| Trumpet 2 | fast | 60 | 117 |
| | slow | 57 | 67 |
| Trombone 1 | fast | 63 | 117 |
| | slow | 64 | 106 |
| Trombone 1 | fast | 54 | 128 |
| | slow | 62 | 84 |

**Table A.2.** – Duration of the excerpts played by each musician in the laboratory study averaged over the recorded performances; number of notes in the excerpts.

# B

# ROOM ACOUSTICAL DATA

## B.1 In-situ measurements field study

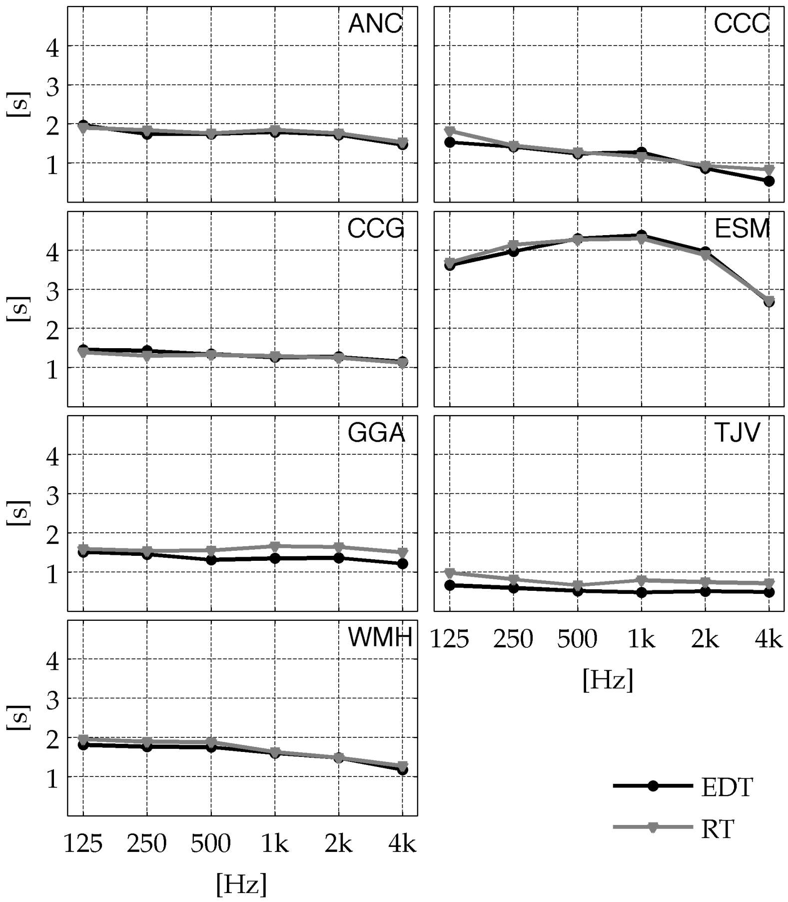



**Figure B.1.** – Frequency behaviour of the room acoustical parameters measured in the audience areas of the seven concert halls of the field study. The parameters are averaged over all audience positions of the respective hall (see figure 5.5).

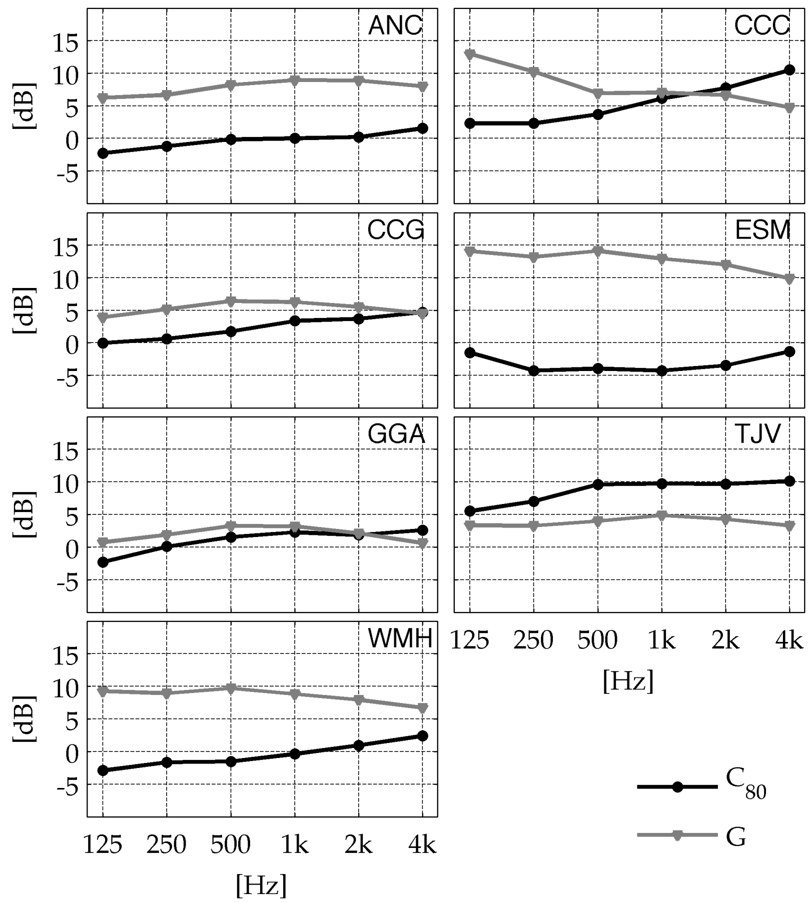
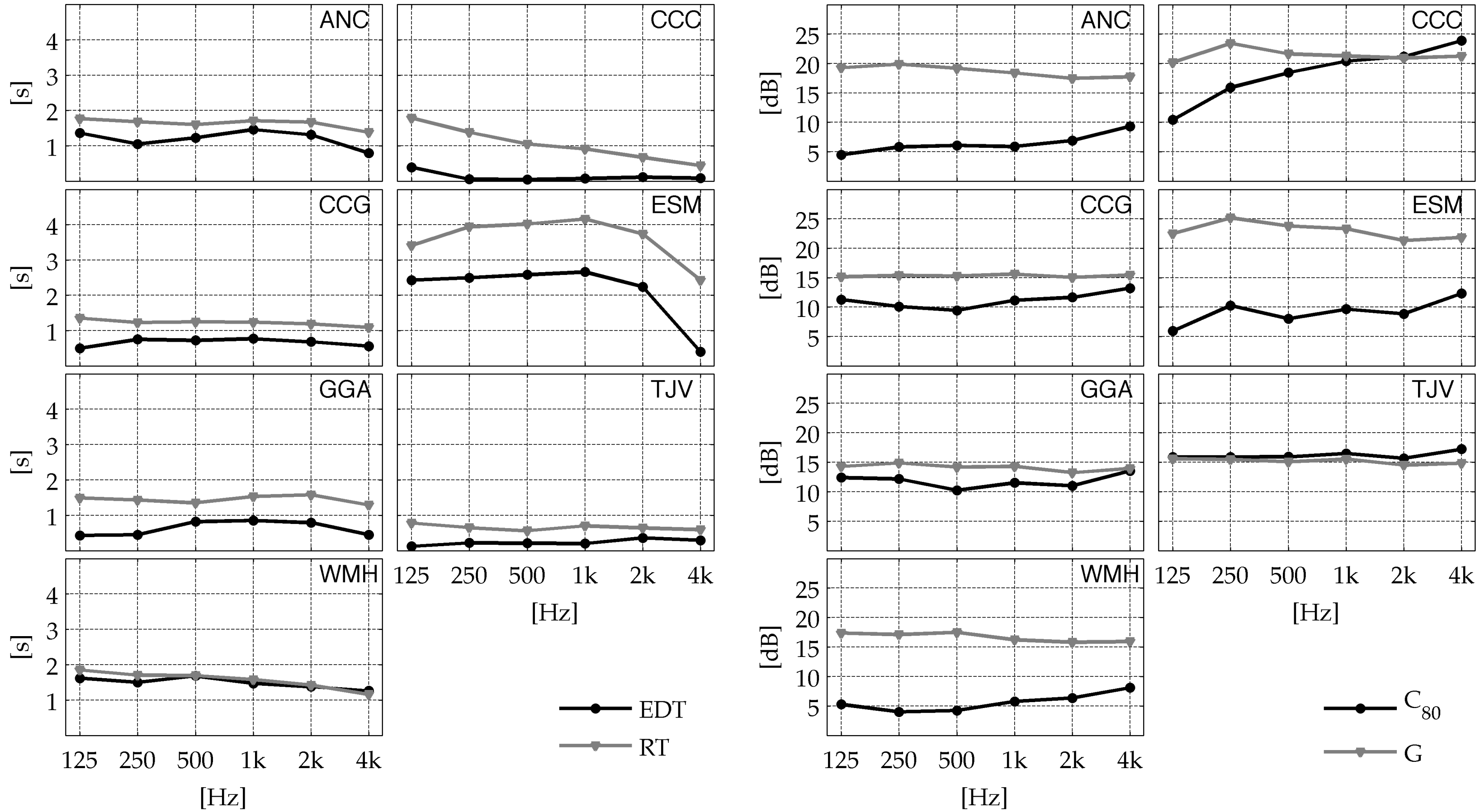
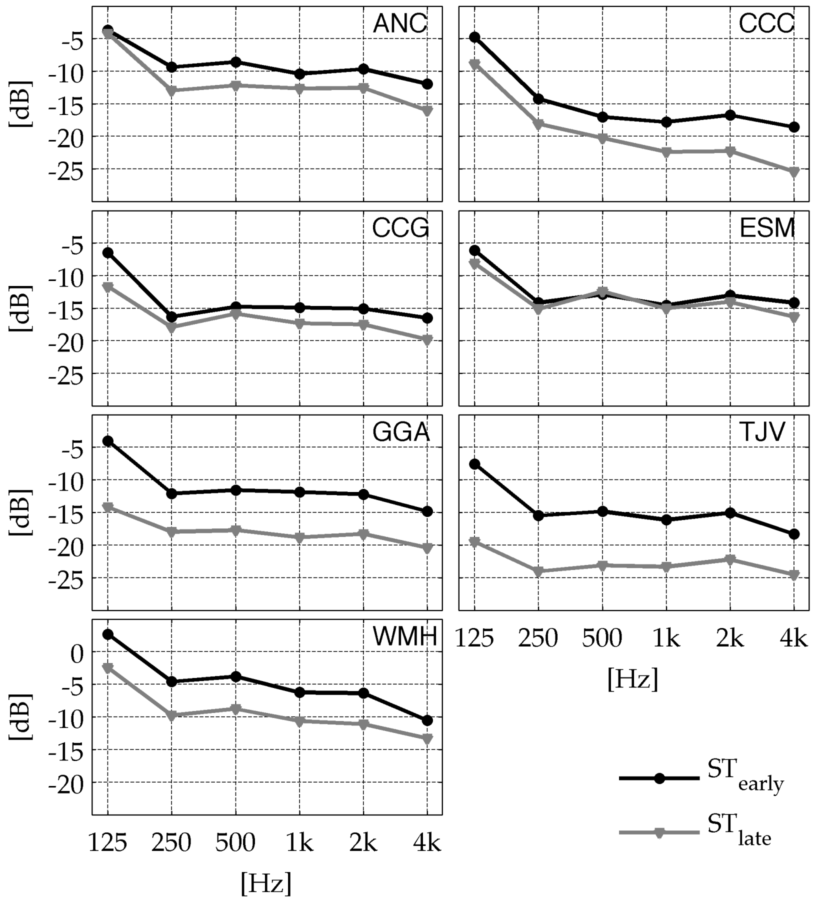



**Figure B.2.** – (continued) Frequency behaviour of the room acoustical parameters measured in the audience areas of the seven concert halls of the field study. The parameters are averaged over all audience positions of the respective hall (see figure 5.5).




(a) (b)

**Figure B.3.** – Frequency behaviour of the room acoustical parameters measured on the stages of the seven concert halls of the field study. The parameters are averaged over all stage positions of the respective hall (see figure 5.5).




**(c)**

**Figure B.4.** – (contiuned) Frequency behaviour of the room acoustical parameters measured on the stages of the seven concert halls of the field study. The stage measures $ST_{\text{early}}$ and $ST_{\text{late}}$ were averaged only over the receiver positions of the respective hall that were at 1 m distance from the source (see figure 5.5).

## B.2 Parameters of room acoustical simulations

The following parameters were adjusted in the AURA Response calculation module of the EASE software when generating reflectograms for the use in the field and laboratory study:

- **Number of particles:** This parameter defines the number of rays emitted by the sources in the computer model. The AURA Response module provides a suggestion of values for different simulation accuracies, with „high resolution“ being recommended for auralisations (EASE 4.3, 2009). In this thesis, the number of particles was further increased, until the late part of the reflectogram was simulated without audible artefacts. The values used for the calculations in the field and laboratory study are shown in tables B.1 and B.2.

- **Length [ms]:** After the time defined with this parameter, the simulation is terminated. A value of 75% of the expected reverberation time is recommended for the calculation of room acoustical parameters (EASE 4.3, 2009). For auralisations, the length should be at least as long as the expected reverberation time, which was maintained in both the field and the laboratory study in this thesis. The values used in the respective simulations are shown in tables B.1 and B.2.

- **Max. diameter after 1 s [m]:** This parameter defines the precision of the early part of the ray tracing with lower values yielding a higher precision. The EASE User's Guide recommends values of around 1 m (EASE 4.3, 2009). In the field study 0.5 m was used for all rooms, while all simulations were run with 1 m in the laboratory study.

- **Cut off order:** This is the order of image sourced after which the CAESAR algorithm switches to the ray tracing method (see section 4.2.2). Values between 1 and 30 are accepted by the AURA response module with 20 being used for the rooms in the field study and 15 for the rooms in the laboratory study.

- **Density factor:** In the late part of the reflectogram, pulses emitted per ms and defined by the density factor are used to generate the detailed structure. While a range between 10 and 30 is recommended (EASE 4.3, 2009), the values used for the simulations in this thesis were 15 for the field study and 30 for the laboratory study.

- **Tail resolution [ms]:** This parameter defines the width of the bins used in the ray tracing algorithm to calculate the energy distribution of the late part of the reflectogram. In both the field and the laboratory study, a resolution of 5 ms was applied for the simulations.

| **Room** | **Particles** | **Length [ms]** |
|---|---|---|
| ANC | 1 639 000 | 1700 |
| CCC | 11 516 000 | 1800 |
| CCG | 3 644 000 | 1200 |
| ESM | 2 741 000 | 4500 |
| GGA | 3 602 000 | 1700 |
| TJV | 3 205 000 | 900 |
| WMH | 2 000 000 | 1900 |

**Table B.1.** – Parameters applied for the generation of reflectograms used to calculate the room acoustical parameters of the EASE computer models in the field study.

| **Room** | **Particles** | **Length [ms]** | **Scattering [%]** |
|---|---|---|---|
| CHA1 | 5 356 000 | 2000 | 60 |
| CHA2a | 5 562 000 | 3200 | 80 |
| CHA2b | 5 562 000 | 1700 | 80 |
| CHUa | 21 559 500 | 3800 | 60 |
| CHUb | 21 559 500 | 3200 | 60 |
| CON1a | 37 272 000 | 3500 | 70 |
| CON1b | 26 000 000 | 2800 | 60 |
| CON2 | 23 542 500 | 3500 | 70 |
| OPR | 30 000 000 | 2200 | 60 |
| ANC | 9 832 500 | 2200 | 60 |
| GGA | 35 000 000 | 2400 | 70 |
| PLE | 2 066 000 | 2400 | 60 |
| TJV | 19 228 500 | 1000 | 60 |
| WMH | 20 000 000 | 2400 | 80 |

**Table B.2.** – Parameters applied for the generation of reflectograms used for the auralisation of the EASE computer models in the laboratory study. The specified scattering values are to be understood as frequency independent.

## B.3 PCA components used in laboratory study

The following tables show the loadings and explained variance for components resulting from PCAs with varimax rotation conducted with 10 room acoustical parameters measured with the source directivity of the specified instrument. Factor loadings > |0.5| are marked bold, highest loadings are underlined.

| | Components | | | | |
|---|---|---|---|---|---|
| Parameters | 1 | 2 | 3 | 4 | 5 |
| $G_{125\ \mathrm{vl}}$ | **<u>0.91</u>** | 0.23 | 0.04 | 0.00 | 0.23 |
| $ST_{\mathrm{late\ vl}}$ | **0.86** | 0.22 | 0.32 | 0.31 | 0.00 |
| $C_{80\ \mathrm{vl}}$ | **-0.84** | -0.21 | -0.24 | -0.37 | -0.18 |
| $G_{\mathrm{l\ vl}}$ | **0.83** | 0.23 | 0.24 | 0.37 | 0.17 |
| $ST_{\mathrm{early\ vl}}$ | **0.62** | 0.44 | **0.60** | 0.17 | -0.09 |
| $G_{\mathrm{e\ vl}}$ | 0.29 | **<u>0.84</u>** | 0.31 | 0.19 | -0.28 |
| $G_{\mathrm{vl}}$ | 0.47 | **0.70** | 0.32 | 0.38 | -0.17 |
| $BR_{\mathrm{vl}}$ | 0.13 | 0.23 | **<u>0.95</u>** | 0.12 | -0.01 |
| $EDT_{\mathrm{vl}}$ | 0.47 | 0.37 | 0.18 | **<u>0.74</u>** | -0.10 |
| $RT_{\mathrm{vl}}$ | 0.26 | -0.23 | -0.02 | -0.04 | **<u>0.94</u>** |
| Expl. var. [%] | 39.41 | 18.28 | 17.17 | 11.40 | 11.17 |

**Table B.3.** – Violin

| | Components | | | | |
|---|---|---|---|---|---|
| Parameters | 1 | 2 | 3 | 4 | 5 |
| $C_{80\ \mathrm{cl}}$ | **<u>-0.96</u>** | -0.16 | -0.13 | -0.13 | -0.12 |
| $G_{\mathrm{l\ cl}}$ | **0.95** | 0.19 | 0.13 | 0.13 | 0.13 |
| $ST_{\mathrm{late\ cl}}$ | **0.91** | 0.31 | -0.02 | 0.14 | 0.18 |
| $ST_{\mathrm{early\ cl}}$ | **0.80** | 0.40 | -0.38 | 0.03 | -0.04 |
| $EDT_{\mathrm{cl}}$ | **0.52** | **0.51** | -0.19 | -0.44 | 0.30 |
| $G_{\mathrm{e\ cl}}$ | 0.22 | **<u>0.94</u>** | 0.00 | -0.10 | 0.24 |
| $G_{\mathrm{cl}}$ | 0.42 | **0.86** | 0.01 | -0.10 | 0.25 |
| $RT_{\mathrm{cl}}$ | 0.05 | -0.00 | **<u>0.98</u>** | 0.12 | -0.08 |
| $G_{125\ \mathrm{cl}}$ | 0.29 | -0.12 | 0.11 | **<u>0.92</u>** | -0.02 |
| $BR_{\mathrm{cl}}$ | 0.19 | 0.43 | -0.10 | -0.05 | **<u>0.87</u>** |
| Expl. var. [%] | 39.33 | 24.08 | 12.09 | 11.40 | 10.36 |

**Table B.4.** – Clarinet

| | Components | | | | |
|---|---|---|---|---|---|
| Parameters | 1 | 2 | 3 | 4 | 5 |
| $ST_{\text{late fg}}$ | **0.96** | -0.06 | 0.08 | 0.17 | 0.09 |
| $G_{\text{l fg}}$ | **0.94** | -0.26 | 0.15 | 0.14 | 0.00 |
| $C_{80\text{ fg}}$ | **-0.93** | 0.29 | -0.15 | -0.14 | -0.00 |
| $ST_{\text{early fg}}$ | **0.90** | 0.05 | -0.28 | 0.12 | -0.20 |
| $G_{\text{fg}}$ | 0.02 | **0.99** | -0.00 | 0.09 | -0.04 |
| $G_{\text{e fg}}$ | -0.14 | **0.99** | 0.01 | 0.06 | -0.00 |
| $EDT_{\text{fg}}$ | -0.39 | **0.87** | 0.13 | -0.09 | 0.16 |
| $G_{125\text{ fg}}$ | -0.04 | **0.77** | 0.07 | 0.00 | **0.62** |
| $RT_{\text{fg}}$ | 0.07 | 0.09 | **0.98** | -0.06 | 0.03 |
| $BR_{\text{fg}}$ | **0.58** | 0.12 | -0.11 | **0.80** | -0.00 |
| Expl. var. [%] | 39.93 | 34.91 | 11.34 | 7.42 | 4.62 |

**Table B.5.** – Bassoon

| | Components | | | | |
|---|---|---|---|---|---|
| Parameters | 1 | 2 | 3 | 4 | 5 |
| $C_{80\text{ trp}}$ | **-0.96** | -0.21 | -0.03 | -0.12 | -0.11 |
| $ST_{\text{late trp}}$ | **0.96** | -0.03 | 0.12 | 0.19 | 0.15 |
| $G_{\text{l trp}}$ | **0.96** | 0.18 | 0.04 | 0.13 | 0.15 |
| $EDT_{\text{trp}}$ | **0.88** | -0.14 | 0.28 | -0.08 | 0.12 |
| $ST_{\text{early trp}}$ | **0.86** | -0.37 | -0.11 | 0.09 | 0.26 |
| $G_{\text{trp}}$ | **0.80** | -0.03 | 0.22 | 0.15 | **0.53** |
| $RT_{\text{trp}}$ | 0.02 | **0.96** | -0.21 | 0.18 | -0.04 |
| $BR_{\text{trp}}$ | 0.13 | -0.19 | **0.95** | 0.11 | 0.11 |
| $G_{125\text{ trp}}$ | 0.15 | 0.17 | 0.10 | **0.96** | 0.11 |
| $G_{\text{e trp}}$ | **0.65** | -0.09 | 0.23 | 0.25 | **0.67** |
| Expl. var. [%] | 53.56 | 12.13 | 11.72 | 11.34 | 8.98 |

**Table B.6.** – Trumpet

| | Components | | | | |
|---|---|---|---|---|---|
| Parameters | 1 | 2 | 3 | 4 | 5 |
| $EDT_{\text{trb}}$ | **0.94** | 0.21 | -0.08 | 0.00 | 0.04 |
| $C_{80\text{ trb}}$ | **-0.92** | -0.22 | -0.19 | -0.20 | -0.16 |
| $G_{\text{l trb}}$ | **0.91** | 0.25 | 0.19 | 0.21 | 0.15 |
| $ST_{\text{late trb}}$ | **0.90** | 0.23 | -0.05 | 0.25 | 0.23 |
| $ST_{\text{early trb}}$ | **0.82** | 0.26 | -0.41 | -0.04 | 0.15 |
| $G_{\text{trb}}$ | **0.70** | **0.66** | 0.08 | 0.25 | 0.08 |
| $G_{\text{e trb}}$ | **0.56** | **0.77** | 0.11 | 0.27 | 0.07 |
| $RT_{\text{trb}}$ | 0.03 | 0.09 | **0.98** | -0.12 | -0.10 |
| $BR_{\text{trb}}$ | 0.18 | 0.19 | -0.13 | **0.95** | 0.03 |
| $G_{125\text{ trb}}$ | 0.21 | 0.05 | -0.11 | 0.03 | **0.97** |
| Expl. var. [%] | 49.19 | 13.47 | 12.50 | 12.09 | 10.84 |

**Table B.7.** – Trombone

# C

# INTERVIEWS AND QUESTIONNAIRE

## C.1 Qualitative content analysis

| Category | Coding rules | Examples |
|---|---|---|
| Performance concept | All statements about general rules or views concerning performance conditions or the way of playing of the chosen pieces | „Also ich variiere eigentlich gar nicht im Tempo.“ |
| Room acoustics | All assessments and descriptions of one or more aspects of the room acoustics of the concert spaces | „...und dann war da noch ein ziemlich diffuser, langer Nachhall.“ |
| Performative adjustment | All statements describing a specific way of playing resulting from the room acoustical conditions of the concert halls | „Ja dann hab ich eigentlich mehr Zeit zwischen den Noten genommen im zweiten Satz weil ich immer den Klang im Ohr hatte, da musste ich einfach ein bisschen warten bis es wieder still ist.“ |
| Artefact | All statements about technical artefacts or influences of the experimental situation | „Das Kabel hinten hat irgendwie ein bisschen gezogen diesmal.“ |

**Table C.1.** – Coding rules and examples of the categorisation system used for the qualitative content analysis of the interviews carried out in the laboratory study. The examples are left in the original language German so that nuances in their meaning are not lost in translation.

| Category | Coding rules | Examples |
|---|---|---|
| Performance concept | All statements about general rules or views regarding performance conditions or the way of playing of the cello suites by Bach | „Ich find bei Bach muss man sowieso mit Klangfarben, muss man relativ nüchtern umgehen." |
| Programme | All statements about the pieces played in the concerts (not the way of playing!) | „Und die [Suite] war eher am Anfang des Programms..." |
| Performance | All statements about the sound production during the concerts | „Ich konnte von der Dynamik her unglaublich runtergehen." |
| Instrument | All statements about the instrument played in the concerts | „...und dadurch der Klang ein bisschen mühsam war. Sowohl von Seiten des Cellos...." |
| Audience | All statements about the audience in the concerts and its behaviour | „...sehr aufmerksam, sehr konzentriert, sehr dabei." |
| Physical state | All statements about the physical constitution of the performer during the concerts | „Ich habs so in Erinnerung, dass ich ein bisschen fest war, sozusagen. Also, ja, physisch." |
| Emotional state | All statements about the emotional constitution of the performer during the concerts | „Ich war etwas enttäsucht..." |
| Room acoustics | All quantitative and qualitative assessments as well as descriptions of one or more aspects of room acoustics | „Es war einfach unglaublich klar..." |
| Room dimensions | All statements about the dimensions of the concert halls | „...in einem großen weiten Raum." |
| Climatic conditions | All statements about the climatic conditions in the concert halls | „Also dass es am Abend sehr warm und sehr feucht war." |
| Atmosphere | All statements about the ambience during the concerts | „...wo da eine unglaubliche Intimität herrscht zwischen Spieler und Zuhörern." |
| Lighting | All statements about the lighting during the concerts | „Beide Konzerte waren im Tageslicht, da kommt ganz viel Tageslicht von oben..." |
| External factors | All statements about circumstances occurring outside of the actual concerts | „Und dann kommt erschwerend noch dazu diese blöde Reise [...], die schief gelaufen ist wegen diesem riesen Stau." |
| Connection | All statements that establish a relationship between two of the other categories | „Es hat auf jeden Fall einen schönen Nachklang und dadurch kann man natürlich eben leicht spielen..." |

**Table C.2.** – Coding rules and examples of the categorisation system used for the qualitative content analysis of the interviews carried out in the field study. The examples are left in the original language German so that nuances in their meaning are not lost in translation.

## C.2 Questionnaire

**Lieber Versuchsteilnehmer,**
**vielen Dank, dass Sie an dieser Studie teilnehmen.**

Sie werden nacheinander in virtuellen Räumen spielen, die Sie jeweils in Bezug auf die unten gelisteten Eigenschaften bewerten sollen. Bitte lesen Sie sich die Beschreibungen sorgfältig durch und fragen Sie bei Unklarheiten.

| **Gegensatzpaar** | | **Beschreibung** |
|---|---|---|
| tragfähig | wenig tragfähig | Trägt der Raum das Spiel oder nicht? |
| ich kann mich gut hören | ich kann mich nicht gut hören | Können Sie Ihr Instrument gut hören? |
| trocken | hallig | Hat der Raum einen langen oder kurzen Nachhall? |
| Raum spricht früh an | Raum spricht spät an | Kommt der Raumklang gleich oder verzögert? |
| groß | klein | Handelt es sich um einen großen oder kleinen Raum? |
| gute Akustik | schlechte Akustik | Gefällt die Akustik oder nicht? |
| hoher Raum | niedriger Raum | Wirkt der Raum niedrig oder hoch? |
| breiter Raum | schmaler Raum | Wirkt der Raum breit oder schmal? |
| dunkel | hell | Wie ist die Klangfarbe des Raums, des Nachhalls? |
| viel Raum | wenig Raum | Wie ist die Balance zwischen Instrument und Raumklang? |
| unterstützend | nicht unterstützend | Hilft der Raum beim Spielen? |
| laut | leise | Nehmen Sie Ihr Instrument laut oder leise wahr? |
| diffus | klar | Ist der Raumklang durchmischt oder klar? |
| dünn | voll | Hat der Raum einen dünnen oder vollen Klang? |
| weich | hart | Wirkt der Raum weich oder hart? |
| rund | metallisch | Hat der Raum einen dumpfen oder eher einen metallischen Klang? |
| Nachhall klingt weich aus | Nachhall bricht ab | Wie klingt der Nachhall aus? |
| ausgewogen | unausgewogen | Bietet der Raum ein in sich stimmiges Gesamtbild? |
| Klangfarbe ist gleichmäßig | Klangfarbe fluktuiert | Bleibt die Klangfarbe im Nachklang gleichmäßig oder schwankt sie? |
| Nachklang wird schärfer | Nachklang wird dumpfer | Wie ändert der Nachklang im Verlauf seine Klangfarbe? |

**Figure C.1.** – Questionnaire answered by the participants of the laboratory study after playing in each of the simulated concert spaces. The attributes are the result of a qualitative study presented in Stahnke (2013), a translation is given in table C.3.

| German attributes | English translation |
|---|---|
| Tragfähig – wenig tragfähig | Sustainable – not sustainable |
| Ich kann mich gut hören – ich kann mich nicht gut hören | I can hear myself well – I cannot hear myself well |
| Trocken – hallig | Dry – reverberant |
| Raum spricht früh an – Raum spricht spät an | Early response of room – late response of room |
| Groß – klein | Large – small |
| Gute Akustik – schlechte Akustik | Good acoustics – bad acoustics |
| Hoher Raum – niedriger Raum | High room – low room |
| Breiter Raum – schmaler Raum | Wide room – narrow room |
| Dunkel – hell | Dark – bright |
| Viel Raum – wenig Raum | Much room – not much room |
| Unterstützend – nicht unterstützend | Supportive – not supportive |
| Laut – leise | Loud – quiet |
| Diffus – klar | Diffuse – clear |
| Dünn – voll | Thin – full |
| Weich – hart | Soft – hard |
| Rund – metallisch | Round – brazen |
| Nachhall klingt weich aus – Nachhall bricht ab | Reverberation fades out softly – reverberation is cut off |
| Ausgewogen – unausgewogen | Balanced – unbalanced |
| Klangfarbe ist gleichmäßig – Klangfarbe fluktuiert | Timbre is even – timbre fluctuates |
| Nachklang wird schärfer – Nachklang wird dumpfer | Reverberation gets sharper – reverberation gets muffled |

**Table C.3.** – English translation of the attributes used in the questionnaire shown in figure C.1.