

PRESENTS

The PhD thesis by Jens Jørgen Dammerud:

## Stage Acoustics for Symphony Orchestras in Concert Halls

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# **STAGE ACOUSTICS FOR SYMPHONY ORCHESTRAS IN CONCERT HALLS**

Submitted by Jens Jørgen Dammerud  
for the degree of  
Doctor of Philosophy  
of the University of Bath  
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# Abstract

The main goals for this study were to better understand what are the acoustic conditions physically within a symphony orchestra on concert hall stages, how these physical conditions affect the players and ultimately how to design venues suitable for symphony orchestras. This was investigated by use of several different approaches, including questionnaire surveys and dialogue with musicians, scale and computer modelling and measurements of existing stages.

The results from the orchestra collaborations indicate that the following are of most concern for players regarding acoustic conditions: hearing all other players in the orchestra clearly and having sound from others well balanced with the sound of their own instrument and the acoustic response from the main auditorium. These subjective aspects appear to relate to complex perceptual effects like the precedence effect, masking effects and the cocktail-party effect. When relating these effects to physical conditions, a narrow and high stage enclosure with the stage highly exposed to the main auditorium appears most beneficial.

Regarding musicians' impressions of actual stages and objective measurement results, existing methods for assessing the stage acoustically by use of omnidirectional transducers without the orchestra present were found to have only limited relevance. The reliability and validity of the most common acoustic measures (including *ST*) were studied in detail.

For the assessment and design of stage enclosures, new methods and objective architectural measures have been proposed. A combination of acoustic and architectural measures are found to successfully discriminate the most preferred from the least preferred stages of purpose-built concert halls. The results from judgements of existing stages support the finding of a narrow and high stage enclosure with a highly exposed stage being most beneficial. The objective measures studied are simplified representations of real acoustic conditions. How to improve the assessment of acoustic conditions on stage is also discussed.



# Preface

This thesis is split into nine main chapters:

**Chapter 1: Introduction.**

**Chapter 2: Background of the study.** The literature review.

**Chapter 3: Musicians' impressions of acoustic conditions.** Studies of impressions of acoustic conditions on stage in general terms.

**Chapter 4: Sound propagation within a symphony orchestra.** Studies of how the symphony orchestra itself affect sound propagation between players.

**Chapter 5: The effect of reflected sound back towards a symphony orchestra.** Studies of how reflected sound may affect perceived conditions among the players.

**Chapter 6: Computer modelling of stage enclosures including a full symphony orchestra.** Studies of how to represent a symphony orchestra in computer models. The developed representation of an orchestra is used to study resulting acoustic responses under different stage enclosure designs, with a symphony orchestra present on stage.

**Chapter 7: Acoustic measures for assessing acoustic conditions on stage.** Studies of the validity and reliability of acoustic responses and measures, assessed without a symphony orchestra present on stage. Values of the acoustic measures are compared with subjective impressions for a set of existing stages.

**Chapter 8: Impressions of eight performance spaces visited regularly.** Studies of one orchestra's impressions of acoustic conditions in eight performance spaces they visit regularly.

**Chapter 9: Overall discussion and conclusions.**

Preliminary results from the research project forming this thesis were presented at international conferences on acoustics ([Barron & Dammerud \(2006\)](#), [Dammerud & Barron \(2007\)](#) and [Dammerud & Barron \(2008\)](#)). Copies of these papers are not included in this thesis.

This thesis was prepared in L<sup>A</sup>T<sub>E</sub>X (set for double-sided printing) using MiKTeX and L<sup>E</sup>D.





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# Chapter 1

## Introduction

This study and studies by others (Gade (1989b), Meyer (2009), Naylor (1988), Ueno & Tachibana (2003)) reveal that acoustic conditions on stage are very important for symphony orchestra musicians. For symphony orchestras, the acoustic conditions within the ensemble itself are different from smaller ensembles like chamber ensembles. The size of a symphony orchestra leads to the sound from most distant fellow players being significantly delayed and attenuated. Concert halls have historically been purpose-built for symphony orchestras, with the size of the stage and auditorium to accommodate the orchestra and the orchestral repertoire. But even among such purpose-built halls, there are stages which are liked and those that are disliked by performers. The overall goals for this project were to learn more about how acoustic conditions affect the players, and how the design of the stage enclosure and auditorium affects the acoustic conditions for the players. These investigations were carried out independent of any hypotheses. More specifically the overall goals can be split up into three: gaining understanding of the musicians' impressions of acoustic conditions, recognise types of venue and thirdly establishing which stage enclosure (stage shell) designs provide good acoustic conditions for the players. Objective measures, both acoustic and architectural, have been studied to search for how good acoustic conditions may be described or detected physically. These goals are at a top level of relations between acoustic conditions and the performers. This means that the focus for this work has been to find the major relations. The underlying mechanisms for the major relations are only partly studied in detail. A major outcome of this study would be to better understand how to design halls and stage enclosures that will provide good acoustic conditions for symphony orchestras, who consequently will perform better.

Historically the focus in auditorium acoustics has been on the acoustic conditions for the audience. Even though acoustic conditions for the performers certainly have been discussed vividly among the performers themselves for centuries, these aspects of concert hall acoustics do not appear to have been given priority among acousticians (investigating the science of acoustics). There might be several reasons for such a weak link between physical acoustic conditions and perceived conditions, but one of the main reasons could be related to the role physical conditions have for a general performer. Musicians have learnt over years of training and experience how to cope with different acoustic conditions. They appear to relate to the



acoustic conditions on a more sub-conscious level of perception. If they consider the acoustic conditions in detail while playing, they risk losing focus on the musical performance. Such mechanisms behind musical performance have been described by for instance [Klaveness \(2008\)](#). When acousticians ask the musicians about acoustic conditions and preference for certain stage conditions, the musicians are (for good reasons) likely to not have many answers which will be informative for the acousticians.

The above observations suggest that it will be very challenging for the musicians to have well founded observations of how for instance the architectural designs of the venue affect them. Some players may have ideas of how different acoustic conditions affect them, but as discussed by [Barron \(1993\)](#) we cannot expect an observer (musician) to unravel a complex situation just from simple experience. The priorities of attention and educational background as a performer can also contribute to challenges being able to communicate such discoveries clearly/efficiently to for instance acousticians. The musicians are not trained within any physical science disciplines, and acousticians often have no formal education or experience in music and performance. There is a high risk of any discovered relations can be lost, simply because the two groups have a different vocabulary, or the reason might be that the two parts rarely communicate at all with regard to perceived acoustic conditions. [Gade \(1981\)](#) interviewed musicians about their impressions and relations to acoustic conditions on stages. One of his findings was that the musicians very rarely discussed acoustic conditions with acousticians. Unfortunately, this work has never been published in any scientific journal. [Blauert \(2007\)](#) has raised concern about the mismatch of focus between acousticians and users of acoustic spaces, and that this mismatch can lead to problems when these two groups try to communicate (exchange ideas/views).

How could studies aiming to raise the understanding of acoustic conditions for performers overcome these problems sufficiently? In other disciplines like audio technology and psychoacoustics, it is common to simulate different acoustic environments/conditions where it is possible to quickly switch between different configurations. Systems have previously been implemented to simulate acoustic conditions for soloistic playing and for two musicians playing together, with and without visual communication ([Naylor & Craik \(1988\)](#), [Gade \(1989b\)](#), [Ueno & Tachibana \(2003\)](#) and [Guthrie \(2008\)](#)). In real conditions, the communication between two players is affected by the sound from the rest of the orchestra playing. Without including the complete orchestra the validity of such laboratory experiments is likely to be limited, though certain aspects of acoustic conditions may be studied. Halls with flexible stage enclosures offer exciting possibilities for research, but such halls are unfortunately rare. Most existing concert halls have fixed architectural designs, where only minor changes are possible (only a few halls exist globally where the stage enclosure is highly configurable). With fixed stage enclosure designs, different halls need to be studied. The number of orchestras involved and how many times the orchestra(s) have played in each hall are factors likely to affect the validity of such studies. There will therefore be significant shortcomings for both approaches – either reduced naturalness and not including a full orchestra in laboratory experiment, or a reduced control and flexibility of the acoustic conditions in studies of real halls.

Given these challenges, a combination of different approaches has been used for this study. The two major types of approaches may be described as subjective and objective approaches.

The subjective approach includes investigations of impressions of acoustic conditions among orchestral players in general and relating to specific existing stages. The objective approach includes studies of physical conditions in the venues that were judged by the players, but also how the arrangement of a symphony orchestra imposes certain acoustic conditions for the players (through scale modelling) and in what way conditions may be improved by a stage enclosure. The results from these two different approaches were compared to each other to guide the focus for the investigations through-out the project, and to search for valid relations between physical acoustic conditions and subjective impressions. Hypotheses with regard to how acoustic conditions are perceived among players have also been developed through the author's own experience as an amateur musician within larger ensembles. This would be on a less scientific level (since amateur and professionals may judge acoustic conditions very differently), but has been very useful for an acoustician (the author) to better understand the players' point of view.

The study of general impressions among the players include what perceptual aspects they find important for good stage acoustic conditions, problems they most frequently face, their favourite hall visited through-out their career etc. Such impressions will be based on several years of experience. Eight different professional orchestras within England and Norway participated in a questionnaire survey covering such general impressions. For the subjective studies of existing stages, there has been aimed for high numbers of stages/halls and players participating in the study. Focus has been on impressions among players visiting a set of halls frequently (excluding home venues), for reducing the influence of factors varying between performances (like repertoire) and allowing the players to have established the most valid impressions. Impression of existing stages were investigated in two different studies: impressions of overall acoustic impression for the halls visited regularly by seven of the eight orchestras mentioned above, as well as a detailed study with one of the professional English orchestras. For the halls visited by the eight orchestras basic objective data were collected, both acoustic and physical dimensions related to the stage enclosure. For the detailed study, the orchestra plays regularly in a set of eight halls, about which most of the players have developed their views over several years. Their impressions were investigated through questionnaires distributed to the players and through interviews with some of the players. Objective data were collected also in this study, but the acoustic conditions in the eight halls were investigated in detail by measuring monophonic room impulse responses on the stages and within the audience area. As a summary, this study includes judgements of totally 20 purpose-built concert halls which the players visit regularly.

The objective studies included theoretical/analytical investigations, scale modelling and computer modelling. Scale models were used to study the acoustic conditions set up by the orchestra itself, in particular how the screening effects caused by players and objects on stage affect sound propagation between players. Scale models were also used to investigate the possible consequences of measuring acoustic conditions on stage without a full symphony orchestra present. How such initial acoustic conditions set up by the orchestra could be improved by the introduction of a stage enclosure, is studied analytically with reference to available literature on perceptual effects that appear most relevant for the players. Computer modelling was used to study acoustic conditions on stage with a full symphony orchestra present, and how the conditions are affected by different enclosure elements and designs.

This thesis is structured in different complete chapters covering different topics. Chapter 2 contains the literature review forming the background of the study. The subjective studies are described in Chapters 3 and 8, while the objective studies are described in Chapters 4–7. Chapter 3 describes the results from questionnaires distributed to the eight different orchestras within England and Norway. Chapter 4 investigates the sound levels within the orchestra itself, and how the screening effects caused by players and objects on stage affect sound propagation between players. Chapter 5 investigates extreme types of stage enclosure designs by simplified analytical methods, where resulting differences are compared to findings related to perception of sound in general and findings by others with regard to enclosure designs. Chapter 6 considers computer modelling of generic stage enclosure designs to get a more complete impression of how the different designs affect acoustic conditions. Chapter 7 covers acoustic measures related to existing stage, while Chapter 8 includes the subjective results in the eight different halls visited regularly by one orchestra – with reference to objective results.

## Chapter 2

# Background of the study

This review of the literature on stage acoustics for symphony orchestras in concert halls is split into four major sections. The first section discusses physical acoustic conditions within the orchestra. The second section covers subjective impressions for musicians on stage. The two final sections cover objective measures proposed for evaluating acoustic conditions for the performers and how design of the stage enclosure affects conditions for the conductor and the audience. These four sections cover the basic concerns of this project. The methods used for this study are discussed in the last section of this chapter.

### 2.1 Physical objective sound behaviour within symphony orchestras

Since around 1950, a lot of research work has been devoted to acoustic conditions for the audience in concert halls. This work is discussed and summarised by [Barron \(1993\)](#) and [Beranek \(2004\)](#), for instance. One outcome of this research is a set of objective measures relating to conditions for listeners being included in the standard ISO 3382 ([ISO, 1997](#)). Study of conditions for musicians on concert hall stages has on the other hand received much less attention. What has become clear is that the acoustic requirements of listeners and performers overlap regarding quality of the sound (like ‘warmth’, tone colour), but performers also need to hear their own instrument and being able to communicate with their colleagues through the sounds they produce. Whether any of the measures used for concert hall listening are likely to be suitable for acoustic conditions for performers is debatable. This question is further explored in [Section 2.2](#).

A significant difference between conditions for audience and players is the range of source-receiver distances. For an audience member 10 m from the stage front, the distance to the closest and farthest musician will typically be in a ratio of 1:2 (a 6 dB difference of direct sound levels). Most listeners are further away from the stage and the range of distances to all instruments will be small. For a performer in an orchestra, some players will be close by,

while other players can be up to 20 m away from each other (for a 16 m wide and 12 m deep stage). The distances involved will depend on how the players are arranged on stage (see Appendix A for more details). This leads to a distance ratio of typically up to 1:20 between the distance to the closest and most distant player. Such a ratio corresponds to a 26 dB difference of direct sound levels – a very significant difference. Additionally, the sound path between distant players will be obscured by other players sitting in between, as well as music stands and instruments. Sound reflections internally within the orchestra will compensate slightly for this attenuation by other players etc.

How the orchestra itself contributes to the attenuation of the direct sound within the orchestra is obviously important for on-stage conditions. This has previously not been studied in detail. Some brief studies have been carried out by Krokstad *et al.* (1980), Ikeda *et al.* (2002) and Skålevik (2007). Krokstad *et al.* (1980) studied sound propagating through a group of nine persons sitting on a flat floor, while Ikeda *et al.* (2002) studied sound levels within a real symphony orchestra at source-receiver distances 2–6 m. Skålevik (2007) studied the sound levels within 0–50 ms (relative to the arrival of the direct sound) with different source heights at one source-receiver distance of 12 m. Mommertz (1993) has studied sound propagation through rows of audience sitting in a theatre, presenting results in terms of attenuation per metre. The results from Mommertz's study cannot be applied directly to the conditions within the orchestra, since the density of people is different for an orchestra and musicians are not arranged in rows. This topic is pursued further in Section 4.3.7. These studies give some indications of the obstruction effect by the orchestra, without any well founded quantification of the attenuation to expect along different paths within the orchestra with the whole range of relevant source-receiver distances. The studies above give some indication of the obstruction effects of orchestra players, but the results are far from comprehensive.

The sound level of musical instruments within an orchestra in particular directions is described by their directivities. The directivity of musical instruments for a symphony orchestra have been measured by Olson (1967) and more extensively by Meyer (2009). See Appendix A for more details on directivities of a violin and a trumpet. These results provide some indication of the directions in which most sound is radiated. A complicating factor with regard to directivity is that the directivity changes depending on the note being played, particularly for string instruments. According to Otondo & Rindel (2004) the directivity of brass instruments is reasonably consistent between each note played. Significant changes of directivity depending on the note being played makes it difficult to use measured directivity patterns of string instruments in calculations of sound levels within the orchestra, while directivity patterns of brass instruments appear sufficiently consistent for estimating sound levels. Music stands and screens between players will also affect the direct sound levels in different directions from the player, particularly at higher frequencies due to limited size of music stands and screens.

Meyer (2004) also studied the source sound power of orchestral instruments. The highest power levels were found for percussion and brass instruments. Normally the percussion and brass instruments sit at the back of the stage pointing their instruments towards the audience/conductor. A major consequence of source levels, directivity of the different instruments and how the orchestra is arranged on stage, is that the direct sound levels from the different instruments vary considerably within the orchestra.

Proximity to some instruments can lead to excess sound levels for nearby players, with a potential risk of hearing impairment. Physical sound levels within an symphony orchestra in an orchestra pit and the risk of hearing loss among orchestral musicians have been investigated by for instance Peters *et al.* (2005), Jansson *et al.* (1986) and Kähäri *et al.* (2001). Lee *et al.* (2005) carried out similar investigations for musicians in orchestra pits. Results by Kähäri *et al.* (2001) showed that many wind instruments, including trombone, flute, piccolo flute, French horn and clarinet are capable of producing sound pressure levels exceeding 100 dBA. The results for risk of hearing impairment vary, with the exposure to other sound events outside the musicians' professional life being one of the uncertainty factors. Suggested methods to reduce exposure to excessive sound levels include the players using ear plugs and placing sound barriers between players.

With regard to low frequency sound levels and vibrations, Lee (1982) studied analytically how reflecting surfaces close to double basses affected total sound level from these instruments, and found that the floor and side walls can contribute to a raised level at low frequencies. Askenfelt (1986) found through measurements on real stages that the stage floor and risers could contribute to perceptually raise the level of double bass. More details are given in Section 5.7.

Bradley (1996) studied how adding a stage enclosure (shell) affected the objective acoustic conditions on stage (as well as for the audience). Two of the three shells studied fully enclosed the stage, while one had the main reflecting surfaces vertically at the sides. He found that adding a stage enclosure (shell) around the orchestra contribute to raise the sound levels on stage by typically about 3 dB. Sound levels of early sound (direct sound and early reflections) increased by less than 3 dB, while the levels of late sound increased by 4 dB. From this, Bradley concluded that temporal clarity, as assessed by for instance the objective measure  $C_{80}$ , did not increase by adding a shell. This could be affected by the type of shells used. Measured reverberation time,  $T$ , on stage increased at lower frequencies when stage shells were added.

The physical separation of players of up to 20 m leads to maximum delays of 60 ms delay for the direct sound if all the players start their note at the same absolute time. Timing is of great concern for performers, because it is among the aspect of performance least affected by the room acoustic response, according to Sundberg (2008). Goodman (2003) includes contributions from musicians with regard to different aspects of musical performance, among them "The illusion of synchrony" by E. Goodman. According to Goodman the players need to take into account the synchronicity of sound as heard by the audience. Players at the back of the stage normally need to compensate for their sound being physically delayed relative to the players at the front part of the stage. Players sitting across the stage must start their note at the same time, otherwise the sound will not arrive synchronised for the audience. This leads to players at opposite sides of the stage having to ignore the delay of sound introduced by physical separation; visual communication is important between many players since the aural cues can be misleading. If they try to wait for each other, the orchestra risks slowing down the tempo, as described by Ihlen (2008). (This is further described in Section 5.4.1.) Fredrickson (1994) found that visual cues in addition to aural cues raised the accuracy ratings of the performed music. The accuracy of onset of notes is also finite. Rasch (1979) found that

trios playing together had a deviation of their onset of notes of 30–50 ms. This indicates that a time span of 60 ms (the delay of string sound across the stage towards the back) for sound from different instruments may be seen as part of the orchestra sound itself, and the players treat such delays as tolerable deviations.

From the investigations regarding physical conditions as described above, there are only limited studies regarding quantification of how players and objects on stage contribute to obstruct sound between the players. Sound levels within the orchestra have primarily been measured with regard to excess sound levels. Regarding contribution of reflected sound from the stage enclosure, only changes of average stage values have been studied. No detailed studies have been found with regard to the level of reflected sound from the different instrument groups provided by the different surfaces of a stage enclosure.

## **2.2 The impressions of acoustic conditions on stage**

Some of the major mechanisms studied by others with regard to how the acoustic conditions affect the musicians include: mutual hearing and communication between players (including the ratio of sound level and time arrival of one's own instrument and other instruments), and the influence of reflected sound (from the stage enclosure or the concert hall as a whole). The latter is likely to affect mutual hearing as well, but the studies focusing on mutual hearing have normally studied general sound level differences, while studies on reflected sound have often looked at specific reflecting surfaces. For the musicians, the sound levels of other instruments within the orchestra will be heard in relation to level of produced sound by their own instrument. This leads to the existence of a masking sound (own sound) which is not present for the audience listener. This makes it difficult to apply findings regarding masking thresholds based on normal listening conditions.

Meyer (1994) defined three different quality levels of acoustic conditions for the musicians:

- The lowest level is associated with the need for playing correctly. If players hear themselves too loudly and the other parts too weakly, the rhythmic precision suffers. In the reverse case the intonation is affected, whereas precision in timing still is possible.
- The second level relates to forming the sound quality. Ease of singing or a good response of their instrument support the musicians' security, enhance the accuracy of tone onsets and articulation, enlarges the dynamic range and avoids a too much enforced tone production. Ease of hearing each other enables the musicians to play with a well-balanced dynamic relation to the other part.
- The third level is associated with creating an integrated entire sound of the orchestra, related to commonly produced articulation of chords and commonly formed temporal fine structure of dynamics. In particular string players need a sense of being integrated into their groups.



Studies on how the acoustic conditions affect the playing conditions can be split up in three different major approaches: studies of general experiences, impressions of specific conditions in a set of existing halls, and laboratory experiments. For all three approaches, questionnaires and interviews have been the major investigative techniques. This section is split up into results from these three different approaches.

### 2.2.1 Studies of general impressions

Gade (1981) interviewed 32 musicians about different aspects of acoustic conditions in general and their relative importance. The most important aspects for the players (in ranked order) came out as: 'hearing each other', 'reverberation', 'support', 'timbre', 'dynamics', 'time delay', 'change of pitch'. Soloists favoured the aspects that the players felt influence the beauty of the sound, believed to be controlled by 'reverberation', 'support', 'timbre' and 'dynamics'. According to the musicians, mere personal differences in judgement on acoustic quality are rare (they try to work as one unit, putting personal taste aside), but differences between instruments were observed. For instance, players of piano and timpani/percussion appeared to have different opinions than the rest of the orchestra. Musicians reported they seldom talk about acoustics with acousticians or others.

Genta *et al.* (2007b) distributed questionnaires to the musicians of two professional orchestras, enquiring which acoustically related aspects/attributes were most important for them. The results indicated that 'ensemble' and 'clarity' were the most important attributes, followed by 'dynamics', 'timbre', 'tonal balance', 'sound strength' and 'sound envelopment'. The Borda count method was found as the most effective method for finding the rank order of the different attributes among the players. Miller (1987) conducted a similar questionnaire study with one symphony orchestra where the results indicated that the musicians' relations to acoustics could be reduced to four factors: 'ensemble', 'interference', 'support' and 'tone quality'. Guthrie (2008), involving nine musicians participating, found the following aspects to be highly relevant, regarding acoustic response: 'ratio of volume between yourself and others', 'common aural space between all musicians', 'reverberance of space' and 'ability to distinguish between individual voices'. The results from these three studies agree reasonably well with the findings by Gade (1981).

Meyer (1994) asked more specifically double bass players for their opinions on stage floor properties in a questionnaire. The results showed that 50 % of the players preferred a wooden floor over a cavity ("more resonance", "more carrying sound") while 50 % preferred a non-vibrating floor ("The sound is more easily controlled", "A cavity makes the sound dull"). The positive impressions were believed to be related to raised sound level at lower frequencies, as found by Askenfelt (1986), while the negative impressions were assigned to the energy loss caused by the energy transmission into the floor.

Ueno & Tachibana (2005) established a cognitive model of musicians' perception in concert halls based on an interview survey. Their model describes how the musicians relate to the physical behaviour of an acoustic space as 'tacit knowing' – a skill acquired over time by repeating the task, without necessarily being able to tell how the skill is acquired and how



the physical conditions actually are perceived. The preference or evaluation of acoustic conditions are found to be affected by the arrangement with other players (solo playing, quartet, orchestra) and the words used to express their experiences will vary. But by taking the background and the intentions of the players into account and considering the semantic aspects of words used, they believed the differences of the judgements can be interpreted.

Overall these results suggest that the musicians relate to the physical conditions at a subconscious level and that the ability to communicate clearly/efficiently is of highest concern among the players.

## 2.2.2 Studies of impressions of specific stages

With regard to studies of perceived acoustic conditions on specific (existing) stages, there are few studies involving a full symphony orchestra. Investigations of acoustic conditions on stage for smaller ensembles, like chamber groups, have been studied by for instance [Barron \(1978\)](#), [Marshall \*et al.\* \(1978\)](#), [D'Antonio \(1992\)](#), [Chiang & Chen \(2003\)](#) and [Sanders \(2003\)](#). These results cannot be seen as directly valid for impressions among player in symphony orchestras, since smaller groups are expected to have less problems with time delay and obstruction of the direct sound. Several investigations of acoustic conditions for symphony orchestras are based on experiences from consultancy jobs, where only a very limited set of halls or different acoustic conditions were included, like for instance [Shankland \(1979\)](#), [Gade \(1989c\)](#), [Allen \(1980\)](#), [Benade \(1984\)](#), [Harkness \(1984\)](#) and [Kan \*et al.\* \(1995\)](#). The musicians' absolute preference for a particular stage is likely to be significantly coloured by individual preferences among the musicians. From studies of perceived audio quality among listeners in general, [Zieliński \*et al.\* \(2008\)](#) found that bias due to affective judgements may result in errors of up to 40 % with respect to the total range of the scale. This suggests that only relative differences in preference between different stages may be valid when studying the relation between objective behaviour and subjective impressions. The most significant studies of relative change of preference are given below.

Some studies involved changing the acoustic conditions for one stage and asking the musicians about the perceived impression of conditions before and after the change. [Rindel \(1991\)](#) studied the effect of adding overhead reflectors on stage, [Kahle & Katz \(2004\)](#) investigated the effect of making the back wall absorbing, while [Berntson & Andersson \(2007\)](#) studied how changes of the stage enclosure in an iterative process with players contributed to improve the conditions for the players. A study by [Halmrast \(2000\)](#) focused on the relevance of comb filtering in the frequency domain on perceived sound across the stage for one symphony orchestra playing at two different venues. The results from these studies are referred to in more detail in Chapter 5, though such single case studies may have low general validity for several reasons: the players may have become familiar with the new conditions over only a very limited time period. If the players have adapted to their existing conditions over several years, the perceived change of conditions could also be misleading. Therefore, the change of preference may only be valid for the particular initial/existing conditions even if the players were sufficiently familiarised with new conditions.

Gade (1989c) carried out a study of three Danish symphony orchestra's impressions of acoustic conditions of nine performance venues including their home venues. This meant that the different stages involved were judged by different orchestras, except for one hall where two of the orchestras regularly performed. One of these orchestras went on a tour within the United Kingdom and the impressions of the visited halls were also studied. The inclusion of different orchestras makes it more difficult to directly compare impressions of the nine Danish halls in Gade's study. The players may as well have adapted to their home venues, which could contribute to make their judgements less valid in general terms. For his UK study, the impressions by the players may suffer from poor validity and reliability since the players only visited these halls once. The venues included in Gade's study include purpose built concert halls, but also smaller venues with short measured reverberation times. This meant that venue type and stage enclosure design both varied at the same time, making it more difficult to isolate cause and effect. Similar, more recent studies were carried out by Cederlöf (2006) and Giovannini (2008), though the halls studied by Cederlöf (2006) included only purpose-built concert halls (within Sweden). The results from these studies are discussed in more detail in Chapter 8.

Halmrast (2000) carried out measurements of impulse responses across the stage with a full symphony orchestra present. He found that if measured responses showed comb filtering in the frequency domain, it would indicate negative colouration effects perceived by the players on stage. The observed comb filtering was due to an early reflection interfering with the direct sound (within-orchestra) sound. If the delay between the direct sound and this reflection was 5–25 ms, the perceived negative effects appeared to be most prominent. This time interval results in a comb filter with a bandwidth between cancelations corresponding to the critical bandwidth of our auditory system. With no further studies of this phenomenon, it is difficult to say if the comb filter observed is the real cause or an indication of the problems reported by the players. See Chapter 5 and Appendix D for further discussions of Halmrast's findings.

Several of the results from the studies mentioned above can be seen as contradicting, for instance with regard to the effect of different time arrivals of early reflections and the benefits of overhead reflecting surfaces. Such contradictions are likely to arise when studies involve only a limited set of halls or orchestras. The studies mentioned above, which involved more than one stage, had the different stages judged by different orchestras or by the home orchestras; it is difficult to know how the preferences and adaptation will differ among the judging orchestras and to draw conclusions that will have general validity.

### 2.2.3 Laboratory experiments

Several studies have investigated mutual hearing between players. The tolerance for delay of the direct sound, audibility of early reflections and preference for later arriving reflections are among other topics considered in laboratory studies.

Gade (1989b) studied how sound levels and delay of sound affected how two players experienced playing together. The effect of early reflections was also studied. The two players were sitting in physically separated anechoic chambers with aural communication provided by

microphones and loudspeakers. Three violin players, three cello players and three flute players participated. The direct sound from the other player was delayed, changed in level and low pass filtered. The changes of delay and level were designed to simulate specific distances between players and the loss at high frequencies to simulate the obstruction effect introduced by the orchestra. The sound of the other player was played from one loudspeaker in front of the players and a set of early reflections and reverberant sound were introduced by a loudspeaker vertically above the players. The results showed that a delay of direct sound delayed more than 20 ms was found disturbing by the players. Such a delay corresponds to a 7 m separation between the players. A loss of high frequency sound and introduction of reverberant sound were found to make mutual hearing more difficult. For some of the instruments, the results indicated that the sound of one's own instrument contributed to completely mask the audibility of early reflections up to 20–100 ms. There was no visual contact between the players. The lack of visual cues may have exaggerated the negative effects of delayed direct sound. The effects observed with early reflections and reverberant sound may have been affected by the simplified method of generating these sound components in the laboratory.

Guthrie (2008) performed similar investigations with two musicians sitting in separate rooms playing together. In addition to transmitting sound from the other instrument and artificially simulating a set of different room acoustic responses, cameras and displays were also included to allow visual communication between the players. The visual communication was switched on and off as an experimental parameter. The results indicated that the self-to-other ratio in sound levels is most crucial for good communication between the players, followed by visual communication.

Nakayama (1986) and Sato *et al.* (2000) found through laboratory experiments with five cello soloists and one alto-recorder soloist that the preferred delay of a reflection depended on the tempo of the musical motif played. A longer delay time was preferred for the slowest motif. Nakayama (1986) found a preference for reflection from above, when simulating two early reflections. A comparable study by Nakayama & Uehata (1986) showed that a reflection in the median plane could create a perceived sound image in the frontal direction. A perceived sound image in frontal directions was believed to be beneficial for the performer giving the impression that their sound was being directly propagated to the listener.

Meyer (1986) studied players' sensitivity to an early reflection depending on direction and musical instrument being played. The results indicated that at 1 kHz the musicians will be more sensitive to reflections arriving from above compared to reflections arriving from the sides or diagonally from above. This was found to be caused by masking effects of their own instrument. This observation led to the proposal of a beneficial layout for overhead reflectors, as shown in Figure 2.1: a flat reflector above the strings would enable reflections back to the string players from the direction from which they were most sensitive. A tilted reflector above the woodwind (facing the audience) would reflect sound from the string players down towards the woodwind players vertically from above, while reflecting sound from woodwind diagonally down towards the strings. Such an arrangement was believed to help the woodwind players hear the strings without woodwinds becoming too loud for the string players. But on the other hand, a horizontal reflecting surface above the string players can make it difficult to hear other string players at a farther distance, since the sensitivity for the reflection from one's

own instrument could be higher than reflections from players at a distance. This is further discussed in Section 5.5.2.

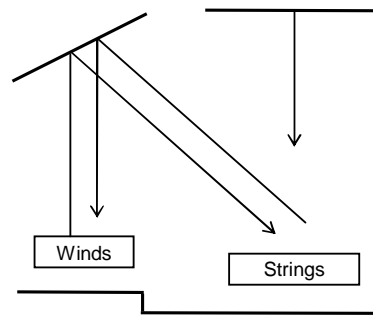


Figure 2.1: Long section view of reflector above strings and woodwinds as proposed by Meyer (1986).

Naylor & Craik (1988) carried out investigations of hearing oneself and other players. Musicians in an anechoic chamber played along to pre-recorded music. Different versions of pre-recorded music were used to simulate different acoustic conditions. Their results showed that increasing the temporal and pitch difference between sound of self and others, improved the impression of hearing self and other players. The optimum total level of others was found to be within  $-23$  and  $+5$  dBA relative to level of own sound. According to Naylor (1985), this interval is for triple counterpoint playing. For unison and single counterpoint the respective intervals were found to be  $-15$  to  $+5$  and  $-21$  to  $+7$  dBA. Naylor (1988) suggested that the level of one's own instrument was almost independent of the room and that the room mainly controlled the level of others. The level balance between self and others was found to be important. This agrees well with Gade's finding with regard to audibility of early reflections of one's own instrument as referred to above. Naylor found that reflectors near a symphony orchestra were found useful for increasing the level of others and the ratio of early to late sound level, but for small enclosures absorption may instead be needed to avoid excessively high sound levels. Reverberation was also found useful for raising the perceived level of others. String players at rear desks (at the sides of the stage) were mentioned as particularly challenged players with regard to hearing within the rest of their sections, and could benefit from receiving reflections. Ternström *et al.* (2005) found comparable limits for level of others from a laboratory study with singers: the singers performed best with regard to intonation with sound level of own their voice being within  $-15$  dB to  $+5$  dB relative to the others. The sound level of the other singers was estimated by recording the sound at both the ears of the singers during an opera performance (by use of miniature microphones).

Ueno & Tachibana (2003) established a system for regenerating room impulse responses from real halls in an anechoic chamber. This enabled a rapid switch between different playing conditions for the players based on real room responses. Impulse responses from real spaces were collected by use of an omnidirectional source and six microphones – four in the horizontal (front, back and left and right) and two in the vertical plane (below and above). These measured responses were convolved with the direct sound from the instrument played in the anechoic chamber. The resulting sound was played back in the same anechoic chamber from six loudspeakers located in the same directions as the six microphones used to capture the real room response. The synthesised impulse responses in the anechoic chamber showed

good agreement with the real impulse responses, also for calculated acoustic measures based on the impulse responses. The simulated impulse responses enabled the early reflections, reverberation and discrete late reflections to be controlled independently. Initial results (Ueno *et al.*, 1998) indicated that differences in the composition of early reflections were hardly recognised by the players. Results from Ueno & Tachibana (2003) showed that for solo playing, the musicians (three flute, one clarinet, two oboe, three violin and three viola players) preferred a low level of early reflections and moderate level of reverberant sound. With regard to a discrete late reflection (arriving at 250 ms), the results indicated that such a reflection was preferred as long as it was at a moderate level. Ueno *et al.* (2004) studied two players playing together in separated anechoic chambers using the developed 6-channel simulation system. The results indicated that both early reflections and reverberation should be at an optimum level for the most preferred conditions for playing together. This was based on impulse response on an empty stage with a source-receiver distance of approximately 6.7 m.

With regard to the validity of the laboratory studies, investigations of mutual hearing between two players without the rest of the orchestra present may have resulted in unnatural conditions for the players – or conditions that better apply to smaller ensembles compared to symphony orchestras. The obstruction effect by players sitting in between and masking effects caused by interfering sound from other instruments will not be fully encountered under such conditions. Only Naylor & Craik (1988) appear to have used interfering sound for studies of mutual hearing. The investigations by Gade (1989b) included high frequency attenuation of the direct sound to simulate the obstruction effect. The omission of other players could represent conditions more valid for smaller ensembles than for symphony orchestras. The limited number of players involved and the number of loudspeakers used for the reproduction of early reflections and reverberant sound may well have contributed to reduced validity of the results from these laboratory investigations. Another critical factor may be the musical repertoire chosen for the studies. Gade (1989b) used, in particular, the Trio Sonata by J. S. Bach and the 40<sup>th</sup> Symphony by W. A. Mozart as source material. On the contrary Guthrie (2008) used a repertoire where the structure and duration of notes produced by the individual players are less predicable (C. Wolff). Such significant differences in source materials can have contributed to different conclusions regarding the importance of different acoustical aspects. The findings with regard to the audibility of early reflections of one's own instrument may be sufficiently valid, since an introduction of other players will make early reflections of one's own sound even more inaudible due to masking effects. This finding suggests that surfaces surrounding an orchestra will mainly control the level of others, not the level of one's own instrument.

## 2.3 Proposed acoustic measures

Some of the laboratory studies mentioned above led to proposals of acoustic measures to assess the acoustic conditions for the performers. Below follows more detail on the most significant measures proposed for assessing the acoustic conditions for the performers: the *ST* measures. Other proposed measures like *MTF* and *RR160* are presented at the end of this section.

The first dedicated stage acoustic measures were proposed by Gade (1989c) and later revised in Gade (1992) – the support  $ST$  measures. The following Support measures,  $ST$  have been proposed by Gade (1992):  $ST_{\text{early}}$  (previously denoted  $ST1$ ) to assess ensemble conditions,  $ST_{\text{late}}$  for assessing the impression of reverberation and  $ST_{\text{total}}$  for assessing support from the room for sound from the musician's own instrument. The  $ST$  measures sum the level of sound reflections returning back to a musician on stage from any direction, by use of an omnidirectional loudspeaker and microphone. The sum of reflections is taken within different time intervals relative to the emission of sound. The time intervals for  $ST_{\text{early}}$ ,  $ST_{\text{late}}$  and  $ST_{\text{total}}$  are 20–100, 100–1000 and 20–1000 ms respectively. The microphone should be 1 m from the centre of the sound source at 1 m height, to emulate an instrument and the room acoustic response of it as received at the musician's ears. The combined level of the measured direct sound and the stage floor reflection is used as the reference level, summed within the time interval 0–10 ms from the measured impulse response. Equations (2.1)–(2.3) are the mathematical definitions of  $ST_{\text{early}}$ ,  $ST_{\text{late}}$  and  $ST_{\text{total}}$ . For the Danish halls studied by Gade (1989c),  $ST_{\text{early}}$  showed correlation at a significant level with subjective measures representing mutual hearing (ensemble measures), while  $ST_{\text{late}}$  (replacing CS as proposed in Gade (1989b)) showed significant correlation with perceived reverberation. Gade (1989c) also proposed a measure called  $EEL$  (Early Ensemble Level). This measure was obtained by measuring across the stage using two microphones, with one microphone for the reference level and one measuring microphone for the response across the stage. Equation 2.4 shows the mathematical definition of  $EEL$ .  $E_m$  is the energy response at the measuring microphone with  $t=0$  referring to time for emission of sound. Due to the absence of significant correlations between  $EEL$  and subjective measures,  $EEL$  was later omitted (Gade, 1992). See Section 7.7 for more details on measurement of  $ST$  on real stages.

$$ST_{\text{early}} = 10 \cdot \log_{10} \left( \frac{E(20-100 \text{ ms})}{E(0-10 \text{ ms})} \right) \quad \text{dB} \quad (2.1)$$

$$ST_{\text{late}} = 10 \cdot \log_{10} \left( \frac{E(100-1000 \text{ ms})}{E(0-10 \text{ ms})} \right) \quad \text{dB} \quad (2.2)$$

$$ST_{\text{total}} = 10 \cdot \log_{10} \left( \frac{E(20-1000 \text{ ms})}{E(0-10 \text{ ms})} \right) \quad \text{dB} \quad (2.3)$$

$$EEL = 10 \cdot \log_{10} \left( \frac{E_m(0-80 \text{ ms})}{E(0-10 \text{ ms})} \right) \quad \text{dB} \quad (2.4)$$

Gade (1989c) investigated the validity of these objective measures through three different studies. His first study included three Danish orchestras impressions of nine venues including their home venues, and his third study investigated how an existing stage could be improved by modifying the stage enclosure. For these two studies significant correlations were found between  $ST$  measures and subjective measures. On the contrary, the results from his second study with one of the Danish orchestras visiting eight halls within the United Kingdom indicated that  $ST_{\text{early}}$  did not correlate well with subjective measures. As discussed in Section 2.2.2



Gade's first and second study may suffer from poor validity and reliability. The validity of  $ST$  is discussed in more detail in Chapter 7. Other studies have covered the technical aspects of  $ST$ , considering the effect of the time limits used, and the importance of having chairs on the stage while carrying out the measurements. Results by van den Braak *et al.* (2005), Jeon & Barron (2005), O'Keefe (1995) and O'Keefe (1994) indicate that the definition of  $ST$  and how it should be measured contribute to reduced reliability of  $ST$ . This is discussed in more detail in Section 7.7. Kim *et al.* (2005) and Giovannini & Gade (2007) found that  $ST_{\text{early}}$  was not very responsive to changes to the stage enclosure, but the perceived impressions of these changes were not investigated.

Naylor (1988) proposed the use of modulation transfer functions ( $MTF$ ) measured across the stage to evaluate conditions for mutual hearing. This was based on the use of  $MTF$  for assessing speech intelligibility, as proposed by Houtgast & Steeneken (1973). The mathematical definition of the modulation transfer function,  $MTF$ , as used by Naylor (1988) was based on Houtgast & Steeneken (1973). In Houtgast & Steeneken (1973),  $MTF$  was applied to perceived speech intelligibility where room reverberation and the background noise contribute to reduce the calculated speech intelligibility. Naylor (1988) set the background noise level to represent the level of interfering sound from other players. In this way the communication channel between two players could be assessed taking into account the influence of disturbing sound. No studies by others have been found which have investigated the validity of Naylor's proposed method.

Griesinger (1995) proposed a measure called 'running reverberation' for assessing perceived reverberation during musical performance. Equation (2.5) shows the mathematical definition of  $RR_{160}$ . No investigations have been found which study the validity of  $RR_{160}$  other than Griesinger, but Kahle & Jullien (1994) found objective measures comparable to  $RR_{160}$  to best correlate with the subjective impression of reverberance.

$$RR_{160} = 10 \cdot \log_{10} \left( \frac{E(160-320 \text{ ms})}{E(0-160 \text{ ms})} \right) \quad \text{dB} \quad (2.5)$$

van den Braak & van Luxemburg (2008) proposed a measure denoted  $LQ_{7-40}$  for assessing acoustic conditions for conductor of a symphony orchestra. This measure was also proposed to be relevant for the players. See Section 2.4 for more details.

von Békésy (1971) proposed the concept of 'auditory backward inhibition' based on laboratory experiments that indicated that discrete reflections arriving within 60–200 ms after the direct sound could contribute to reduced clarity of sound. Based on the concept of auditory backward inhibition, it was suggested in Ashley (1979) and Ashley (1981) that the arrival of such reflections could explain the preference for certain concert hall stages among orchestral musicians. This was not developed to define an acoustic measure. Blauert & Ttemann (1980) tried to reproduce the laboratory experiments initially carried out by von Békésy (1971). Their results did not show any evidence of the mechanism 'auditory backward inhibition'. After the publication by Blauert & Ttemann (1980), 'auditory backward inhibition' has not been found mentioned in literature.

Two objective measures were also proposed at an early stage of this project, based on monophonic omnidirectional impulse responses measured on stage without a full symphony orchestra present. The first measure proposed (*EB* – Ensemble Balance) was designed for assessing the balance between early reflections from another player compared to early reflections from one's own instrument. The second measure (*EMDT* – Early-Mid Decay Time) was designed for assessing temporal clarity of sound from forward integration of the measured acoustic response, mimicking the temporal integration in the human auditory system as used by [Cremer \(1989\)](#). From the investigations of real halls and perceived conditions, these objective measures did not show any significant correlations with the subjective measures investigated. Results by [Gade \(1989c\)](#) and [Naylor \(1988\)](#) indicate that early reflections from one's own instrument will be masked by the direct sound of one's own instrument. This may explain why *EB* was not found significant when relating to subjective characteristics. The low significance of *EMDT* may relate to both its mathematical definition and how it was assessed for this project – without musicians present on stage. These two proposed measures are therefore here not described any further, but the definition and failure of these measures (described in further detail in Section 9.5) may provide relevant information for future investigations. See [Barron & Dammerud \(2006\)](#) and [Dammerud & Barron \(2007\)](#) for more details on these measures.

The objective acoustic measures listed above have mainly been investigated by the authors who originally proposed the measure(s). Only the *ST* measures have been investigated by others, but mainly regarding the physical behaviour of the measures. No studies are found in the literature regarding the correlation between the acoustic measures and subjective characteristics, where a large number of professional symphony orchestra playing in purpose-built concert halls has participated.

## 2.4 Effect of stage enclosure for conductor and audience

When studying preferred conditions among the players, it is relevant to study how the design of the stage enclosure affects the conditions for the conductor and the audience as well. This section covers the main results found in the literature with regard to optimum stage enclosure design for these two groups.

In [Meyer \(1994\)](#) and [Meyer \(2008\)](#) conditions for the conductors (of symphony orchestras) were studied. According to [Meyer \(1994\)](#) the acoustic conditions at the conductor's position are important for reaching a well-balanced orchestra sound for the audience. He found that an overhead reflector above the centre of the orchestra could lead to a lack of perceived reverberant hall sound and that it could lead to strings becoming too loud, in particular compared to woodwind instruments. The following conditions were found to result in favourable conditions for the conductor: walls at the side of the stage, a large volume in front of the conductor (exposed stage) to link with the rest of the hall volume, and overhead reflectors designed to mainly reflect woodwind sound towards the conductor.



van den Braak & van Luxemburg (2008) experimented with the effects of stage enclosure by looking at two specific stages. Looking at values of  $ST$  did not reveal any significant differences in acoustic conditions for the different configurations and did not agree with the impressions among the musicians and conductor performing on these two stages. They proposed a new measure (further investigated in van den Braak *et al.* (2009)), called  $LQ_{7-40}$ , as defined in Eq. 2.6. This measure represents the energy ratio of measured early reflections within 7–40 ms (relative to arrival of the direct sound) and measured late energy level within 40– $\infty$  ms. The measurements were carried out with the sound source at different positions within the orchestra and a receiver at the conductor's position (both omnidirectional). Their measured values of calculated values  $LQ_{7-40}$  agreed well with the actual conductors' impressions of the acoustic conditions, as well as the impressions among the players.

$$LQ_{7-40} = 10 \cdot \log_{10} \left( \frac{E(7-40 \text{ ms})}{E(40-\infty \text{ ms})} \right) \quad \text{dB} \quad (2.6)$$

In some cases a reflector above the orchestra may be needed to raise the sound levels or improve the balance of the orchestra instruments for some sections of the audience area. Cremer & Müller (1982) found that maximum 30 % of the space above the orchestra should be covered by reflectors for the audience's point of view, whereas Beranek (1992) set this limit at 50 %. Meyer (1977) found the ceiling (or overhead reflector) to be important for the brilliance, whereas the sidewalls were important for volume and sonority. Bradley (1996) found from his experiments with added stage enclosures (shells) on three existing stages, that the changes of objective acoustic conditions were more significant on stage compared to in the audience. Only looking at objective acoustic measures could for this study have limited the apparent changes for the audience.

Griesinger (2006) found that too high a level of early reflections, or too low a level of direct sound, could contribute to an impression of a remote and muddy sound (lack of definition/clarity) for the audience. In Griesinger (2007), more details were provided regarding this hypothesis.

Miller (1987) carried out experiments with risers (raised platforms) for brass and percussion and found that risers contributed to raise the direct sound level of these instruments. In some cases this led to brass and percussion being too loud compared to strings and woodwinds, but with brass and percussion on a flat floor, the direct sound levels from these instruments in the stalls area were found to be too low.

These results suggest that from the conductor's and the audience's point of view, the stage enclosure should not have a major, solid reflecting surface at low height above the orchestra. The results also suggest that side walls close to the orchestra are beneficial and that the stage enclosure should not be too reflective or enclosed around the orchestra. Smaller areas of reflector above the orchestra can be beneficial for the level balance between different instruments and perceived clarity.

## 2.5 Approaches used for this study

The literature review has shown there are still many unresolved questions with regard to how musicians relate to acoustic conditions on concert hall stages and what their main concerns are. A qualitative understanding of how musicians relate to acoustic conditions could be essential before trying to find objective quantitative measures that correspond with their rating of different acoustic aspects. A focus on quantitative physical measures could result in what could be described as a positivistic approach, as used in social sciences. Positivism has been described by [Smith \(1998\)](#) as follows: “Positivist approaches are united in their attempt to eradicate metaphysics and other hangovers from rationalism from scientific knowledge. In particular, they are strongly attached to grounding all our knowledge of things in perceptions, impressions and sensations as evidence of their tangible and observable existence.” Positivism has been seen related to rationalism – as defined by [Smith \(1998\)](#): “In knowledge construction rationalism is often seen as opposed to experience (with the strongest contrast being between rationalism and empiricism). For positivists, rationalism was the source of metaphysical speculation and it undermined the healthy sense of doubt which empiricism was supposed to engender – many failed positivists were attacked for their rationalist leanings.” Reference to positivistic approaches have been made for instance in musical science by [Duffin \(2007\)](#). The different temperaments of notes in musical scales have more or less disappeared after the introduction of the equal temperament. Equal temperament is mathematically elegant, but lacks the possibility of harmonic variation between different keys. From [Duffin \(2007\)](#): “In general terms positivism looks for empirical data to justify knowledge or beliefs. As a result it excludes things that cannot be studied by quantification or that do not fit theories assembled by documented evidence. This means that something so complex and irrational as the division of sounds into a musical scale was bound to prefer the order and apparent simplicity of equal temperament”. [Blauert \(2007\)](#) raised a concern for acousticians not having a sufficient understanding of the higher (less quantifiable) levels of communication within acoustic spaces. Acousticians are normally trained in natural sciences, while musicians have a musical education which includes very little that is related to natural sciences. There may therefore be a risk of studies carried out by acousticians having a focus on the physical aspects while paying less attention to other less easily quantifiable aspects. With such a positivistic approach there could be an overly optimistic belief in the importance of the quantifiable aspects.

The main aims for this project were to better understand how stage acoustic conditions are perceived by symphony orchestra musicians and how auditorium and stage enclosures should be designed for optimum aural working conditions for the musicians. From the literature review above, few systematic studies of acoustic conditions specifically for symphony orchestras have been carried out. Studies of physical conditions imposed by the orchestra configuration have been very brief. Laboratory studies carried out have not included a full symphony orchestra, only a few players or single players. For studies of specific stages there are only a few investigations carried out, which may have low validity caused by the halls and orchestras covered. For this project, laboratory and modelling investigations have been limited to scale and computer modelling – laboratory investigations including professional musicians were not possible due to a lack of an anechoic chamber. Studying impressions of acoustic conditions

with a limited set of players and different acoustic conditions, will normally lead to high uncertainties associated with their judgements. With regard to relations between subjective and objective measures, most previous studies have only investigated impressions of home stages or halls visited occasionally. The level of adaptation by the players to certain acoustic conditions could have contributed to reduced validity of these studies.

The early part of this thesis covers investigations of how acoustic conditions are experienced by the musicians. By use of questionnaires and dialogue with musicians, their point of view has been studied. This study is followed by investigations of physical conditions on stage and how these physical conditions are likely affect subjective impressions like the ability to hear other players clearly. To minimise the effect of uncertainties related to specific cases, generic acoustic conditions on stage have been studied objectively (by use of scale and computer modelling as well as analytical studies) with reference to general findings within the field of sound perception (psychoacoustics). With these approaches, the investigation will not be limited to existing acoustic measures (quantitative methods) with the risk of too limited an approach. In addition to such investigations, the players' impressions of halls visited on a regular basis have been studied. These two approaches avoid enquiring about impressions of acoustic conditions only experienced occasionally. While the majority of subjective data used here is for halls visited regularly, some impressions of halls visited only occasionally have also been included.

The above approaches were motivated by searching for relations between objective acoustic conditions and perceived conditions, by use of quantitative but also more qualitative methods. It will also be relevant to study how objective acoustic conditions should be assessed. In particular, should the acoustic conditions be assessed with a full symphony orchestra (or equivalent group of people) present? Scale modelling have been used in this study to investigate in detail the acoustic conditions within an orchestra configuration and how the room impulse responses on stage are affected by the presence of the orchestra. Computer modelling was used to study how different stage enclosure designs affect acoustic conditions. Measured responses on existing stages (without a full symphony orchestra present) were also studied, to find the most valid and reliable way to assess real objective acoustic conditions.

## Chapter 3

# Musicians' impressions of acoustic conditions

### 3.1 Introduction

To get a better understanding of how musicians within symphony orchestras experience and relate to the acoustic conditions on stage, the first subjective study involved distributing questionnaires to eight symphony orchestras – six English and two Norwegian. The six English orchestras were: BBC Philharmonic, Bournemouth Symphony Orchestra, City of Birmingham Symphony Orchestra, Hallé, London Philharmonic Orchestra and Royal Philharmonic Orchestra. The two Norwegian orchestras were Oslo Philharmonic Orchestra and Trondheim Symphony Orchestra. The results from this study are reported in this chapter, while the results from the second subjective investigation are presented in Chapter 8. Musicians' impressions of stage acoustic conditions have previously been investigated by several authors. Gade investigated this through both laboratory experiments and interviews with musicians (Gade (1981) and Gade (1989b)). Which aspects of stage acoustics that appear most important for the musicians were investigated through questionnaires by Genta *et al.* (2007b). Laboratory investigations have also been carried out by Naylor & Craik (1988), Meyer (2009) and Ueno *et al.* (2004). A lot of findings came out of these studies – in brief the results consistently show that the most important aspects for the players appear to be hearing each other clearly, with hearing of others well balanced with their own sound. A suitable amount of acoustic response from the auditorium also appears crucial for them.

The questionnaire distributed to the eight orchestras consisted of questions related to staging conditions (like risers and space available), acoustic and non-acoustic conditions. Some of the questions were open (where the players could comment freely), whereas for most of the questions the musicians were asked about their preferences on bipolar semantic differential scales (Likert rating scales), ranging 1–5. For some of these rating questions they were asked to further comment on their preference or experiences. The musicians were also requested to list the hall they remember as providing the best acoustic conditions they had

ever experienced in their career, along with comments on why they preferred this particular hall. The British orchestras were asked to rate the halls they regularly perform in, with respect to overall acoustic impression (OAI), with 33 halls being judged by the orchestras overall. One of the Norwegian orchestras was asked to rate 12 halls within Europe, USA and Japan which they have visited over several occasions (3–4 times). They were asked to provide reasons for their least and most preferred hall. Some of the questions mentioned here were not included for all the orchestras, but the response rate on all individual questions was sufficient to draw some conclusions.

The responses from the different instrument groups (string, woodwind, brass and percussion) have been compared. For the purpose-built concert halls regularly visited, the ratings have been compared with available objective acoustic measures and architectural measures obtained from hall drawings. Some of the halls were rated by more than one orchestra. This has allowed investigation of the consistency of judgements of overall acoustic impression. The statistical analyses were done using SPSS version 14 and MATLAB R2006a.

The chapter is organised into three major parts with discussion/conclusion sections at the end of each part. The first part covers the open questions in the questionnaire including their favourite halls, while the second part covers the preference questions. In the third part, the halls rated by the players are studied with reference to objective measures related to the halls.

## **3.2 Questionnaire method**

Questionnaires consisting of two sides of A4 were distributed to the players by their orchestra administration. Typically they were given two weeks to respond and return the questionnaire back to the administration. Their responses on individual halls were based on memory. The questionnaires were initially piloted with a set of players and orchestra representatives.

The top of the questionnaire contained a brief introduction and asked which instrument they play and how many years they have been playing professionally in a symphony orchestra. The body of the questionnaire contained preference and open questions. The details on these questions are given in respective sections below. See Appendix B for a sample of the questionnaire distributed.

## **3.3 Questionnaire results in general**

In total 180 players responded – 108 string players (60 %), 28 woodwind players (16 %), 32 brass players (18 %) and 11 percussion players (6 %). The number of responses within each orchestra varied from 5 to 55 (response rates of 6–81 %).

With regard to years of experience as professional symphony orchestra musician, the averages for the different instrument groups were: 21 years for string players, 24 for woodwind

players, 22 for brass players and 27 years for percussion players. Among all the players the average was 22 years of experience, with a maximum of 45 years and a minimum of 1 year. Ten players (6 %) reported they had less than 5 years of experience. This indicates that the players who responded have considerable experience.

## 3.4 Open questions

### 3.4.1 Non-acoustic issues important on stage

The players were asked: “What non-acoustic issues are significant to you that differentiate between the halls you play in (such as visibility of other players, lighting, thermal comfort etc.)?” Table 3.1 shows the relative frequency of different non-acoustic issues mentioned as significant by the players. The results show that temperature and air quality are of most significance to them, with about two thirds of the players finding this important. Not only is this for comfort reasons, but also for instrument conditions – several woodwind players mentioned problems with their reeds in dry halls. Lighting is mentioned equally frequently. Visibility and space is mentioned by about one third of the players. Being able to see the conductor, principal and leading players appears as important for the players, especially if aural cues are not easy to hear. 20 % of the respondents mentioned that stage conditions are important. 10 % of the players mentioned staging (risers and overall stage design) as significant. Some mentioned being able to get on and off the stage safely (no holes in the stage floor etc.), and the flexibility the stage offers for the players to arrange themselves as they wish. Backstage facilities, quality of nearby restaurants, contact with the audience and hearing each other were also mentioned, but only by a few players.

Table 3.1: Relative frequency of non-acoustic issues mentioned by the players.

Issue	Relative frequency (%)
Thermal/air quality	64
Lighting	63
Visibility	39
Space	36
Chairs/stands	20
Staging	10

### 3.4.2 Favourite halls

More than 40 different halls were mentioned by the players as their favourite hall (the best hall they had ever performed in). Their memory of the hall providing best acoustic conditions may be less reliable compared to halls visited regularly (as discussed in Section 3.6.1). How much the musicians have travelled throughout their career will affect the halls they mentioned. The halls being mentioned by at least three players were (in alphabetical order after city): Concertgebouw (Amsterdam), The Anvil (Basingstoke), Konzerthaus (Berlin), Symphony Hall (Boston), Philharmonie (Berlin), Symphony Hall (Birmingham), KKL Concert

Hall (Lucerne), Bridgewater Hall (Manchester), Royal Concert Hall (Nottingham), Carnegie Hall (New York), Liederhalle (Stuttgart), Suntory Hall (Tokyo), Großer Musikverein (Vienna), Konzerthaus (Vienna) and Minato Mirai Hall (Yokohama).

The explanations for why they enjoyed playing in their favourite hall are qualitatively interesting. With respect to communication on stage the players mentioned these aspects: could hear oneself and everyone else clearly (at the same time); sound is clear, but without feeling too exposed as a player; easy to hear everything; being able to hear across the stage (string players); immediate sound (string players); brass and percussion not overpowering (string players); feeling close and intimate (string players). Regarding overall acoustic conditions in their preferred hall, the players gave descriptions like: full-bodied, warm, natural or resonant sound; right amount of reverberation; good blending; overall sound wonderful; good sound of the orchestra as a whole; low noise levels; being able to play loudly and quietly with little effort and project comfortably; combined and open sound at the same time; good communication with audience; great bloom; not too boomy; homogenous sound; big sound without overpowering. For non-acoustic aspects they mentioned: flexible stage; nice appearance; visually attractive. They also mentioned analogies to musical instruments or certain beliefs: “like a Stradivarius”; wooden; shoe-box hall. Some of these halls also received some negative comments, like problematic staging conditions (VIM) or hearing too much of oneself (MAB, BIS). (Hall abbreviations are listed in Section 3.6.) Such problems appear to be well compensated by good sound quality from the hall itself.

### 3.4.3 Preference for risers

The question relating to risers (stage platforms) was: “What is your preferred riser configuration for providing best conditions for the orchestra as a whole?” Figure 3.1 shows the results for the preferred riser configuration among the different instrument groups and for the orchestra as a whole. ‘No risers’ would mean all players sitting on a flat stage floor, whereas ‘Rear only’ represents only woodwind, brass and percussion players on risers (the most common configuration). ‘Curved’ represents risers with a semi-circular plan where the rear players (as for ‘Rear only’) and the string players sitting at the outer regions on both sides (back desks) are all on risers. ‘Other’ allowed the players to specify an alternative layout they preferred, or define their preference if they found the other options ambiguous. Figure 3.1 shows that most players prefer some kind of riser system. The string players tend to prefer curved risers, whereas woodwind players tend to prefer risers for the rear stage only. Brass and percussion players appear to be less discriminating between ‘Curved’ and ‘Rear only’.

For the ‘Other’ category, a 2<sup>nd</sup> violin player would prefer woodwind on risers only (with the brass and percussion not elevated above the woodwind players), while a viola commented on preference for shallow risers. Several players indicated a preference for a flexible riser system and that risers at the outmost string desks are useful. One woodwind player responded that they prefer sitting in a straight line, not on a curved riser. One percussionist commented that curved risers can be too curved (without giving any reasons or examples). Below are some of the comments made by the players. From a bassoon player: “Curved helps to hear left/right,



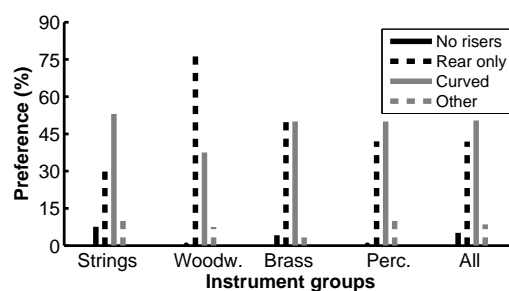


Figure 3.1: Preference for types of riser configurations. Rear only = only woodwind and brass on risers. Curved = curved risers for strings, woodwind and brass. Other = as described by the players.

height is very important. It would be best to have low risers for the woodwind and consistently higher ones for the brass. This would enable the brass to blow over the heads of the woodwind instead of into the heads! I regularly have to sit with my head less than a metre from a trumpet or trombone bell that is pointing straight at me". And from a trumpet player: "Brass on straight line at least 60 cm above woodwind. Percussion high enough so skins are not near ears".

### 3.4.4 Hearing others and oneself

The question relating to experiences of hearing others and self was: "Are you aware of a hall (or halls) where you can hear yourself well but not hear others, or the other way round, you can hear others but not yourself?" This was followed up with: "What do you think is responsible for this?" One of the orchestras (55 players) was given these questions, where 93 % of the players responded 'Yes', 2 % responded 'No' and the rest blank. The suggested reasons for this happening were very varied. Some players mentioned the shape of the hall, the acoustics of the hall, curtains, too much or too little resonance (reverberation), poor stage design, stage spacing, risers separation and ceiling height. A cellist mentioned the Royal Albert Hall as an example of a hall where the players can hear themselves, but not the others sufficiently.

The general response from all eight orchestras is that most players need to hear within their own group and hear solo instruments. Many players say they need to hear all instruments and being able to hear particular instruments depending on repertoire. Hearing the strings and bass instruments (double bass in particular) appears important for many players.

### 3.4.5 Statements on good acoustics for performers

For the statement "Acoustics for performers depends on the correct balance between hearing yourself and hearing other players", 81 % of the players agreed with this statement. For the second statement "Good acoustics depends on clarity of sound from others", 70 % of the players agreed. The quality of acoustic response from the auditorium area was also mentioned as an important criterion for good acoustic conditions on stage – often described as a 'rich', 'warm' or 'resonant' sound, 'good bloom' or 'good projection'. This was mentioned with respect to both the sound of one's own instrument and sound from the other players. Hearing others in the auditorium response was linked to hearing a well blended orchestra sound. They comment



that the hall should not be too dry and not too reverberant. One 2<sup>nd</sup> violin player commented that the time lag of sound from others is as important as clarity.

### **3.4.6 Information contained in, and direction of reverberant sound**

Players were asked: “Please comment on these two questions: 1 – What type of useful information would you say there is in the reverberant sound coming back to you from the hall? 2 – Does the direction of the reverb sound matter?”. The players tended to fall into two groups without much reference to the instrument they play. One group was aware of reflections coming back to them, commenting that the reverberant sound contains useful/relevant information. The other group considered reverberant sound not to be important or relevant, commenting that they preferred to work on the immediate sound and that the reverberant sound arrives too late to be of any use. One player wrote that professional orchestras need clarity, while amateur orchestras need more reverberation to put a bloom on the sound.

Good hall sound appears to aid confidence (hearing what the audience hear), it is useful for gauging the balance of oneself relative to the others and serves as an indication of how much one needs to ‘play out’ and how to articulate. As one bassoonist commented: “Awareness of how it’s going, and when to play”. In a dry hall (not much reverberation), the players comment they will extend the length of the notes to compensate. In a very reverberant (‘wet’) hall, the players will play more articulated. On the other hand, some halls were reported as distorting intonation (no particular hall references). Reverberant sound was said to be useful for blending of sound – being able to hear the sound of the complete orchestra. It was also mentioned that reverberant sound contributed to a fuller orchestra sound and some softening of the sound, but can be off-putting if it is too loud – reverberant sound should not be at the expense of definition. An excessively bright or ‘tinny’ string sound from the hall was reported as contributing to mask the sound from other instruments which they need to hear.

Most of the players appear to be unaware of the direction of the reverberant sound. A few players wrote they prefer diffuse reverberant sound – reverberant sound from only one direction can confuse (like from a curved back wall).

### **3.4.7 Bloom and projection**

One of the orchestras was asked: “What do you associate with the words ‘bloom’ and ‘projection’ in terms of acoustic quality of a space?” Two individual responses summarise the general meaning of these terms among the musicians. As defined by a 2<sup>nd</sup> violin player: bloom is “How much reverberation plus warmth is present” and projection is “How the sound carries outward into the hall”. As defined by a oboe/cor anglais player: “It’s helpful and encouraging to hear your sound travel somewhere – therefore being allowed to relax into the sound, not having to force it. If your sound rings, it’s easier to breathe and sing through long phrases. ‘Bloom’ literally means like a flower opening, your sound opens up.”

### 3.4.8 Discussion and conclusions of results for open questions

Several non-acoustic conditions appear significant for the players. The most frequently mentioned are thermal conditions, air quality, lighting and visibility. The significance of different non-acoustic conditions is likely to be affected by the problems they normally experience in the halls they regularly play in. One player says it is easier to adapt to the acoustic conditions compared to non-acoustic conditions like lighting, ventilation, visibility, so these non-acoustic conditions can be more difficult for the players to cope with, compared to what they would describe as acoustic conditions. Even if these conditions can be seen as non-acoustic, they also influence acoustic conditions in certain aspects. For instance humidity is reported by woodwind players to affect the acoustic properties of their instruments and visibility will affect how well the direct sound is transmitted between players (which affect the level balance between the different instruments). Space and staging conditions are also mentioned by several players, which are likely to affect how the players can arrange themselves on stage. This will also affect the direct sound levels. There is a potential bias by the mention of three conditions as examples in the question itself (thermal conditions, lighting and visibility). The low frequency of noise levels being mentioned as a significant condition is likely to be related to the question focusing on non-acoustic conditions. It is reassuring that backstage facilities do not appear to be of most concern for the players.

That some players mention hearing each other among non-acoustic issues, could indicate that the conditions for hearing others, and maybe other ensemble conditions as well, are not necessarily seen by the players as being controlled by the acoustic conditions or the presence of reflecting surfaces close to the orchestra. This could be caused by the precedence effect, contributing to the presence of early reflections being suppressed by our auditory system – effects relating to reflecting surfaces close to the orchestra could be associated with the source itself, not the stage enclosure. When players comment on acoustic response, it frequently refers to the acoustic response from the main auditorium (the hall sound from the audience area).

Risers will contribute to improved visibility and less attenuation of the direct sound between players – most players prefer having risers on stage. The preference for curved risers among string players could indicate that string players often have problems communicating across the stage if all string players sit on a flat stage floor. A flexible riser system appears to be beneficial for the orchestra so they can adapt the staging to repertoire.

A good balance of hearing self and others appears to be a crucial part of stage acoustic conditions. For many players, good acoustic conditions are further described as everyone being able to hear each other clearly, but also the audibility and quality of the acoustic response from the main auditorium are mentioned as important factors by a large number of players. With regard to acoustic response there appears to be an optimum level; both a lacking or excessive level is found to be not beneficial for the players. These results agree reasonably well with results by [Gade \(1981\)](#), [Genta \*et al.\* \(2007b\)](#) and [Guthrie \(2008\)](#). Even if some instruments might be more important to hear than others, the repertoire affects which players are most important to hear. Therefore, if the acoustic conditions enable all players to hear each other, the stage will be most versatile.

The reverberant response from the main auditorium at an appropriate level appears to provide a better impression of level balance between instruments as heard by the audience, as opposed to perceived balance based on the early sound on stage (direct sound and early reflections). Hearing the acoustic response from the audience was described as ‘projection’ by several players – the impression of hearing what the audience hear – an element of communication and reassurance. This suggests that the level of reverberant sound within the stage enclosure itself should not be dominating. (How to assess this objectively is discussed in Chapter 7.) The players do not appear to have any clear opinions on what objective conditions contribute to such an impression. Some players report on taking advantage of using the reverberant sound coming from the main auditorium for intonation, balance, articulation and timing purposes. Other players appear to prefer working on the immediate sound, the early sound on stage, and this could be a matter of different playing styles and training/education among the players.

### 3.5 Preference rating questions

The questions with bipolar semantic differential scales (Likert rating) were:

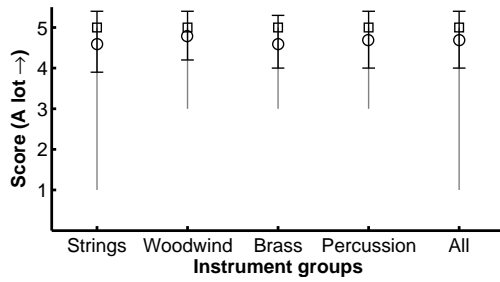
- Variation of acoustics (*AcouVar*): “To what degree does the acoustics for you as a performer vary between the halls in which you play?”  
1 = A little – 5 = A lot
- Space importance (*SpaceImp*): “How important is the floor area and space available to you on stage?”  
1 = Seldom an issue – 5: Very important
- Stage size preference (*SizePref*): “What is your preference regarding stage area for whatever reasons?”  
1 = Compact – 5 = Large
- Risers preference (*RisersPref*): “What is your preferred riser configuration for providing best conditions for the orch. as a whole?”  
1 = No risers, 2 = Woodw., brass, perc. only on risers, 3 = Curved, 4 = Other
- Loud instruments not a problem (*LoudNP*): “How often do loud instruments near you complicate your ability to play your own instrument?”  
1 = Frequently – 5 = Rarely
- Spatially separating sound (*SpatialSep*): “How important is it for you being able to spatially separate the sound from different instruments?”  
1 = Seldom an issue – 5 = Very important
- Ease of focusing on particular instruments (*FocusNP*): “How often do you have problems with focusing on particular instruments?”  
1 = Rarely – 5 = Frequently
- Surface awareness (*SurfAware*): “Are you aware of surfaces close to the stage which contribute positively or negatively to the acoustics for you?”  
1 = Not aware – 5 = Very aware

- Ability to hear the hall sound (*HallSound*): “How important is it to hear the sound coming from the audience area?”  
1 = Seldom an issue – 5 = Very important

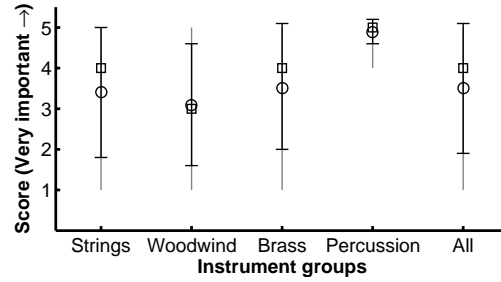
To avoid the ‘halo effect’, some of these scales were reversed on the questionnaire with the positive statement being on the opposite side of the page (left-right). Average (arithmetic) values of the responses were found within the four instrument groups and the orchestra as a whole (based on all the individual responses). One of the eight orchestras was not asked about *SpatialSep*, *FocusProbl* and *SurfAware*.

Figure 3.2 shows the results for the eight rating questions. For variation of acoustics, *AcouVar*, we see that all players experience the acoustics as varying a lot between different stages. The median value is 5 for all instrument groups and the orchestra as a whole, and the standard deviation is small ( $\sigma = 0.6$ ). A few players chose a value below 3 which increased standard deviation. This leads to the average value plus standard deviation becoming higher than 5. The importance of the space available on stage, *SpaceImp*, is on average moderately important for string, woodwind and brass players, while being very important for percussion players. For the first three groups standard deviation is high (around 1.5). With regard to size preference, *SizePref*, only a few string players prefer a small stage. On average, the players prefer a moderately large stage. For problems relating to some instruments becoming too loud, *LoudNP*, this appears to be a problem for the brass players in particular, but also for the woodwind and string players. The percussionists appear to have the least problems with other instruments becoming too loud. For *LoudNP* standard deviation is high (at 1.3 among all the players). From the Student’s t test analysis, the responses from the percussion players differ significantly (at the 5 % level) from the other players and orchestra average with regard to *SpaceImp*, and from the woodwind players with regard to *SizePref*. With regard to *LoudNP*, responses from the string and percussion players differ significantly from the woodwind and brass players. Apart from this, no significant differences are found between the instrument groups. Correlation analysis has also been conducted on the data; see Section 3.5.4 for more details.

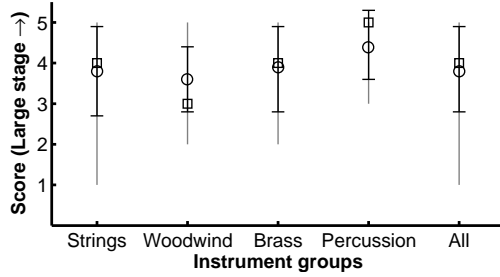
From Figure 3.2, being able to spatially separate between different instruments, *SpatialSep*, appears important for most string, woodwind and brass players while being of less concern among the percussion players. Most of the players also reported they sometimes experience problems with focusing on particular instruments, *FocusNP*. The standard deviations are moderate for these two questions ( $\sigma = 0.8\text{--}1.2$ ). With respect to awareness of reflecting surfaces close to the orchestra, *SurfAware*, there appears to be some awareness, but  $\sigma$  is high (1.3–1.6). None of the percussion players responded to this question. Hearing the reverberant sound from the hall, *HallSound*, is on average moderately important, but there is a large variation in the responses with  $\sigma = 1.4\text{--}1.8$  as the players tend to split up in two groups with regard to this (as mentioned in Section 3.4.6). With regard to differences between instrument groups (Student’s t test analysis), there are no significant differences found, except that string players responded differently from the woodwind and brass on *SurfAware*, and percussion players responded differently from the woodwind players on *SpatialSep*.



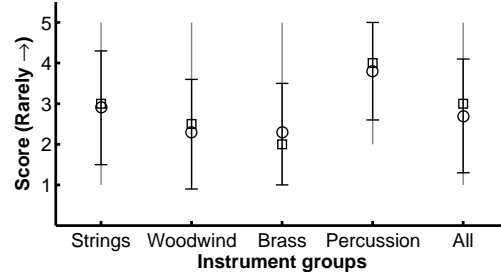
(a) Variation of stage acoustics, *AcouVar*.



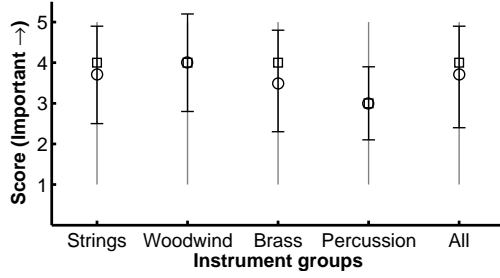
(b) Importance of stage size, *SpacImp*.



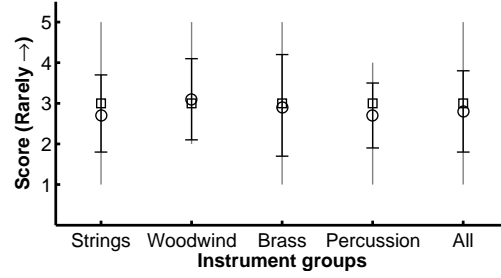
(c) Stage size preference, *SizePref*.



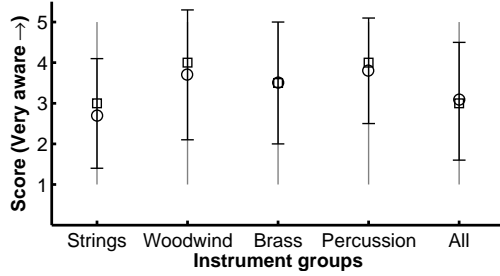
(d) Problems with loud instruments, *LoudNP*.



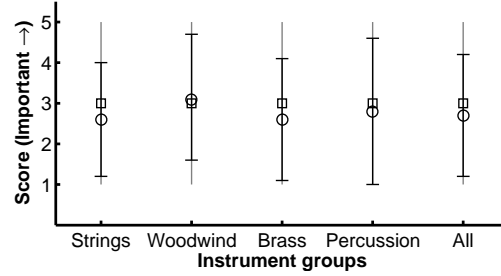
(e) Spatial separation, *SpatialSep*.



(f) Problems focusing on particular instr., *FocusNP*.



(g) Awareness of close surfaces, *SurfAware*.



(h) Hearing reverberant hall sound, *HallSound*.

Figure 3.2: Results for rating questions. | = range,  $\circ$  = arithmetical average,  $\square$  = median average,  $I = \pm\sigma$ .

For all the eight questions the agreement between the arithmetic average value and median value is good, except for the question relating to surface awareness, *SurfAware*, and to some degree also stage size preference, *SizePref*.

### **3.5.1 Comments on loud instruments**

The players were asked to indicate which instrument(s) they normally find too loud (if relevant). For the string players, brass in general, percussion, piccolo and woodwind in general appear to be most frequently too loud (in this order). For the woodwind players, brass and percussion are mentioned as being too loud, while brass players mention percussion most frequently, but also other brass players (including oneself). Percussion players mentioned French horns, brass in general and other percussion, with a comparable number of players mentioning these different groups.

### **3.5.2 Comments on problems with focusing on particular instruments**

The question regarding to problems related to (mentally) focusing on particular instruments resulted in a variety of comments from the players. Many players commented that problems with focusing on particular instruments result in ensemble problems (difficult to get a correct impression of level balance, intonation and hard to hear 'cues'); a lack of confidence; becoming more tense or hesitant. Below are quoted some of their comments to this question, sorted according to the instrument they played:

"Sometimes a wider stage makes it difficult to hear across to the basses. Sometimes mid-range instruments are 'swamped' acoustically" (1<sup>st</sup> violin).

"Can be very hard to play together with 1<sup>st</sup> violins, especially when sitting opposite" (2<sup>nd</sup> violin)

"It helps to see a fellow musician – I'm often looking the wrong way" (2<sup>nd</sup> violin).

"If there is a delay in the sound of someone else reaching me, it can cause ensemble problems" (viola player).

"Mainly distance related, contact with the first violins or cellos etc." (oboe player).

"Can't see, or not able to distinguish where people are playing" (bassoon player).

"If too far from basses and woodwind it is difficult to latch on intonation-wise" (trumpet player).

"Dominance of an instrument I don't need to hear over one that I do need to hear" (trombone player).

### **3.5.3 Comments on awareness of reflecting surfaces**

With regard to awareness of reflecting surfaces close to the stage, a small portion of the players appear to have clear opinions on how surfaces near them affect their playing conditions (as found in Section 3.4.8). Many players comment that curtains and drapes absorb sound too much and that they like wooden surfaces. Several French horn players commented that the surface behind them affects their sound. They expressed dislike for very reflective surfaces close behind them or the contrary – having overly absorbing surfaces or a lack of any surface at all behind them. Below follow some quotes from players, sorted according to the instrument they play:

"I like what the [overhead] glass reflectors do to the sound at Bridgewater Hall" (1<sup>st</sup> violin).

"Canopies above stage can often help – e.g. new panels at Royal Festival Hall" (2<sup>nd</sup> violin).

“A dead floor is easy to notice for cello and bass” (2<sup>nd</sup> violin).  
 “Reflection from the back wall can interfere with strongly rhythmic passages” (viola).  
 “Reflective baffles can help clarity. Too enclosed stage makes the whole thing too loud.” (cello).  
 “Amplification of some instruments when near a wall and ‘odd’ echoes” (cello).  
 “Perspex dishes above the stage significantly change the acoustics sitting at different heights on stage” (bassoon).  
 “Stage ceiling and back wall give a feeling of sound reaching out to the audience” (oboe).  
 “Low ceilings are bad – deaden the sound” (trombone).  
 “A lacking ceiling leads to poor exposure to the [sound from the] audience [area]” (percussion).

### 3.5.4 Correlation of the rating responses

Correlation analysis was conducted to see the relations between the rating responses/subjective characteristics. The results from the correlation analysis show only weak correlations. Because of the large number of questionnaires however, some of these weak correlations are highly significant. The highest correlation coefficient,  $r$ , is seen between *LoudNP* and *FocusNP* ( $r=0.36$ ), and between *FocusNP* and *SpatialSep* ( $r=-0.27$ ) – both significant at the 1 % level. This indicates that those players reporting problems with focusing on particular instruments also have a tendency of having problems with some instruments becoming too loud. They also tend to find it important to be able to spatially separate different instruments. The players who find it important to hear the hall reverberation also tend to report awareness of reflecting surfaces. The number of years of experience did not show any significant correlation with the other rating measures.

### 3.5.5 Discussion and conclusions of preference rating results

The results indicate that most of the players clearly experience variations of acoustic conditions between different stages. The measure *AcouVar* has the smallest standard deviation of the eight preference measures. The measure relating to preference for stage size, *SizePref*, shows the second smallest standard deviation. Most players prefer a moderately large stage, though a few string players prefer a small stage. From the comments by the players, a small depth of the stage appears to be more frequently a problem than lack of space across the width of the stage. Sitting too far apart sideways on stage appears to make it difficult for the whole string section to communicate with each other aurally. This is supported by comments from 1<sup>st</sup> and 2<sup>nd</sup> violin players and that some string players prefer a compact stage.

For the other questions there are larger deviations in the responses. For a few of the questions there appear to be significant differences between the instrument groups. All the percussion players reported space available on stage as very important, while the other groups show larger deviations with regard to this. The space available is important for most of the players. There appears to be a link between the preference for a moderately large stage among most players and most players reporting problems with some instruments becoming too loud (*LoudNP*). Particularly the depth of the stage will affect how close players sit to the loud



instruments at the back half of the stage (woodwind, brass and percussion). For string and percussion players who would normally sit either far away from or behind the brass players, the results show that excessively loud instruments are less frequently a problem. The loudness of other instruments will affect the level balance within the orchestra as well as physical comfort.

The results indicate that being able to spatially separate the different instruments within the orchestra is important for the string, woodwind and brass players. The percussionists appear less concerned about this. The significant and moderate correlation between *FocusNP* and *SpatialSep* suggests that being able to spatially separate different instrument makes it easier to focus on certain instruments they need to hear. Problems with separating and focusing on different instruments appear to relate to proximity to loud instruments and direct sound attenuation. Percussionists reporting less problems with separating and focusing are on risers and the results show moderate and significant correlation between *LoudNP* and *FocusNP*. These results suggest that the perceptual effects, like the cocktail-party effect and masking affect the ability to hear other players clearly. The comments made by the players indicate that loud instruments contribute to make aural communication with other players difficult. The comments also suggest that for string players, difficulties with focusing on other instruments are related to their ability to hear across the stage. Such problems were reported to lead to stress and hesitation among the players.

The players had mixed responses regarding reflecting surfaces around them. Not many players have a clear view on where reflecting surfaces close to them should be located except for the French horn players. The players could have problems being able to see cause and effect of nearby reflecting surfaces, also indicated by the large spread in responses with regard to surface awareness (*SurfAware*). This could be related to the precedence effect as mentioned in Section 3.4.8. French horn players appear to relate clearly to the presence of reflecting surfaces behind them, though it is difficult to understand precisely how this ideally should be arranged for them. A reflecting surface very close behind them appears to be disadvantageous, but they do need a reflection at a certain level from behind, since the sound of their instrument (particularly at higher frequencies) is projected in that direction. A ceiling or overhead reflection are mentioned as being both positive and negative and it is not so easy to understand from their brief comments what they see as beneficial overhead conditions. For smaller reflectors hung above the orchestra (as in Bridgewater Hall, Manchester), a string player commented positively about these, whereas a bassoonist responded negatively. Bassoonists will have their instruments radiating upwards at higher frequencies (like a tuba player). The presence of an overhead reflector can make the impression of their own sound vary considerably, particularly at high frequencies. Some players comment on getting disturbed by a reflection off the back wall (of the main hall). Such a late arriving reflection could be rhythmically/temporally disturbing if too prominent.

With regard to being able to hear the reverberant hall sound, the players split into two groups (as mentioned in Section 3.4.6): those finding the reverberant sound somehow useful and those finding it disturbing (arriving too late). Separation into these two groups shows no clear relation to the instrument they play, nor years of experience. These findings agree with comments from the players in Section 3.4. Based on the correlation analysis, the players regarding it useful appear to be more aware of reflecting surfaces close to them. The reason



for this relation is not evident, but it could indicate that the awareness of aspects of acoustic conditions differ between the players.

### 3.6 Specific halls rated by the players

For each of the British orchestras, a set of eight halls was selected which the players could rate according to overall acoustic impression (OAI) on a scale from 1 to 10. The selected halls were halls they regularly perform in. A total of 33 halls were included. An orchestra average value of OAI was found for all the halls taken as the arithmetical average value of individual responses. The results showed that musicians consistently gave a low score, below 4 out of 10, with regard to overall acoustic impression for two types of auditorium: proscenium theatres and large nineteenth century city halls with long reverberation times. The comments from the players on these halls were largely related to a lack of acoustic response in the proscenium theatres and excess of acoustic response in the city halls. These comments and the findings in Section 3.4 suggest that a suitable level of acoustic response from the main auditorium is essential for symphony orchestras. For valid comparisons of stage enclosures it therefore appears necessary to only include the 12 halls receiving OAI above 4. All halls with an OAI above 4 happen to be concert halls purpose-built for performance by larger acoustic ensembles. One of the Norwegian orchestras were asked to rate 12 purpose-built concert halls they have visited over several occasions – 3 to 4 times over the last 15 years. One of these halls was the Royal Albert Hall (London), also rated by some the British orchestra. Objective data for the halls were collected from [Barron \(1993\)](#), [Beranek \(2004\)](#) and [Gade \(1989c\)](#). Data on Oslo Concert Hall is from [Jordan \(1980\)](#) and personal communication with Magne Skålevik.

The 22 purpose-built concert halls rated by the players, for which objective data are available, were:

Amsterdam, Concertgebouw	(AMC)
Basingstoke, The Anvil	(BAA)
Berlin, Philharmonie	(BEP)
Birmingham, Symphony Hall	(BIS)
Cardiff, St David's Hall	(CAS)
Chigaco, Orchestra Hall	(CHO)
Croydon, Fairfield Hall	(CRF)
London, Royal Albert Hall	(LRA)
London, Barbican Hall	(LBA)
London, Royal Festival Hall (before 2007)	(LRF)
London, Queen Elizabeth Hall	(LQE)
Lucerne, KKL Concert Hall	(LUC)
Manchester, Bridgewater Hall	(MAB)
Munich, Gasteig	(MUG)
New York, Carnegie Hall	(NYC)
Northampton, Derngate Centre	(NOD)
Nottingham, Royal Concert Hall	(NOR)
Oslo Concert Hall	(OSC)

Poole, The Lighthouse	(POL)
Vienna, Großer Musikvereinsaal	(VIM)
Zurich, Großer Tonhalleaal	(ZUT)
Washington, DC, JFK Center, Concert Hall	(WAC)

### 3.6.1 The effect of which orchestras judging acoustic conditions

Of the 44 halls rated totally (33 judged by the British orchestras, and 11 other halls judged by the Norwegian orchestra), 9 were rated by more than one orchestra. Six of these are included above, whereas the other three were Sheffield, City Hall (SHC); Leeds, Town Hall (LET) and Hanley, Victoria Hall (HAV). These three halls have an average score below 4 out of 10, are not purpose-built concert halls, or there was a lack of objective data available. Table 3.2 shows the orchestra average values of *OAI* for these nine halls among the orchestra who rated them.

Table 3.2: Average overall acoustic impression, *OAI*, in halls rated by more than one orchestra. The number of players contributing to the orchestra average values is given as subscript. Statistically different judgements are given as pairs in bold or underlined.

Hall	Orchestra							All
	1	2	3	4	5	6	7	
BIS	<b>6.9</b> <sub>11</sub>		<u>9.0</u> <sub>31</sub>		<u>6.8</u> <sub>5</sub>			8.2 <sub>47</sub>
CAS		<b>8.4</b> <sub>23</sub>			<b>7.3</b> <sub>5</sub>		7.1 <sub>15</sub>	7.7 <sub>43</sub>
HAV	6.3 <sub>11</sub>		5.6 <sub>30</sub>	6.4 <sub>9</sub>				5.9 <sub>50</sub>
LET	5.7 <sub>11</sub>		5.2 <sub>28</sub>	5.4 <sub>9</sub>				5.4 <sub>48</sub>
LBA					4.8 <sub>5</sub>		6.1 <sub>15</sub>	5.8 <sub>20</sub>
LRA	6.0 <sub>11</sub>				<b>4.0</b> <sub>5</sub>	<b>7.2</b> <sub>20</sub>	<u>5.0</u> <sub>16</sub>	5.9 <sub>52</sub>
LRF					5.0 <sub>5</sub>	6.1 <sub>15</sub>		5.8 <sub>20</sub>
MAB	7.9 <sub>11</sub>			7.3 <sub>9</sub>	7.7 <sub>5</sub>			7.7 <sub>25</sub>
SHC	3.7 <sub>11</sub>			3.1 <sub>9</sub>				3.4 <sub>20</sub>

Student's t tests were carried out to see if the different values of *OAI* between the orchestras were statistically significant (at 5 % level). The pairs of judgements which differ significantly are indicated as bold or underlined pairs in Table 3.2. For London, Royal Albert Hall (LRA), the orchestra showing a significantly different value of *OAI* is one of the Norwegian orchestras. This indicates that judgement of seldom visited halls may be questionable due to lack of experience of the particular conditions. For Birmingham, Symphony Hall (BIS), the orchestra showing a significantly different value of *OAI* is the home orchestra for this hall. This indicates that the players will adapt to the characteristics of a certain hall over a long period of time, leading to biased judgements of the conditions. (Some players within the orchestras visiting BIS commented that they hear too much of themselves and this makes them feel very exposed. The players in the home orchestra could have adapted to this). But the validity of judgements of home venue may be affected by to what degree an orchestra regularly visits other venues. For the other halls, the differences between the orchestras cannot be seen as significant. For CAS, HAV, LET, LRF, MAB and SHC (halls regularly visited by the judging orchestras) *OAI* is reasonably consistent.

### 3.6.2 Objective measures associated with the purpose-built concert halls

The reverberation time,  $T$ , measured in the audience area with unoccupied seats were available for all the purpose-built concert halls (except for LUC where only occupied values were available). From knowledge of  $T$  and hall volume,  $V$ , average late sound level  $G$  ( $G_{80-\infty}$ ) within the audience area was estimated using Equation 3.1, according to Barron's revised theory of sound distribution in enclosed spaces (Barron & Lee (1988) and Chiles & Barron (2004)). A source-receiver distance of  $r = 15$  m was used, representing mid stalls. The estimated  $G_l$  will indicate the level of acoustic response from the main auditorium the front line of the stage will be exposed to.  $G_{80-\infty}$  was used instead of  $G_{50-\infty}$  since  $G_{80-\infty}$  can be estimated using Equation 3.1 or calculated from measured  $G$  and  $C_{80}$ . Obtaining  $G_{50-\infty}$  from measured  $G$  would additionally require measured  $D_{50}$  which is less available in the literature compared to  $C_{80}$  for concert halls. For some halls, results for the Support measure  $ST_{early}$  ( $ST1$ ) for evaluating stage acoustic conditions, as proposed by Gade (1989b), was also available. Architectural measures based on stage enclosure dimensions were also found, with reference to distance to reflecting surfaces, not related to stage floor dimensions.

$$G_l = 10 \cdot \log_{10} \left( \frac{31200 \cdot T}{V} \cdot e^{-0.04r/T} \cdot e^{-1.11/T} \right) \quad \text{dB} \quad (3.1)$$

Figure 3.3 illustrates how the architectural measures were obtained.  $W_{rs}$  (width reflecting surfaces strings) is found as the average distance between surfaces likely to reflect sound on the sides within the front half of the stage, where the string players normally sit.  $H_{rb}$  (height reflecting surfaces brass) is found as the average height from the average floor height between brass and string section, up to a reflective surface likely to reflect sound from brass (as well as percussion) instruments down towards the string section. With tilted or smaller reflecting surfaces above the orchestra, there will be a question about how significantly these surfaces reflect the brass down towards the string section. Often an overhead reflector is tilted to project sound towards the audience – in such a case the presence of the reflector is ignored when obtaining  $H_{rb}$ . The height up to reflecting surface(s) above the string players,  $H_{rs}$ , was also considered. Since this measure was found to correlate highly with  $H_{rb}$  ( $r = 0.88$ ) it was not included among the architectural measures studied in detail for this project.  $D$  is found as the distance between the back end of the stage accessible to the orchestra and the average stage front. If the line defining the back of the stage for instance is curved, an average value is found. The distance to reflecting surface relating to  $D$  was ignored for the following reasons: the vertical surface behind the orchestra are in some halls made absorbing, and the space accessible to the orchestra significantly affects direct sound levels within the orchestra. The ratios  $H_{rb}/W_{rs}$  and  $D/W_{rs}$  were also calculated. One could potentially also study  $H_{rb} \cdot D/W_{rs}$ , combining all the effects of  $W_{rs}$ ,  $H_{rb}$  and  $D$ . This has not been implemented, since such a measure for instance will make it difficult to isolate the effect of  $H_{rb}$  from the effect of  $D$ .

Table 3.3 shows results for  $OAI$  (orchestra average) and the objective measures obtained for the 22 rated purpose-built concert halls listed in Section 3.6, sorted according to  $OAI$ . The volumes of the halls are not included in Table 3.3, but have been used to estimate the late

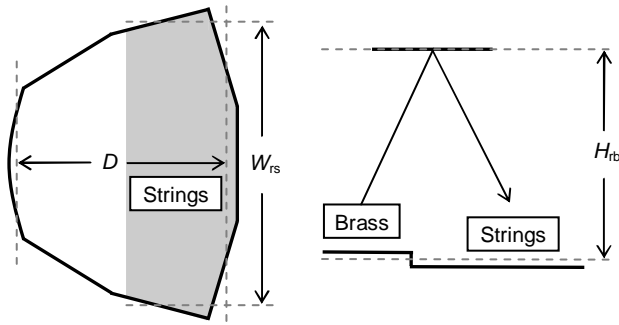


Figure 3.3: Plan and long section of a generic stage showing the method for obtaining the proposed architectural measures.

sound level on stage,  $G_i$ . The presence of risers on stage ( $r$ ), stage exposed to (acoustically highly integrated with) the main auditorium ( $e$ ) and the overall type of concert hall plan ( $p$ ) is also included in Table 3.3. The halls with hall identification in bold have  $OAI$  based on judgements by orchestras visiting regularly only – these halls were used for the main analysis (Section 3.6.3).

Table 3.3: Objective measures for rated purpose-built concert halls, sorted according to average overall acoustic impression,  $OAI$ . Subscripts to  $OAI$  represent the number of players rating the particular hall. Bold halls were judged by orchestras visiting regularly.  $r$ =risers,  $e$ =exposed,  $t$ =type of hall, where  $A$ =arena/surround,  $S$ =shoebox,  $P$ =parallel sided,  $V$ =vineyard terraced,  $F$ =fan-shaped type hall.

Hall	$OAI$	$T$	$G_i$	$ST_{early}$	$W_{rs}$	$H_{rb}$	$D$	$\frac{H_{rb}}{W_{rs}}$	$\frac{D}{W_{rs}}$	$r$	$e$	$t$
VIM	9.7 <sub>22</sub>	3.1	5.6	−13.9	20.5	17.3	9.0	0.84	0.44	✓	✓	S
<b>BAA</b>	9.1 <sub>23</sub>	2.0	2.6	−12.8	17.6	19.6	12.6	1.11	0.72	✓	✓	A
LUC	9.1 <sub>18</sub>	2.1	1.9		21.2	14.8	12.1	0.70	0.57	✓	✓	P
BEP	8.9 <sub>18</sub>	2.2	1.8	−16.8	18.6	12.1	9.7	0.65	0.52	✓	✓	V
<b>NOR</b>	8.7 <sub>9</sub>	2.0	1.6		20.0	11.0	8.8	0.55	0.44	✓	✓	V
NYC	8.0 <sub>19</sub>	2.1	0.6		20.4	15.5	12.1	0.76	0.59	–	–	S
<b>CAS</b>	7.7 <sub>28</sub>	1.9	2.9	−17.4	19.5	18.5	11.0	0.95	0.56	✓	✓	V
<b>MAB</b>	7.7 <sub>25</sub>	2.4	1.8		23.0	22.0	14.5	0.96	0.63	✓	✓	P
AMC	7.6 <sub>15</sub>	2.6	3.5	−17.8	29.0	15.8	9.0	0.54	0.31	✓	✓	S
CHO	7.5 <sub>16</sub>	1.9	−0.5		21.8	10.2	11.9	0.47	0.55	✓	–	V
MUG	7.5 <sub>17</sub>	2.2	0.3	−17.9	20.3	14.8	11.6	0.73	0.57	✓	✓	V
<b>CRF</b>	7.4 <sub>16</sub>	1.9	1.9		24.0	10.5	10.8	0.44	0.45	✓	✓	S
ZUT	7.4 <sub>15</sub>	2.1	3.9		15.5	11.6	9.2	0.75	0.59	✓	✓	P
<b>BIS</b>	6.9 <sub>16</sub>	2.5	2.0		24.0	14.0	14.0	0.58	0.58	✓	✓	P
WAC	6.3 <sub>6</sub>	1.9	0.4	−18.1	19.4	10.6	11.9	0.55	0.61	–	–	V
<b>LBA</b>	5.8 <sub>20</sub>	1.9	1.3	−13.2	18.0	7.8	10.0	0.43	0.56	✓	–	S
<b>LRF</b>	5.8 <sub>20</sub>	1.9	3.2	−16.0	23.0	11.5	10.0	0.50	0.43	✓	✓	S
<b>LQE</b>	5.4 <sub>5</sub>	2.1	6.5		20.0	8.4	12.5	0.42	0.63	✓	–	S
<b>NOD</b>	5.3 <sub>16</sub>	1.9	4.2	−14.6	23.0	11.3	9.5	0.49	0.41	✓	✓	A
<b>LRA</b>	5.2 <sub>36</sub>	3.0	−2.1		35.0	9.5	8.0	0.27	0.23	✓	✓	A
<b>POL</b>	5.2 <sub>23</sub>	2.2	3.9	−13.9	27.5	9.0	9.1	0.33	0.33	✓	–	S
OSC	4.4 <sub>22</sub>	2.1	1.3	−13.7	25.0	7.5	13.0	0.30	0.52	✓	✓	F

Figure 3.4 shows the relative difference between values of  $OAI$  for the 12 halls visited regularly, with standard deviations indicated as  $\pm\sigma$ . Student's  $t$  test analysis indicate that values of  $OAI$  do not differ significantly between the six least preferred halls (at the 5 % level). Several differences between the six most preferred halls are also found insignificant, but all the six most preferred halls differ significantly from the six least preferred halls except for BIS.

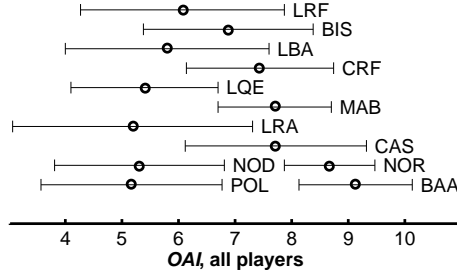


Figure 3.4: OAI (orchestra average) for the 12 purpose-built concert halls visited regularly, including standard deviation ( $\pm\sigma$ ).

Results from correlation analysis show that the correlations between  $T$ ,  $V$  and  $G_l$  are moderate as we would expect, but no high correlations coefficients are seen between  $T$ ,  $G_l$  and  $ST_{early}$ .  $V$  shows significant correlation with  $W_{rs}$ . The stage width would often be related to the overall width of the hall, which significantly will control the hall volume. There are no high correlation between the metric architectural measures ( $W_{rs}$ ,  $H_{rb}$  and  $D$ ), but the ratio measures show significant and high correlation coefficients with some of the metric measures. These significant correlations indicate that there are not many narrow and low or wide and high stage enclosures. Wide stages tend to also be shallow.

### 3.6.3 Relationships between average overall acoustic impression and objective measures

To study the relationships between OAI (among all players) and objective measures, judgements of home halls or halls visited only occasionally have been excluded, for reasons mentioned in Section 3.6.1. This reduced the set of 22 purpose-built concert halls to a total of 12 (all within the UK and marked bold in Table 3.3). Table 3.4 shows the correlation coefficients,  $r$ , between the orchestra average OAI and the objective measures for these 12 halls. The acoustic measures show no significant correlations. In fact the two highest and the two lowest scoring halls on OAI have very comparable values of  $T$ ,  $G_l$  and  $ST_{early}$ . The architectural measures  $W_{rs}$ ,  $H_{rb}$ ,  $H_{rb}/W_{rs}$  and  $D/W_{rs}$  show correlation coefficients significant at the 10 % level or below.  $H_{rb}/W_{rs}$  shows the highest and most significant correlation with  $r = 0.78$  (significant at the 1 % level). The results for  $H_{rs}$ , only included in the preliminary study, are very comparable to  $H_{rb}$ . For the data set with all 22 halls in Table 3.3 (also including home and occasionally visited stages), the correlation coefficients are slightly reduced. For  $H_{rb}/W_{rs}$  the correlation coefficient is reduced from 0.78 to 0.71, whereas for  $H_{rb}$   $r$  falls from 0.69 to 0.67.

Table 3.4: Correlation coefficient,  $r$ , between OAI (all players) and objective measures. Bold numbers indicate significance at the 1 %, underlined at the 5 % level. Total number of samples  $N = 12$ .

Var.	$T$	$G_l$	$ST_{early}$	$W_{rs}$	$H_{rb}$	$D$	$\frac{H_{rb}}{W_{rs}}$	$\frac{D}{W_{rs}}$
OAI	-0.24	-0.14	0.00	-0.52	<u>0.69</u>	0.39	<b>0.78</b>	0.55

Figure 3.5 shows values of OAI (all players) versus the eight objective measures, considering the 12 halls visited regularly. The standard deviation of OAI is indicated as  $\pm\sigma$ . Linear and

parabolic (2<sup>nd</sup> order polynomial) regression curves with corresponding correlation coefficients  $|r|$  (the absolute value of  $r$ ) are indicated.

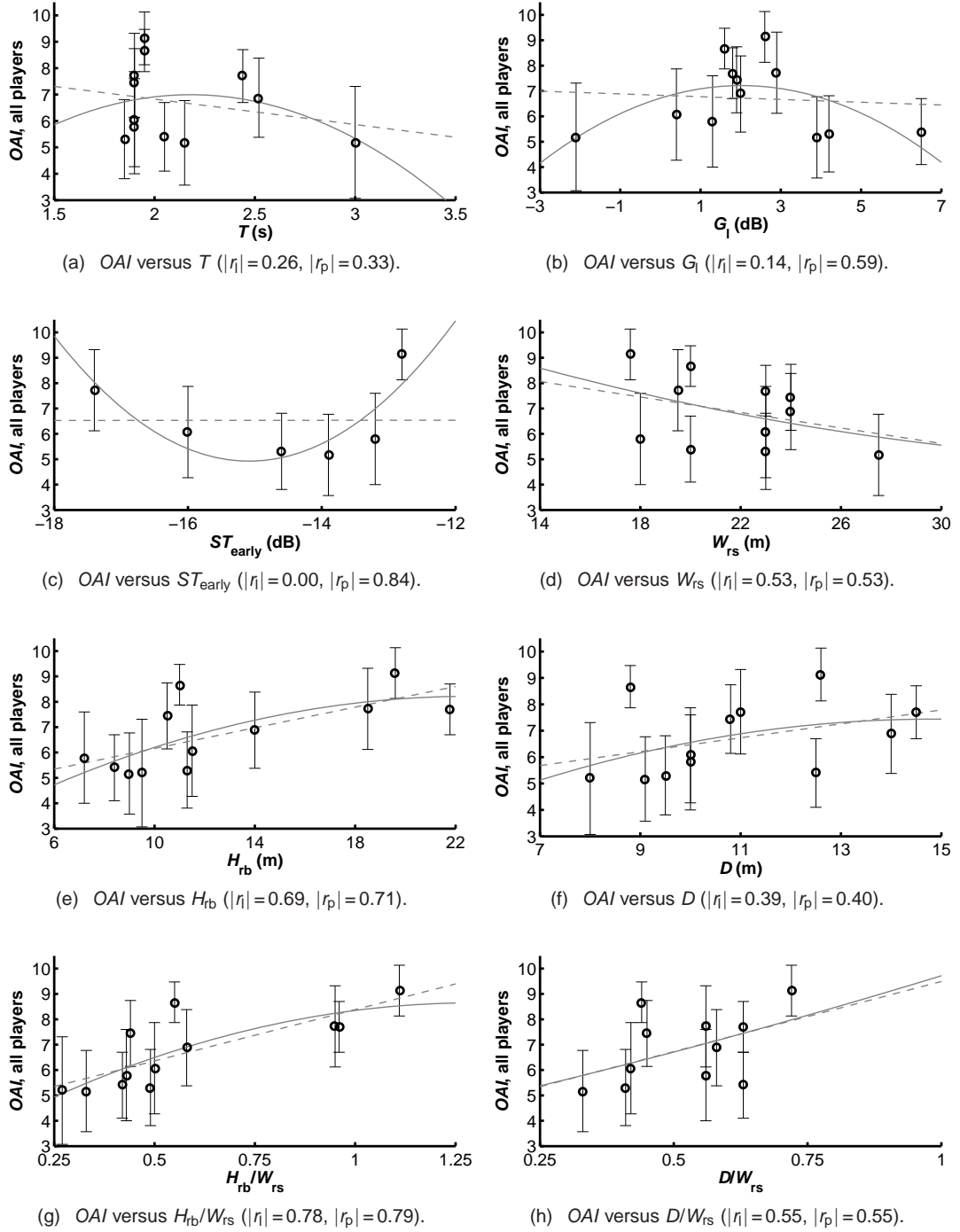


Figure 3.5:  $OAI$  versus acoustic and architectural measures for the 12 purpose-built concert halls visited regularly. Standard deviation of  $OAI$  marked as  $\pm\sigma$ . The curves represent linear (dashed) and parabolic (solid) regression curves. The correlation coefficients  $|r_l|$  (linear regression) and  $|r_p|$  (parabolic regression) are indicated.

For  $T$  and  $G_l$  there is slight evidence of an optimal range of values. Particularly for  $G_l$  the parabolic regression shows significantly higher correlation coefficient compared to the linear regression,  $|r|$  of 0.59 instead of 0.14. All halls having  $OAI$  above 7 have  $G_l$  within 1–3 dB. This apparent optimal range is based on measurements carried out with unoccupied audience

seats, moderately upholstered. To what degree the measured levels correspond to occupied conditions will depend on the seating design for the halls studied. Most modern halls have the audience seats designed to result in only minor differences in acoustic conditions between unoccupied and occupied seats, which contribute to increased validity of estimated/measured  $G_i$  in the audience area. A similar tendency is seen for  $T$  within 1.8–2.5 s, but this relation is not as significant compared to  $G_i$ . For  $ST_{\text{early}}$ ,  $|r|$  is high for the parabolic regression. But the parabola has an inverted shape of what would be expected based on conclusions in Gade (1992) – highest values of  $OAI$  are seen for the most extreme values of  $ST_{\text{early}}$ . Values of  $ST_{\text{early}}$  are also very comparable for the most (WIM and BAA) and the least (POL and OSC) preferred halls, out of the 22 halls studied. For  $W_{rs}$ ,  $D$  and  $D/W_{rs}$  there are no clear distinctions between the least and most preferred halls, though a tendency of preference for stages not being too wide or too shallow is seen. For  $H_{rb}$  and  $H_{rb}/W_{rs}$  there is evidence of the most preferred halls having higher values. For the architectural measures there are not significant differences between resulting  $|r|$  for linear versus parabolic regression, though the parabolic regression curves suggest that  $OAI$  ‘saturates’ for high values of  $H_{rb}$  and  $H_{rb}/W_{rs}$ .

### 3.6.4 Comparison of high and medium scoring halls

The results in Section 3.6.1 indicate that several differences of  $OAI$  between the six most and the six least preferred halls are statistically not significant. Based on this, the six most preferred halls receiving a score of  $OAI$  within 7–10 were assigned to a group H. The six remaining halls receiving a score within 4–7 were assigned to a group M. By categorising into these two groups instead of individual results, there will be less emphasis on the small insignificant variations of  $OAI$ .

With regard to comments made about the halls within these two groups, there were only a few comments made regarding halls within group M (as the players were only asked to give reasons for their lowest and highest score). Those few available are however valuable (see below). For the halls within group H, the comments are similar to those reported in Section 3.4.2.

For medium scoring halls with wide and low stage enclosures:

“Everything sounds loud and coarse on the platform, dull & lacking in detail in the auditorium” (viola).

“Very difficult to hear instruments or section sitting not very far away” (viola).

“The hall is too boomy” (cello). “Hall creates a hard brass sound” (tuba).

For medium scoring halls with wide and high stage enclosures:

“I struggle to hear myself and others well” (double bass)

“The sound disappears” (trumpet player).

Discriminant analysis was carried out to see to which degree values of the objective measures could be used to discriminate between these two groups (H and M). One of the outputs



of discriminant analysis is Wilks' lambda, where a low value indicates that an independent measure is good at discriminating between a certain set of groups. Table 3.5 shows the results for Wilks' lambda for the objective measures. These results indicate that the acoustic measures show poor discrimination abilities, whereas the architectural quantities show discrimination abilities, in particular  $H_{rb}$  and  $H_{rb}/W_{rs}$ . Figure 3.6 shows how the architectural measures differ for the two groups H and M. The good discrimination capabilities found for  $H_{rb}$  and  $H_{rb}/W_{rs}$  agree well with the results of correlation analysis in Section 3.6.3.

Table 3.5: Results for discriminant analysis, Wilks' lambda.

Var.	$T$	$V_h$	$V_s$	$G_l$	$ST_{early}$	$W_{rs}$	$H_{rb}$	$D$	$\frac{H_{rb}}{W_{rs}}$	$\frac{D}{W_{rs}}$
Wilks' lambda	0.99	0.99	0.16	0.96	0.96	0.65	0.09	0.23	0.06	0.41

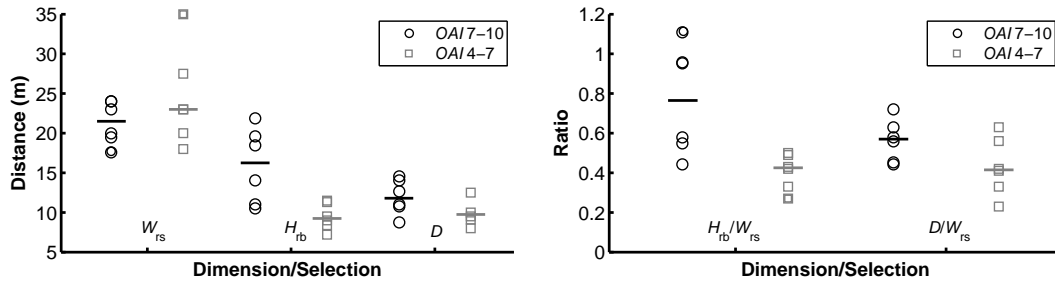


Figure 3.6: Architectural measures for the hall groups H ( $OAI = 7-10$ ) and M ( $OAI = 4-7$ ). Median values within each data set indicated as bold line.

Based on these results, Fisher's linear discriminant functions have been calculated for each of the architectural measures. From these functions the transition values between the two groups have been calculated. The results show that  $W_{rs} = 22.9$  m,  $H_{rb} = 12.8$  m,  $D = 10.9$  m,  $H_{rb}/W_{rs} = 0.59$  and  $D/W_{rs} = 0.50$  define the transition values between group H and M. If taking the mid point between the median values shown in Figure 3.6, similar transition values are found (only within up to 0.6 m difference).

### 3.6.5 Discussion and conclusions of results for specific halls

With regard to the least preferred halls (receiving  $OAI$  below 4 out of 10), the unsuitable level of reverberant sound appears to be the dominant reason for why they do not prefer these halls (mainly proscenium theatres and large city halls). From comments on the specific halls, an optimum level of acoustic response from the main auditorium is apparently more important compared to the results from Section 3.4. This may indicate that audible reverberant sound is important, and that it is easier for the players to report on this importance for cases where they actually experience a lack or excess of reverberant response.

To study the relations between judgements of overall acoustic impression,  $OAI$ , and objective characteristics, only halls with  $OAI$  above 4 out of 10 were included (which happen to all be purpose-built concert halls). The motivation for this was that an unsuitable level of acoustic response from the main auditorium was dominating in the comments from the players, making it difficult to compare impressions of the stage enclosure. The halls receiving  $OAI$  above 7



all have a level of late (reverberant) sound,  $G_l$ , within 1–3 dB (estimated values based on average  $T$  assessed within the audience area and hall volume  $V$ ). This optimum range is clear from parabolic regression analysis, but not from linear regression (correlation) analysis. That the level of reverberant response ( $G_l$ ) is more relevant than reverberation time, agrees with findings by [Griesinger \(1995\)](#). The tendencies of an optimum level of late sound is likely to relate to inaudible reverberant response if the level is not sufficient – the orchestra sound will mask it. If the late sound level is too high, clarity will suffer. The size of ensemble is likely to affect the optimum range of the acoustic response from the main auditorium. The limits of  $G_l$  for having  $OAI$  above 4 is more difficult to define, since the halls with  $OAI$  within 4–6 show  $G_l$  varying within –2.1 to 6.5 dB. With  $G_l$  not available (if not measured or with the hall volume unknown), measured  $T$  shows similar relations to  $OAI$  with  $T$  within 1.8–2.5 s. The results for  $ST_{early}$  show no optimum level, contradicting the findings by [Gade \(1992\)](#).

The architectural measures proposed, in particular  $H_{rb}$  and  $H_{rb}/W_{rs}$ , show significant correlations with  $OAI$  for halls having  $OAI$  within 4–10. There are found close to linear relations between  $OAI$  and the architectural measures. This could relate to the span of the architectural measures. Values of  $W_{rs}$ ,  $H_{rb}$  and  $H_{rb}/W_{rs}$  from this study may include extreme ends of possible variation, but for instance  $D$  may be larger for other halls. Hence, there could be parabolic relations for  $D$  and  $D/W_{rs}$ . The relevance of the architectural measures appears to relate to these measures assessing the proximity and location of reflecting surfaces (and direct sound levels). The results from Sections 3.4 and 3.5 indicate that the string players struggle to hear across the stage while instruments at the back of the stage are frequently too loud for most of the players. The location of reflecting surfaces is likely to affect these conditions in a negative or positive way. The direction of reflections from the stage enclosure is not encountered when measuring  $ST_{early}$  (see [Gade \(1992\)](#) for more details). This may explain why  $ST_{early}$  is not found relevant for ensemble conditions in this study. The results for the architectural measures suggest that the most preferred stage enclosures provide reflecting surfaces close to string players at the sides, do not provide reflections of percussion and brass at a high level, and makes the stage highly exposed to the main auditorium. Some reflecting surfaces above the players appear to result in improved clarity of sound for the players, but could result in unfavourable local variations of acoustic conditions or too high levels of percussions and brass. That the subjective relevance of  $H_{rs}$  was found to be comparable to  $H_{rb}$  suggests that reflecting surfaces above the string players have a less positive effect compared to reflecting surfaces at the sides of the string players. Though  $H_{rs}$  and  $H_{rb}$  were found to be highly correlated for the stage enclosures covered in this study. If only providing reflecting surface(s) above strings or woodwinds the results may have been different. Maybe contradictory, a wide and high may be better than a low and wide stage enclosure. A low stage enclosure appears to impose more negative conditions than a wide and high stage enclosure. The Concertgebouw in Amsterdam (AMC) could fall into the category of a wide and high stage, being among the high scoring halls.

There are found insignificant differences of  $OAI$  between several of the halls. This is likely to be associated with the number of players who responded and personal preferences between the players. Also, the architectural measures are simplified representation of the real architectural design of the enclosure, contributing to another uncertainty factor when comparing  $OAI$  to architectural measures. Results from the statistical analysis show it is only possible to

confidently discriminate between specific halls belonging to a group M which has  $OAI$  within 4–7 or a group H which has  $OAI$  within 7–10 (out of 10). Based on this, assessment of acoustic conditions for a specific hall may be carried out in the following way: first the level of the acoustic response within the audience area should be assessed from measured or estimated  $G_l$ . If the level is found suitable, the architectural measures can be studied to see if the specific hall with its stage enclosure is likely to belong to group M or group H based on the transition/threshold values found. All architectural measures should be studied, since the correlation between the architectural and subjective characteristics are likely to be stochastic variables (due to the uncertainties mentioned above), but  $H_{rb}$  and  $H_{rb}/W_{rs}$  have showed the best discrimination qualities in this study.

The apparent likelihoods for resulting  $OAI$  based on measured  $G_l$ , and  $H_{rb}$  and  $H_{rb}/W_{rs}$  are shown in Figure 3.7. These graphs are based on the results from Section 3.6.3. The white areas in this figure represent optimum values of the objective measures and the objective measures are mutually dependent – both  $G_l$  and the architectural measures need to be in the optimal range for being likely to achieve a high value of  $OAI$ . Within the optimum range there is a significant spread in possible values of  $OAI$ , but the lowest values of  $OAI$  is likely to be avoided. The significant spread is associated with the exclusion of other objective measures that could be relevant, the simplified representation of the acoustic response by the objective measures, and insignificant differences between mid-ranging halls when relating to average  $OAI$ . This demonstrates the limitations of quantitative objective and subjective studies. For instance the finer details of the stage enclosure are not represented by  $H_{rb}/W_{rs}$  and the direct sound levels are affected by the riser system used. Though the finer details of the stage enclosure appear to be most critical for intermediate values of  $H_{rb}/W_{rs}$  and  $H_{rb}$ . The halls with  $H_{rb}/W_{rs} \geq 0.6$  and  $H_{rb} \geq 14$  m all have  $OAI$  above 7, while the halls with  $H_{rb}/W_{rs} \leq 0.4$  and  $H_{rb} \geq 10$  m all have  $OAI$  below 6. The overall shape of the area describing the likelihood for  $OAI$  based on  $H_{rb}$  and  $H_{rb}/W_{rs}$  is based on that  $OAI$  is likely to ‘saturate’ at approximately 4–6 for extremely low or at approximately 8–10 for extremely high values of  $H_{rb}$  and  $H_{rb}/W_{rs}$ . A similar saturation will also occur for extreme values of  $G_l$  as indicated by the overall shape of the area of likelihood regarding  $G_l$ .

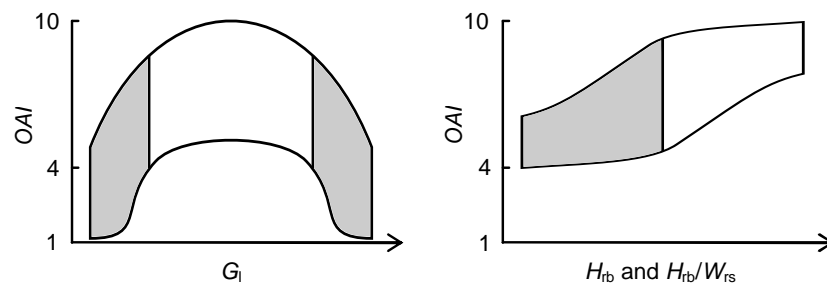


Figure 3.7: Tendencies of overall acoustic impression judgements relating to the acoustic measure  $G_l$  and architectural measures  $H_{rb}$  and  $H_{rb}/W_{rs}$ . The white areas define  $OAI$  within 4–10 regarding  $G_l$  and within 7–10 regarding  $H_{rb}$  and  $H_{rb}/W_{rs}$ .

### 3.7 Overall conclusions

This study has looked at how musicians within symphony orchestras perceive and relate to the acoustic conditions on stage. The results suggest that hearing all other players clearly is essential for good stage acoustic conditions. Hearing the others appears to relate to perceptual effects like masking and the cocktail-party effect. The string players are found to frequently have problems hearing within their own group across the stage or experiencing excess delay of the sound from other string players at the opposite side of the stage. Brass and percussion are reported as often being too loud by the strings, woodwinds and other brass players. Staging conditions and the level and quality of acoustic response from the main auditorium also appear essential for achieving the most preferred conditions. The results show that most players find it crucial being able to hear the reverberant sound from the main auditorium (not from within the stage enclosure itself) at an optimum level. Such conditions appear to provide a sensation of what frequently is described as ‘bloom’ and ‘projection’ among the players.

With regard to objective measures corresponding with the subjective judgements of overall acoustic impression, only a limited set of the objective measures have been studied. A multidimensional set of objective measures appear relevant for assessing stage acoustic conditions, a wider set of objective measures were included for the subjective study described in Chapter 8. For the objective measures included in this study, the acoustic measure  $G_l$  (late/reverberant sound level) is found relevant for assessing the level of acoustic response in the audience area (which will indicate the level of acoustic response from the main auditorium that the stage will be exposed to). The most popular purpose-built concert halls studied have estimated  $G_l$  in the main auditorium within  $1 \leq G_l \leq 3$  dB. When including only purpose-built concert halls which are not reported to have a lacking or excessive acoustic response, best correlations with overall acoustic impression are found with the proposed architectural measures, in particular  $H_{rb}/W_{rs}$ . Results for  $ST_{early}$  (where the direction of early reflections is ignored) show no clear relation to the judgements by the players. This suggests that the location of reflecting surfaces close to the orchestra is highly relevant for perceived acoustic conditions on stage.

A fundamental issue is which halls should be included when investigating the players’ impressions of stage acoustic conditions. The results suggest that only relative differences between stage enclosures should be studied for halls which all provide a suitable level of acoustic response and which the players visit regularly (i.e. home venues, venues only visited occasionally, too ‘dead’ or ‘live’ venues being excluded).

## Chapter 4

# Sound propagation within a symphony orchestra

### 4.1 Introduction

The topic for this chapter is the basic objective situation on a stage with no enclosure around it. It is necessary to distinguish between the objective situation for small ensembles and large ensembles, such as symphony orchestras. For large ensembles, sound travelling between musicians more than a short distance apart is obscured by other musicians, their instruments and music stands. The primary aim here is to quantify this effect.

Only limited studies of this situation are to be found in the literature. [Krokstad \*et al.\* \(1980\)](#) investigated sound levels for sound propagating through two rows of eight persons sitting on a flat floor. The results however only provide an indication of the attenuation to be expected within symphony orchestras. [Ikeda \*et al.\* \(2002\)](#) studied how to model sound behaviour within symphony orchestras by use of BEM (Boundary Element Method). Measurements of impulse responses across the stage with orchestra present were carried out to investigate the validity of the BEM modelling. [Skålevik \(2007\)](#) studied propagation of sound with orchestra present for one specific path within the orchestra using a directional loudspeaker as the sound source. The effect of source height and rotation were among the conditions investigated. No systematic study has been found which has investigated sound propagation within symphony orchestras along different paths and with or without risers on stage. However measurements by Krokstad and Ikeda were at full-scale and have proved very valuable to validate scale modelling techniques reported here.

The study reported here begins by looking at the empty stage for propagation between two points for the direct sound and floor reflection combined. To establish the influence of the orchestra, acoustic scale modelling was used to study the ‘within-orchestra’ sound (or more generally the ‘within-ensemble’ sound). This approach enables any stage configuration to be studied with ease and avoids the need for patient people that would be required for full-size

measurements. The accuracy of the scale modelling was checked by modelling the situations tested by Krokstad and Ikeda and comparing full-size and model results.

Musical instrument directivity is a complicating feature of the real life situation. For the scale model measurements, an omnidirectional source and microphone were used. The effect of source directivity on the results quoted is discussed.

## 4.2 Analytical investigations of sound levels on stage without orchestra present

On an empty stage, there will only be the direct sound and the floor reflection, when we are ignoring reflections from any surfaces surrounding the stage. The flat floor provides a specular reflection of the direct sound. The combined level of the direct sound and the floor reflection can be calculated in two ways: either by taking phase relations into account or ignoring them. Ignoring the phase relation between the two sound components will result in summing levels purely on the basis of energy. Such a combined level is denoted  $L_{df,e}$  – direct sound and floor reflection, energy summing. If using the direct sound level at 10 m distance as reference,  $L_{df,e}$  will become  $G_{df,e}$  – the Strength of the direct sound and the floor reflection.  $G_{df,e}$  is calculated according to Equation (4.1), where  $d$  is the propagation distance for the direct sound and  $f$  is the propagation distance for the floor reflection. Two examples of combined levels,  $L_{df,e}$ , as a function of source-receiver distance are shown in Figure 4.1. The calculated levels in Figure 4.1 are seen relative to the free-field direct sound level,  $L_d$ , at the corresponding source-receiver distance. An omnidirectional source and receiver have been assumed with a source height of 1.0 m and receiver heights of 1.2 and 2.2 m (corresponding to the ear height of a musician sitting on the flat floor or on a 1 m high stage riser). The stage is assumed to be fully reflective.

$$G_{df,e} = 10 \cdot \log_{10} \left( \frac{1}{d^2} + \frac{1}{f^2} \right) + 20 \quad \text{dB} \quad (4.1)$$

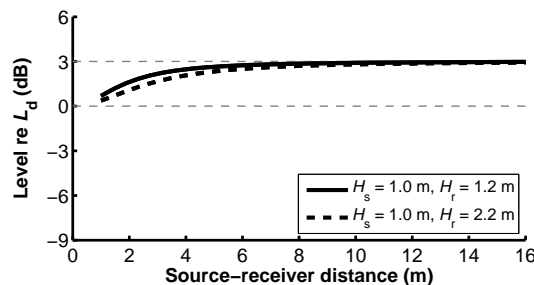


Figure 4.1: Analytically combined level of direct sound and floor reflection,  $L_{df,e}$ , based on energy summing. The level is seen relative to corresponding free-field direct sound level,  $L_d$ .  $H_s$  and  $H_r$  are source and receiver height.

The maximum source-receiver distance, 16 m, represents the typical width of a symphony orchestra. At large distances the propagation distance for the floor reflection will be similar to that of the direct sound, which leads to a combined level of +3 dB relative to the direct

sound level alone (energy doubling = +3 dB). At shorter distances, the direct sound level will be significantly higher than the floor reflection level, so for instance at 1 m source-receiver distance the level is only raised about 1 dB when the floor reflection is included. Since this calculation ignores phase relations, the combined level is independent of frequency.

Due to different propagation paths/delays, the floor reflection will not arrive simultaneously with the direct sound. This will lead to phase differences between these two sound components. If taken these phase differences into account, the combined level depends on both source-receiver distance and frequency. The combined level based on pressure is denoted  $L_{df,p}$  – direct sound and floor reflection, pressure summing. Due to interference effects, the combined level at an individual frequency can vary relative to the free-field direct sound level,  $L_d$ , between close to +6 dB (close to pressure doubling for constructive interference) and approaching  $-\infty$  dB (where destructive interference occurs). These extreme levels assume a point source and a point receiver.

To obtain combined levels based on pressure relations,  $L_{df,p}$ , within octave bands, ideal impulse responses (Dirac delta functions,  $\delta$ ) have been synthesised representing the direct sound and the floor reflection at source-receiver distances 1–16 m. The source height was set at 1.0 m and the receiver at either 1.2 or 2.2 m height. These ideal impulse responses have been octave band filtered to give the combined level within octave bands 63–2000 Hz. The results for octave band values at 1–16 m source-receiver distance using these source and receiver heights are shown in Figure 4.2.

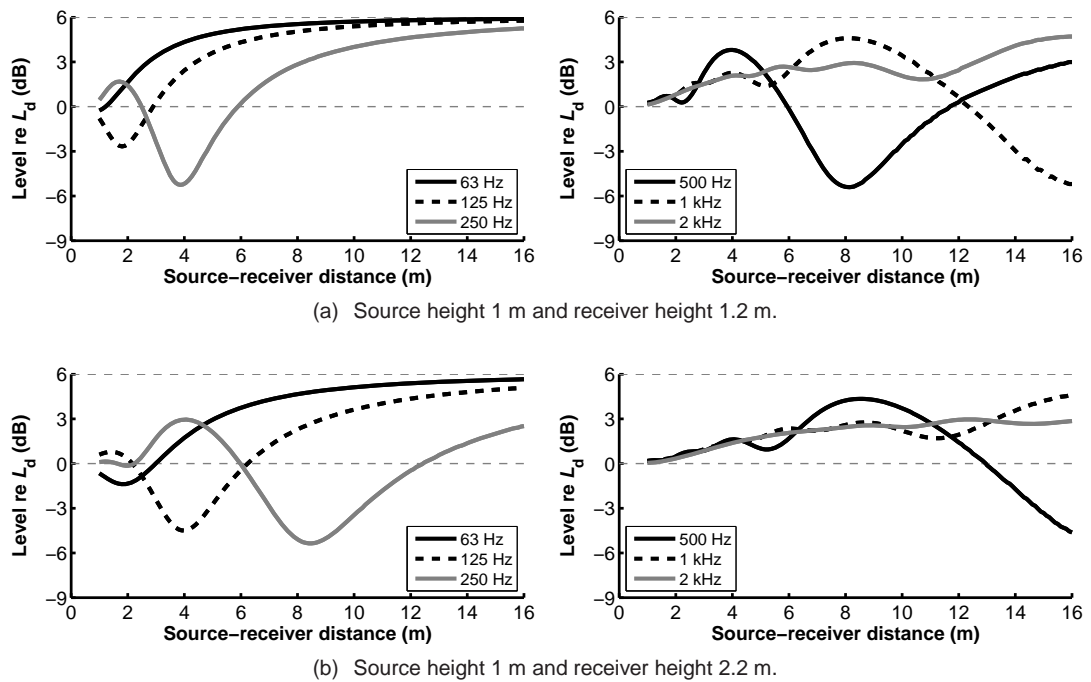


Figure 4.2: Analytically combined level of direct sound and floor reflection,  $L_{df,p}$ , based on pressure summing. The level is seen relative to corresponding free-field direct sound level,  $L_d$ .

For an infinite source-receiver distance the difference in propagation distance for the floor reflection compared to direct sound will be infinitely small and the two wave components will combine constructively, raising the level by +6 dB. For shorter source-receiver distances,

path length differences become comparable with the wavelength. For long wavelengths (low frequencies) at large distances this distance difference will correspond to only a small phase difference, whereas the phase difference becomes more significant as the frequency increases. This is seen in Figure 4.2(a) where the combined level is +6 dB for almost all source-receiver distances for the 63 Hz octave band.

For the octave bands above 63 Hz, the source-receiver distance for maximum destructive interference doubles for each octave increase. The distance at which this occurs varies between 2 m at 125 Hz to 32 m at 2 kHz. If the level were calculated for single frequencies, where cancellation occurs the level would tend to  $-\infty$  dB. Since the levels shown in Figure 4.2 are for octave bands, the level will not reach such an extreme value since the octave band will also include frequencies where destructive interference does not fully occur. For the three octave bands 500 to 2000 Hz the combined level does not fully reach +6 dB for the source-receiver distances studied (very small path length differences required). The interference effects seen are essentially equivalent to comb filtering in the frequency domain, with a pattern of cancellations and additions occurring evenly spaced on a linear scale of frequency (instead of distance).

When the receiver is raised from 1.2 to 2.2 m, the difference in propagation distance between the direct sound and the floor reflection increases for corresponding source-receiver distances. This leads to destructive interference occurring at larger source-receiver distances at all frequencies. With a receiver height of 2.2 m the destructive interference will occur at approximately 4 m at 125 Hz, 8 m at 250 Hz and 16 m at 500 Hz. At 1–2 kHz, the distances at which destructive interference occurs have moved beyond 16 m (to about 32 and 64 m).

The results above show that the combined sound level on an empty stage is significantly affected by the phase relations between the floor reflection and the direct sound (assuming point source and receiver). The height of the source and the receiver also affects the combined level at different source-receiver distances. With the addition of an orchestra, musicians and stands act both as small barriers and as the source of additional reflections. Calculating the within-orchestra sound analytically becomes difficult. This has therefore been investigated experimentally by the use of scale modelling.

### 4.3 Experimental investigations of sound levels on stage with orchestra present

The sound within the orchestra itself, called here the within-orchestra sound level (or within-ensemble in more general terms), consists of the direct sound, the floor reflection and reflections from players, instruments and music stands within the orchestra. This combined level has been denoted  $L_{\text{dfo}}$  – direct sound, floor reflection and orchestra reflections. To investigate the within-orchestra level,  $L_{\text{dfo}}$ , scale modelling has been employed. Carrying out such studies at full-scale would require a large semi-anechoic space and involve a minimum of 80 persons attending for the whole measurement period.



The scale modelling was carried out at a scale of 1:25. All dimensions on the scale model are given as corresponding full-size dimensions. Models of 95 musicians and 40 music stands were set out on a flat stage that was 22 m wide and 10 m deep (approximately 2.3 m<sup>2</sup> per musician). Figure 4.3 shows a photograph of the model configuration with the players on the flat floor.

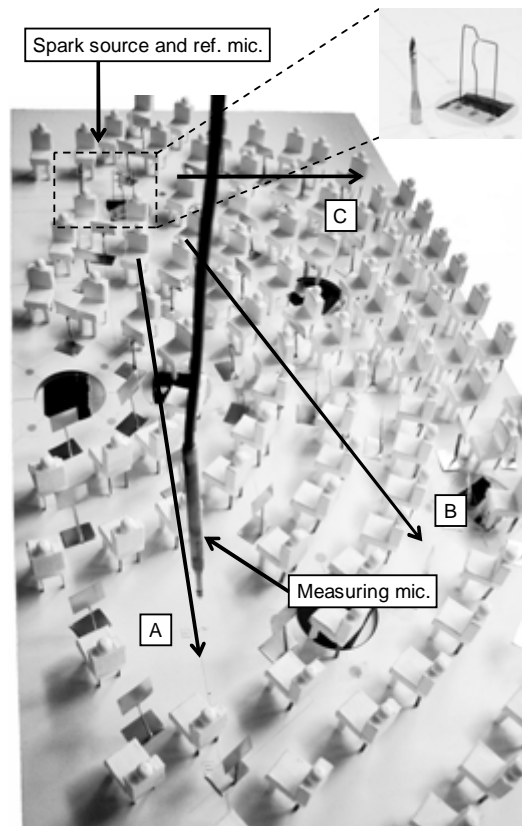


Figure 4.3: Scale model measurement configuration with orchestra on a flat floor, showing microphone paths A, B and C. The reference microphone is 1 m (full-size) to the left of the spark source.

### 4.3.1 Scale modelling system and configuration

The scale model measurement system (Barron & Chinoy, 1979) of a 1:25 scale consisted of a spark source and 1/8 inch omnidirectional microphones. The sound was sampled at a frequency of 500 kHz, corresponding to a 20 kHz full-scale sampling rate. All dimensions below refer to full-scale unless otherwise specified. The spark source was designed for obtaining responses within the 2 kHz octave band and below. The spark source had a spectrum with maximum emitted sound energy around 2 kHz full-scale (= 50 kHz in the model). Above the peak frequency, the emitted power level falls off very quickly, making it difficult to achieve adequate signal-to-noise ratio above the 2 kHz octave band. Below this frequency the spectrum falls off at approximately 9 dB per octave, but this skewed spectrum was compensated for by applying a 6 dB/octave low pass filter with cut-off frequency at 2 kHz at the microphone input. The impulse responses were corrected for the influence of air absorption, according to absorption coefficient values taken from ISO 9613-1 (ISO, 1993), themselves based on frequency, temperature and relative humidity. Repeating measurements four times and deriving the average response had the effect of suppressing random noise and



allowed values to be extracted down to the 63 Hz octave band. The details of the measurement system are: two Brüel & Kjær 4138 1/8 inch microphones with nose cones and Brüel & Kjær 2670 pre-amplifiers, Brüel & Kjær 2690 NEXUS conditioning amplifier including custom-made 2 kHz high-pass filters, National Instruments PCI-6111 A/D converter and computer interface and data acquisition using MATLAB R2006a. The spark source had an electric discharge voltage of approximately 680 V; the peak frequency is about 2 kHz (50 kHz model scale). For more details on the scale modelling system used, see [Chiles \(2004\)](#).

Figure 4.4 shows photographs of the spark source and microphone used. The spark source was set at a height of 1 m above the floor (corresponding to typical instrument height), and the reference microphone 1 m from the spark source and the floor. The choice of the position of the reference microphone (relative to the spark source) was related to obtaining a sufficient time window where only the direct sound of the spark source was present. Figure 4.5 shows the models for musicians and music stands. The model musicians had the equivalent full-size dimensions of 0.45 m width and 1.2 m overall height, and were covered with cloth over their legs and main body. The music stands were 0.5 m wide with maximum height varying between 1.0–1.1 m. Table 4.1 shows the measured sound absorption per musician as measured in a model reverberation chamber ([Spring \*et al.\*, 1971](#)). The corresponding full-size measurement results with the same density of musicians ( $2.3 \text{ m}^2$  per musician) by [Harwood \*et al.\* \(1972\)](#) are also included in Table 4.1. From observation of full-size results by others ([Kuttruff, 2000](#)), there is reason to question whether the coefficient of 0.00 for real musicians at 125 Hz as measured by Harwood *et al.* is realistic.



Figure 4.4: Scale model spark source and microphone, 1 m apart.

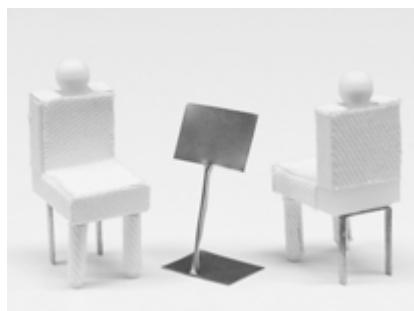


Figure 4.5: Scale model musicians and music stand.

The measuring microphone at 1.2 m height above the floor/riser (corresponding to the ear height of musicians) was placed at intervals of 1 m along the three different paths A–C (indicated in Figure 4.3) from 3 m up to the maximum distance possible. The maximum source–receiver distances along paths A–C were 16, 14 and 7 m respectively. The areas within a 2 m

Table 4.1: Absorption area in metric sabins ( $\text{m}^2$ ) per musician used in the scale model at a density of  $2.3 \text{ m}^2$  per musician. The absorption area is the area of 100 % absorption material that provides the same absorption. Full-size results from [Harwood \*et al.\* \(1972\)](#).

	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz
Scale model	0.07	0.24	0.41	0.70	0.86
Full-size	0.00	0.16	0.43	0.74	0.86

radius around the source and microphones were cleared of musicians and music stands for each measurement position. This ensured there were no disturbing reflections from near the microphones, which helped to improve consistency in level between the positions measured.

### 4.3.2 Measurement analysis

A 1 m distance between the spark source and the reference microphone provides a 3.6 ms (full-size) time gap to observe the direct sound without any disturbing reflections. The direct sound signal was extracted by using a 0–3.5 ms rectangular time window. Figure 4.6 shows the impulse response of the direct sound from the spark source. At lower frequencies (full-size 63–500 Hz) non-linearity of the direct sound level is observed at short distances such as 1 m. Beyond 3 m distance the level decrease is sufficiently close to inverse square law behaviour. The direct sound level of the spark source at source-receiver distances 1–15 m has been investigated and level corrections have been applied at each octave band to the response of the reference microphone to compensate for the non-linear behaviour. The applied level corrections were verified by measuring the sound levels with the corresponding receiver positions on an empty stage and the measured levels show good agreement with the analytical level on an empty stage as presented in Figure 4.2.

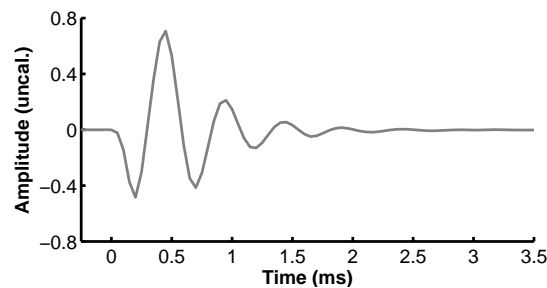


Figure 4.6: Measured pressure response of spark source. Time scale as for full-size.

Figure 4.7 shows an example of impulse responses measured 7 m from the source without and with the orchestra present. The reflections arriving around 4–10 ms after the direct sound in Figure 4.7(a) are reflections off the mounting disk of the spark source. These disturbing reflections were found to contribute to the total measured response (0–50 ms) by less than 0.5 dB. The measured responses on empty stage were verified by comparing calculated levels with the analytical levels found in Section 4.2. This exercise also served to verify the correction factors applied to the reference microphone response due to non-linearity. A rectangular time window within 0–10 ms was used for the responses measured on an empty stage to isolate the direct sound and the floor reflection. The results showed some slightly higher levels than

the analytical level caused by the reflections off the edges of the spark source mounting disk (appearing within the 0–10 ms time window), but these discrepancies were all less than 1 dB.

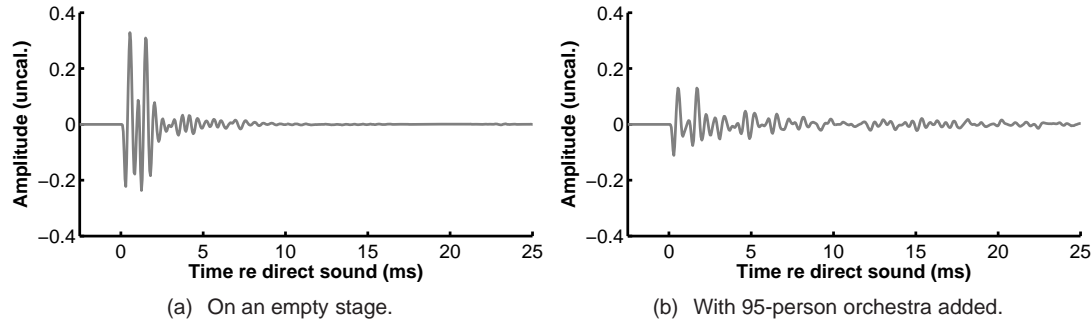


Figure 4.7: Impulse responses along path A at 7 m source-receiver distance with an empty stage (a) and an occupied stage (b).

The attenuation introduced by the orchestra was calculated by comparing sound levels at the measurement microphone and the reference microphone for the same spark signal fired off. A rectangular time window was applied to the measuring microphone to include only the orchestra response. This time window was set to 0–50 ms relative to the arrival of the direct sound. A typical measured response within 0–50 ms with the musicians present is shown in Figure 4.7(b) (along path A at 7 m distance). With musicians present we see that the direct sound and floor reflection are diminished, while reflections arriving with delays of 4–25 ms are at a higher level. These added reflections from the orchestra contribute to reducing the destructive interference effects between the direct sound and floor reflection.

By correcting for non-linearity of the spark source, the total direct sound energy at the reference microphone 1 m from the source,  $E_r(0-3 \text{ ms})$ , was calculated. The inverse square law was applied to find the equivalent free-field direct sound energy at 10 m distance based on  $E_r(0-3 \text{ ms})$  at 1 m. By comparing this free-field reference energy at 10 m distance and the total energy at the measurement microphone,  $E_m(0-50 \text{ ms})$ , the acoustic measure  $G$  (Strength – total sound level relative to 10 m free-field level) was found for each measurement position according to Equation (4.2).

$$G_{\text{dfo}} = 10 \cdot \log_{10} \left( \frac{E_m(0-50 \text{ ms})}{E_r(0-3 \text{ ms})} \right) + 20 \quad \text{dB} \quad (4.2)$$

To find the level of the attenuation,  $\Delta L$ , introduced by the orchestra, the measured level  $G_{\text{dfo}}$  is presented relative to the analytically calculated sound level  $G$  with no orchestra present,  $G_{\text{df,e}}$  as shown in Equation (4.3). As before, the level  $G_{\text{df,e}}$  is calculated based on energy summing, not pressure summing. Using  $G_{\text{df,e}}$  as the reference level as opposed to  $G_{\text{df,p}}$  leads to  $\Delta L$  including both wave effects as well as the obstruction effect introduced the orchestra. But the wave effects are only obvious for the octave bands of 500 Hz and below.  $G_{\text{df,e}}$  as the reference level also has the advantage that the reference level is independent of frequency.  $\Delta L$  has been calculated for the octave bands 63–2000 Hz.

$$\Delta L = G_{\text{dfo}} - G_{\text{df,e}} \quad \text{dB} \quad (4.3)$$

### 4.3.3 Measurement conditions

The source was set 6 m from the centre line of the stage and 1.5 m from the stage front (within the string section for a normal orchestra configuration). The sound level was measured along the three different paths A–C within the orchestra as shown in Figure 4.3 (straight across, diagonally across and straight backwards, see also Figure 4.8(a)). For path A and C all obstructing musicians were set along the path line, so as to provide maximum obstruction. Due to the slightly limited number of music stands, the music stands were set next to musicians near the measuring path studied. Risers were also used for a second investigation as shown in Figure 4.8(a). The risers had three different heights – the height above the stage floor for each riser level was respectively 0.2, 0.5 and 0.95 m. The two lowest riser levels were 1.6 m deep, while the highest level was 2.6 m deep. Figure 4.8(b) shows the vertical floor profiles along paths B and C with risers.

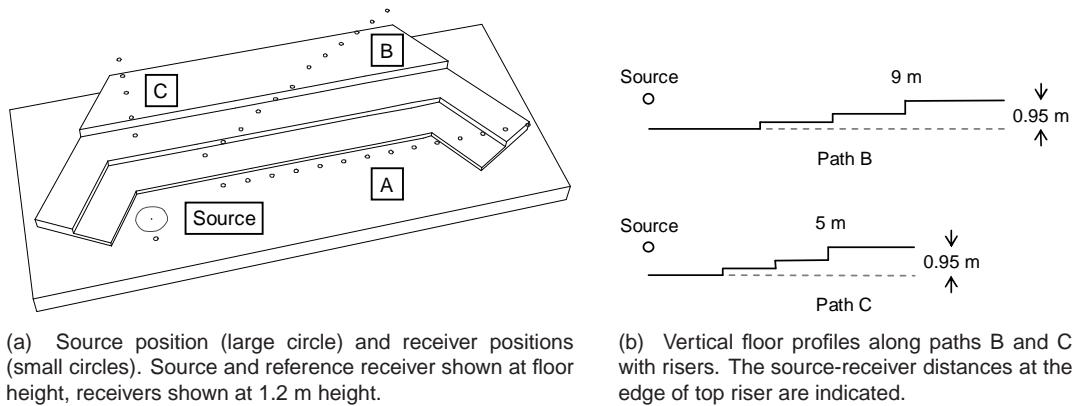


Figure 4.8: Scale model measurement configuration with risers.

### 4.3.4 Results and discussion for orchestra on flat stage floor

#### 4.3.4.1 Along path A

Figure 4.9 shows the results of  $\Delta L$  for the sound within the orchestra along path A on a flat stage floor. This is along a direction where the highest attenuation can be expected since players were arranged to block the direct sound along this path as much as possible. At low frequencies 63–125 Hz the measured attenuations are similar to those predicted analytically on an empty stage in Figure 4.2. The attenuation at large distances indicates constructive pressure interference and the relative level is +3 dB (3 dB higher than what would be expected from energy summing of the direct sound and floor reflection). This result shows that at 63–125 Hz the orchestra does not affect the sound levels significantly – sound diffracts around individual musicians. At 250 Hz the level starts to deviate from the analytical level for an empty stage – the effect of musicians and stands starts being significant.

For the octave bands 500–2000 Hz in Figure 4.9 the interference between the direct sound and floor reflection as seen on an empty stage (Figure 4.2(a)) is much less apparent. The measured attenuation approximates a linear dependency on source-receiver distance and

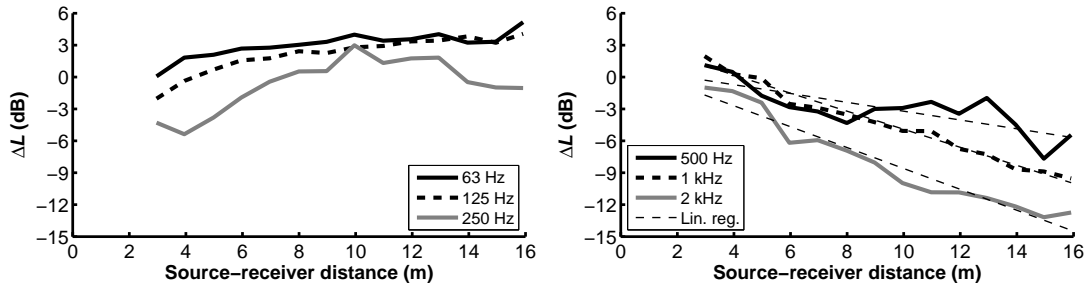


Figure 4.9:  $\Delta L$  for sound level within the orchestra on a flat floor along path A. Linear regression lines (thin, dashed) are shown for the octave bands 500–2000 Hz.

the rate of attenuation increases with frequency. This effect at higher frequencies must be caused by the orchestra presenting more significant obstructions and higher absorption when compared with lower frequencies.

The high attenuation at 500 Hz at 6–8 m distance could be caused by destructive interference still being significant (obstruction effects being less significant at this octave band). At 500 and 1000 Hz over the distances 3–5 m,  $\Delta L$  is positive. This is likely to be caused by some of the interference effects remaining significant at short distances, due to a small number of players blocking the sound at such short distances. Both these interference effects are seen analytically for an empty stage (Figure 4.2(a)).

Figure 4.10 shows the within-orchestra level ( $G_{\text{dfo}}$ ) as function of frequency, along path A at the source-receiver distances 3, 7, 11 and 15 m. The level is here seen relative to the direct sound level ( $G_{\text{d}}$ , not  $G_{\text{df,e}}$ ) at corresponding distances. From Figure 4.10 we see that at 63 Hz pressure doubling occurs (+6 dB) except at 3 m where the level and time arrival differences between the direct and floor reflection become significant. A 3 m distance the frequency response is close to being flat, except for low levels at the 250 Hz octave band. At large source-receiver distances, the spectrum is strongly dominated by low frequencies.

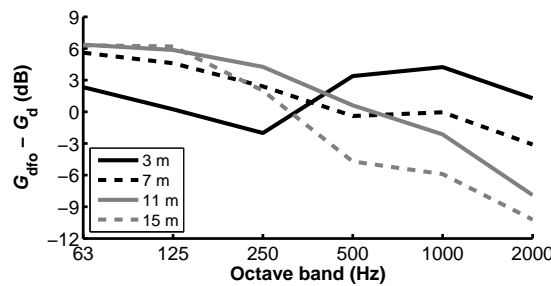


Figure 4.10: Orchestra attenuation versus frequency, within the octave bands 63–2000 Hz. Along path A with source-receiver distances of 3, 7, 11 and 15 m.

#### 4.3.4.2 Along paths B and C

The results for  $\Delta L$  along paths B and C are shown in Figures 4.11 and 4.12. At 63–250 Hz along paths B and C, levels are very similar to the analytical response, as with path A. At 1–2 kHz, levels are influenced by the degree of obstruction. Along path B, the source could at some positions still be seen (free sight-lines), even at larger source-receiver distances, so the

sound is generally less attenuated here at 1–2 kHz compared with the results for path A. For path C,  $\Delta L$  at 500–2000 Hz is similar to the results for path A, since for this path the players were also arranged to block the direct sound as much as possible. These results are quantified in Table 4.2 to be described in Section 4.3.6, with the value of variable  $c$  reflecting the effect of the degree of obstruction.

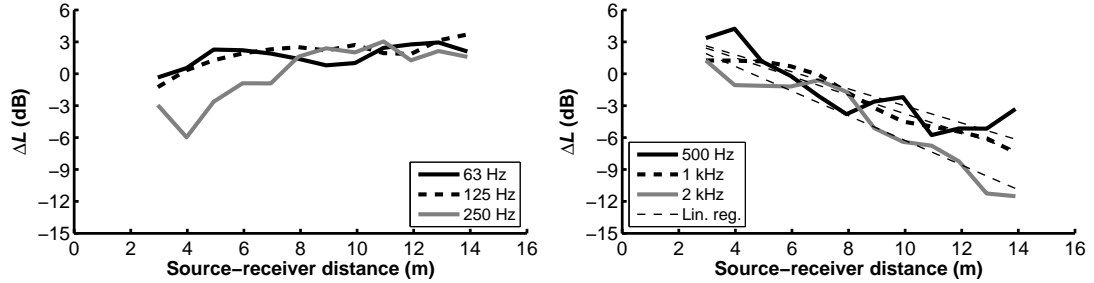


Figure 4.11:  $\Delta L$  for sound level within the orchestra on a flat floor along path B. Linear regression lines (thin, dashed) are shown for the octave bands 500–2000 Hz.

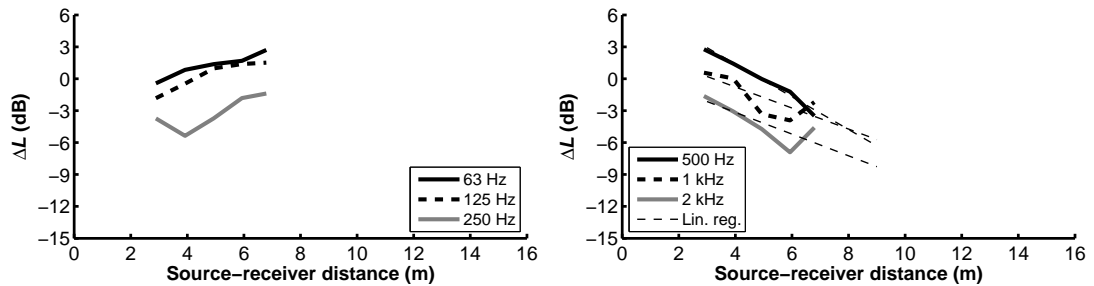


Figure 4.12:  $\Delta L$  for sound level within the orchestra on a flat floor along path C. Linear regression lines (thin, dashed) are shown for the octave bands 500–2000 Hz.

#### 4.3.4.3 The effect of reflections within the orchestra

An orchestra not only introduces attenuation of the direct sound and the floor reflection, but as described in Section 4.3.2 it also introduces scattered reflections from players and other objects on stage near the direct sound path. To reveal how much the reflections within the orchestra (from musicians and music stands in scale model) contribute to raising the total sound level, measured sound levels based on the direct sound and floor reflection only,  $G_{df}$ , were studied.  $G_{df}$  with the orchestra present was derived by applying a rectangular time window to the measured responses, with the upper limit of the time window sliding depending on source-receiver distance to ensure that only the direct sound and floor reflection were included. Figure 4.13 shows the results along path A on a flat floor. This is presented as  $G_{df}$  on top (a) (excluding all of the orchestra reflections, only direct sound and floor reflection), the total level  $G_{dfo}$  (b) and the difference of  $G_{dfo}$  minus  $G_{df}$  (c).

The results indicate that the reflections within the orchestra contribute to raise the level by up to 4 dB within the frequency range 500–2000 Hz. At short distances  $G_{df}$  is the dominant part, so the orchestra reflections do not significantly raise the total level,  $G_{dfo}$ . For distances above 12 m the contribution of orchestra reflections is also low. The possible reasons for the low contribution above 12 m has not been investigated, but it could be related to a lower

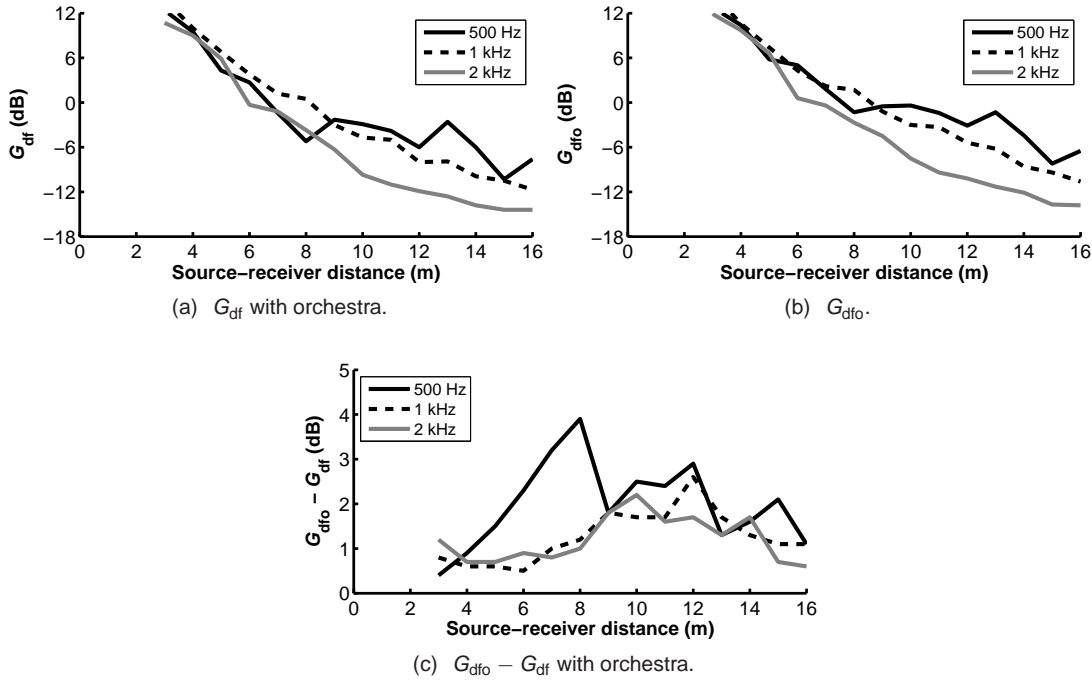


Figure 4.13: Contribution of reflections from within the orchestra, along path A.

number of musicians and music stands surrounding the musicians who sit at the outer regions of the orchestra. The high contribution of the orchestra reflections at 8 m distance at 500 Hz is likely to be caused by the significant destructive interference of the direct sound and floor reflection at this distance, as shown in Figure 4.2(a). Orchestra reflections tend to be most significant for mid-range distances, making relationships between total sound level,  $G_{dfo}$ , and source-receiver distance more linear.

#### 4.3.4.4 The influence of source directivity

The directivity of musical instruments normally deviates significantly from omnidirectional at frequencies of 1 kHz and above (Meyer, 2009). This implies that the significance of reflections within the orchestra for the total sound level,  $G_{dfo}$ , will depend on the type of musical instrument and in which direction the instrument is pointing, particularly in the horizontal direction. If an instrument radiates most of its sound towards a particular player in the orchestra, the level of the orchestra reflections will be low compared to  $G_{df}$  for this particular player. Whereas with an instrument pointing away from the source-receiver path, the level of orchestra reflections will become more significant. From Figure 4.13 we see that for an omnidirectional source along path A, the most significant reflections are at 500 Hz since  $G_{df}$  is low due to interference effects (as described above).

Most musical instruments are close to omnidirectional at the octave band 500 Hz and below (Meyer, 2009). This indicates that what was measured with an omnidirectional source should be reasonably valid at 500 Hz and below. The most directional instruments at 1 and 2 kHz, the trumpets and trombones, will normally be on risers which leads to high levels of  $G_{df}$  (no significant obstruction effect). The influence of orchestra reflections and directivity of the

source could therefore be seen as most relevant for the string section where  $G_{df}$  is low for players far apart. If the string instruments have low level of radiated sound in directions where significant reflections could occur, the total within-orchestra sound level  $G_{dfo}$  will be close to  $G_{df}$ . For the players experiencing this effect, the obstruction effect will be more significant compared to the measurement configuration used for this study. The results from this study appear to give a reasonably valid estimate of average figures of the obstruction effect within whole instrument sections.

### 4.3.5 Results and discussion for orchestra on risers

#### 4.3.5.1 Along path B and C

The results for measurements along path A with risers are omitted since only the players at the largest distances from the source are affected by the riser system on the model stage along this path. The results for  $\Delta L$  with orchestra on risers along path B and C are shown in Figures 4.14 and 4.15 respectively. The results are similar for both paths.

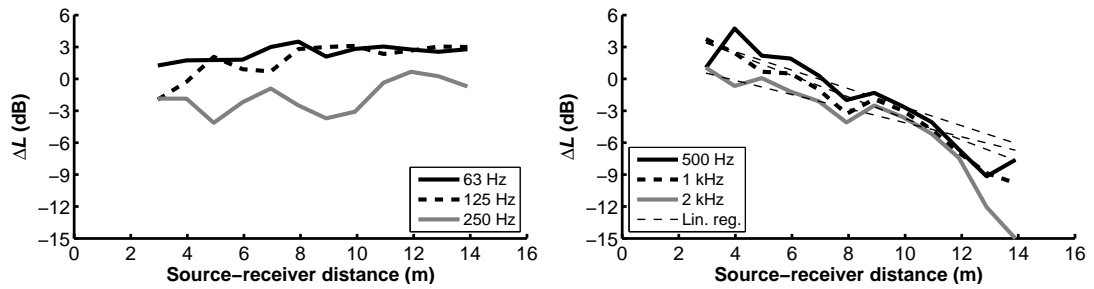


Figure 4.14:  $\Delta L$  for sound level within the orchestra on risers along path B. Linear regression lines (thin, dashed) are shown for the octave bands 500–2000 Hz.

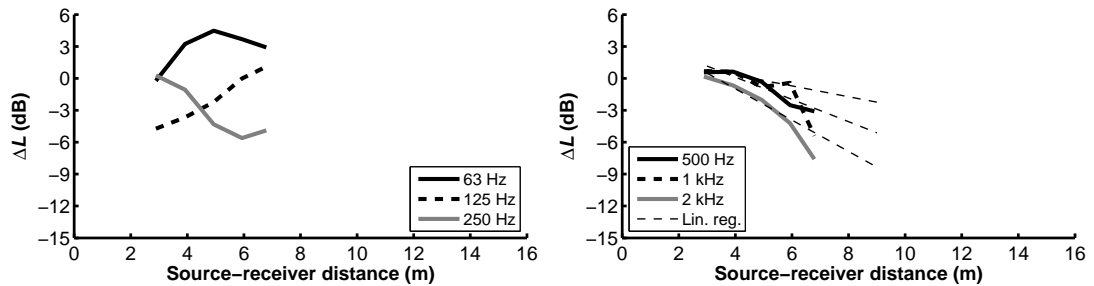


Figure 4.15:  $\Delta L$  for sound level within the orchestra on risers along path C. Linear regression lines (thin, dashed) are shown for the octave bands 500–2000 Hz.

At low frequencies, 63 and 125 Hz, the level appears to be mostly controlled by the interference of the direct sound and the floor reflection, as with the results without risers (in Section 4.3.4). With the receiver on the top riser (0.95 m above the main stage floor), the expected interference patterns at low frequencies would be similar to the analytical responses shown in Figure 4.2(b), as long as the floor reflection reflects off the main floor and not off a riser. Along path B the receiver will be on the 0.95 m riser at distances of 9 m and more, so at shorter distances we expect the response at lower frequencies to be something between Figure 4.2(a) and Figure 4.2(b). Along path C the receiver will be on the 0.95 m high riser at distances



greater than 5 m (as shown in Figure 4.8(b)); the responses at 63 and 125 Hz are significantly different to those predicted for a flat floor in Figure 4.2. This may be caused by one or more of the following: the floor reflection occurs off a horizontal riser rather than the stage floor, the stage reflection is obscured by a riser and edge diffraction occurring at the riser edge. The attenuation at 250 Hz is generally high beyond 4 m distance, which corresponds with what we could expect from the analytical level with a receiver height of 2.2 m as shown in Figure 4.2(b). This could indicate that risers can contribute to reduce the levels around 250 Hz especially for players being 5–10 m apart.

At 500–2000 Hz the attenuation is less at shorter distances, compared to no risers on stage, which would be expected due to improved sight-lines. But at a certain distance the attenuation becomes abruptly higher, especially at 2 kHz. The abrupt changes happen at source-receiver distances of 12 m (path B) and 5 m (path C). Beyond these distances the attenuation becomes significantly higher than with a fully flat floor at corresponding distances. As shown in Figure 4.8, the highest riser is very deep (2.6 m) and for receiver positions well onto this riser level (above 9 and 5 m for paths B and C respectively), very high attenuation is seen. This could be due to players in front on the same riser level causing a more significant obstruction of the direct sound when being on a high riser. The direction toward the source will be downwards for some players on a riser (with the source on the flat floor), so the direct sound has to pass ‘through’ the chests of other players instead of ‘through’ heads. In addition, on the riser the geometrical floor reflection may also not arrive due to the height differences of the floor/risers – the front edge of the riser will block this geometrical floor reflection path.

These results indicate the raised height of the receiver contributes to lower the sound level at 250 Hz, compared to conditions with both source and receiver on a flat floor. The improved sight-lines with risers lead to a significantly raised level at 1 and 2 kHz as long as the receiver is not too far back on a riser.

#### **4.3.6 Linear models of the orchestra attenuation**

The results above indicate that the presence of the orchestra becomes significant for the sound level within the orchestra at the octave band 250 Hz and above. For the octave bands 500–2000 Hz the influence of the orchestra is clearly evident. The results for the sound levels at 1 and 2 kHz show a nearly linear relationship between the attenuation and source-receiver distance. Based on this, a linear model has been developed to describe the within-orchestra sound level attenuation at 500–2000 Hz. Such a model will depend on the stage conditions (orchestra arrangement and presence of risers). For estimating levels within the orchestra in the frequency range 63–250 Hz, summing the sound pressure of the direct sound and floor reflection based on the inverse-square law and phase differences appears to be a valid first approximation. The results indicate that presence of risers on stage can contribute to reduced validity of estimated level at 63–250 Hz. Risers will lead to a change of height for the floor reflection at some positions. Even if this is taken into account, the risers will contribute to scatter the sound which is not taken into account in such a simple analytical method.

Linear regression analysis has been performed on data for  $\Delta L$  presented in Figures 4.9, 4.11, 4.12, 4.14 and 4.15. The attenuation,  $\Delta L$ , can be described by an attenuation factor  $a$  describing dB loss per metre, where  $d$  is the source-receiver distance, and a constant  $c$  for the overall shift of attenuation up or down due to the interference effect of the floor reflection and contribution of orchestra reflections, as in Eq. (4.4). Equation (4.5) gives the sound level (Strength value  $G$ ) within the orchestra,  $G_{\text{dfo}}$ , based on Equation (4.3) and Equation (4.4).  $G_{\text{df,e}}$  is calculated according to Equation (4.1). For measurements with risers,  $a$  and  $c$  were derived for distances less than 9 m along path B and less than 5 m along path C, since measured level beyond these distances were apparently strongly influenced by a shadow effect on the deep riser at the back of the stage (as discussed in Section 4.3.5.1).

$$\Delta L = a \cdot d + c \quad \text{dB} \quad (4.4)$$

$$G_{\text{dfo}} = G_{\text{df,e}} + \Delta L = G_{\text{df,e}} + a \cdot d + c \quad \text{dB} \quad (4.5)$$

Regarding the reference level for measured sound levels on full-size stages, a common choice has been to use the direct sound at a reference microphone at 1 m from the source as the reference (Krokstad *et al.* (1980), Ikeda *et al.* (2002), Gade (1989c)). With the reference level taken at such a short distance from the source, it will be very sensitive to source directivity and interference of the floor reflection. As an alternative, if the (full-scale) measurement system is calibrated for measuring  $G$  according to ISO 3382 (ISO, 1997), measured levels become more consistent and results are easier to compare. Calibrating for  $G$  according to ISO 3382 involves measuring responses with the actual measurement system in an anechoic chamber and averaging responses over 29 different source rotations.

#### 4.3.6.1 Linear model coefficients and RMS errors

Table 4.2 shows the resulting coefficients ( $a$  and  $c$ ) from the linear regression analyses of the results along the different paths without and with risers (path A without risers only). On a flat floor the value for attenuation per metre,  $a$ , is similar for all the three paths at 1 and 2 kHz, and in general the slopes,  $a$ , become more negative with increased frequency. At 500 Hz the attenuation is significantly more negative along path C. This is likely to be caused by the source-receiver distance being limited to 7 m. All paths show a dip in level at 6–8 m at 500 Hz (probably caused by interference effects as discussed in Section 4.3.4.1). For paths A and B there are higher levels beyond 7 m at 500 Hz which contribute to a less negative value of  $a$ . The generally higher values of  $c$  for the results along path B could be caused by generally better sight-lines along this path (diagonally across the stage). For paths A and C, values of  $c$  at 1 and 2 kHz are very comparable, which is likely to be caused by the same arrangement of musicians blocking the direct sound (as much as possible). With risers, some of the values of  $a$  at 1 and 2 kHz are lower compared with a flat floor; this is probably due to improved sight-lines. But the depth of the top riser appears to have led to high level of attenuation even with risers, as discussed in Section 4.3.5.

Table 4.2: Coefficients for linear models of  $\Delta L$ .

Condition	a (dB/m)			c (dB)		
	500 Hz	1 kHz	2 kHz	500 Hz	1 kHz	2 kHz
Flat floor, path A	−0.42	−0.85	−0.98	0.9	3.6	1.2
Flat floor, path B	−0.80	−0.88	−1.16	5.0	5.0	5.3
Flat floor, path C	−1.53	−0.99	−1.02	7.5	3.2	0.9
Risers, path B	−0.87	−1.00	−0.66	6.0	6.6	2.5
Risers, path C	−1.05	−0.51	−1.47	4.3	2.4	4.9

Table 4.3 shows the root-mean-square (RMS) values for the errors between the measured values and values based on the linear models of  $G_{\text{dfo}}$ . The results indicate that the attenuation on flat floor at 1 and 2 kHz are best described by the linear models. The linear models for 500–2000 Hz must be seen as a guide-line, since the attenuation will be affected by how close the players sit together and how many players between source and receiver block the direct sound path.

Table 4.3: Root-mean-square (RMS) errors between measured  $\Delta L$  and linear models of  $\Delta L$ .

Condition	RMS (dB)		
	500 Hz	1 kHz	2 kHz
Flat floor, path A	1.3	0.5	1.0
Flat floor, path B	1.5	0.6	1.2
Flat floor, path C	0.3	1.1	1.1
Risers, path B	1.8	1.2	3.1
Risers, path C	0.5	1.9	1.2

#### 4.3.7 Comparisons with full-size measurements by others

As mentioned in the Introduction, three sets of full-scale measurement results are reported in the literature regarding sound propagation within larger ensembles/orchestras. [Krokstad \*et al.\* \(1980\)](#) did some experiments with eleven persons sitting in two separate lines on a flat floor with no other reflecting surfaces close to them. Five persons sat along the first line and six along the second, as shown in Figure 4.16. A loudspeaker was set in front between the two lines, while a measuring microphone was placed behind the person at the back of the row of five persons. This meant that five persons were sitting along the line of sight between the loudspeaker and the measuring microphone. A reference microphone was set 1 m from the loudspeaker, between the two persons at the front of the two lines. To measure the attenuation introduced by the players, the difference in sound level between these two microphones was measured. The levels were measured using a continuous noise signal which did not allow them to isolate the direct sound from the reference measurement (as in the scale model of this study), but the measured sound level at the reference microphone at 1 m distance is likely to have been dominated by the direct sound and the floor reflection. This was carried out for three different loudspeaker heights, 0.6, 0.9 and 1.3 m, and the average levels for the three heights were calculated. Details of the type of loudspeaker they used are not available.

To investigate the validity of the scale model used, Krokstad *et al.*'s measurement setup was reproduced at 1:25 scale. The results in the scale model with the corresponding configuration

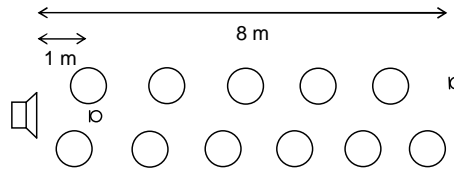


Figure 4.16: Plan view of measurement configuration for measuring orchestra attenuation as used by Krokstad *et al.* (1980). Large circles represent seated people.

and analysis showed good agreement with measured attenuation at 1 and 2 kHz – within  $\pm 0.5$  dB. If trying to find corresponding values of  $\Delta L$  for the results by Krokstad *et al.*, their results deviate +1 to –2 dB at 1 and 2 kHz. The absence of people surrounding the measurement microphone in Krokstad’s experiment, as well as loudspeaker directivity, have probably contributed to the differences between the results.

Ikeda *et al.* (2002) conducted full-scale measurements with a full orchestra on stage including music stands and instruments, but only for source-receiver distances of 2–6 m. They also used a reference microphone at 1 m from the source (a dodecahedron loudspeaker) without any obstructions between the source and the reference microphone. A measurement microphone was set at 1 m intervals away from the source across the stage among the string players along a path similar to path A, but their selected sound path was not parallel to the stage front as was for this study. Ikeda has very kindly supplied for this study a full set of measured impulse responses for this study. The measured impulse responses were not calibrated for absolute sound level, so only relative differences were accessible. Additionally, since this was measured on a real stage, there were reflections from the stage enclosure arriving from 20 ms after the arrival of the direct sound. Uncalibrated octave band levels using a rectangular time window up to 20 ms were calculated using WinMLS 2004. The analysis indicates they measured an attenuation per metre,  $a$ , of –1.0 dB/m at 1 kHz and –0.9 dB/m at 2 kHz (within 2–6 m). Corresponding values for the scale model based on  $G_{dfo}$  would be –0.9 dB/m at 1 kHz and –1.0 to –1.2 dB/m at 2 kHz (paths A and B). Due to the differences in the measurement configurations, it is difficult to make exact comparisons, but the differences with regard to attenuations per metre are within 0.2 dB/m.

Skålevik (2007) measured room impulse responses across the orchestra (from violins to bassoons typically) with a full symphony orchestra present. One source and receiver position was used with a source-receiver distance of 11.7 m. Uncalibrated sound levels within 0–50 ms (relative to arrival of direct sound) were studied using a directional loudspeaker, omnidirectional microphone and various loudspeaker and microphone heights. By the use of a directional source with unknown directional characteristics and uncalibrated levels, it is difficult to compare Skålevik’s results with results from this study. In general, his results show that the obstruction effect of the orchestra is highly significant above 500 Hz, while mainly controlled by source and receiver heights below 500 Hz. This agrees well with findings from this study. Skålevik measured responses up to the 16 kHz octave band. The results indicate that sound levels at 8 and 16 kHz across the orchestra are highly affected by free sight-lines: sound levels with the source visible are close to unattenuated levels (inverse square law behaviour), while

being significantly attenuated with no free sight-lines. At 1 and 2 kHz levels are less influenced by the presence or absence of free sightlines, due to greater diffraction at lower frequencies.

Mommertz (1993) conducted similar studies with audience in typical theatre seats for source-receiver distances 2–16 m. For a source height of 1.4 m and receiver height of 1.2 m an attenuation of about 1.15 dB/m was found. This result was obtained without staggered seating (all listeners sitting along the line of sight between source and receiver) and 1 m distance between each audience row. The results from this study indicate an attenuation within an orchestra of 0.85–1.0 dB/m at 1 kHz. A large orchestra will normally not sit so closely together as in Mommertz's experiment. For this study 9 players were blocking the sound at a 16 m distance as opposed to 15 in Mommertz's study, which helps explain the differences.

Based on the large variation in the sound level that may occur due to different arrangements of the orchestra/individuals and positioning of the source and the receiver, the agreement between results from this study and what has been found by others must be seen as satisfying. When we were able to accurately reproduce at model scale the full-scale measurement configuration, the difference between the scale model results and full-scale results were close to experimental error. This indicates that the scale models and the scale modelling system itself are valid, but some variations compared to other studies will occur due to differences in measurement configurations and the type of reference level used.

## 4.4 Practical implications of the results

As seen in Figure 4.2, at low frequencies (63 and 125 Hz), the direct sound and floor reflection interfere constructively at almost all distances on a flat floor. This means that the low frequencies will propagate well to all the players on the flat floor and may benefit from the floor reflection for the deepest notes of instruments like cellos and double basses. The total levels presented in Section 4.3 may be overestimated since real sources are not point sources. The double bass, for instance, radiates from the whole body of the instrument.

At 250 Hz, destructive interference can be observed at distances 5–10 m when risers are present (Fig. 4.14). This could be beneficial for string players since the level for them of sound from percussion and brass at the rear of the stage will be reduced in this important frequency range. Destructive interference lowers the level by about 3–5 dB compared to levels found with a flat floor at similar distances. This could be beneficial for string players since a reduced level of sound from percussion and brass at the rear of the stage will reduce the risk of percussion and brass masking mutual sound between the string players. Koenig *et al.* (1977) studied the threshold for being able to hear a 250 Hz tone of 150 ms duration. They found the threshold to be ca. 3.4 dB below the level of uncorrelated narrow band noise in the range 150 and 600 Hz.

At large source-receiver distances, the orchestra attenuation on a flat floor becomes high at high frequencies. For players sitting far apart across the stage, early reflections from a stage enclosure are likely to be beneficial to compensate for the low within-orchestra levels. With early reflections most needed at frequencies above 500 Hz, surfaces compensating for low

within-orchestra levels may be small and still provide reflections at a sufficient level. For all players at the sides and the back of the orchestra, risers may be beneficial to reduce the direct sound attenuation at higher frequencies, as an alternative to reflections from a stage enclosure. By having the risers raised by small steps between each tier and each level not being too deep, destructive interference effects at lower frequencies and significant shadow effects at higher frequencies may well be avoided as long as the final tier is not too high. If the final riser height for outer string players is as high as about 1 m above the stage floor, the lowering of sound levels seen at 250 Hz could be unfavourable between string players. Double bass and cello players may prefer not to sit on risers at all if this leads to a lack of floor resonance. [Askenfelt \(1986\)](#) and [Guettler \*et al.\* \(2008\)](#) found the floor resonance important for these players.

The results from this study suggest that very deep riser levels (2.6 m deep in this study) will lead to high attenuation between players at the back of the riser and players at front of the stage. This high attenuation observed at 1 and 2 kHz may be beneficial for reducing the sound level of instruments at the back stage (normally percussion and brass), which often can become excessively loud for players in front (normally strings). But at the same time, the sound of instruments at the front of the stage may be attenuated too much for the players at the back with regard to mutual hearing with such a deep riser section.

Conducting objective measurements on stage with musicians in place is in most cases difficult and expensive to arrange. Conducting measurements with chairs and music stands on stage is closer to the reality but introduces extra variables. How realistic would it be to make measurements on empty stages and use corrections based on the measured results presented above? While the linear models can deal with the direct sound and floor reflection, the presence of an orchestra will also influence other early reflections, in particular an orchestra will block reflections off vertical walls around the stage, as well as reflections off the vertical surfaces of risers. Unfortunately it appears therefore that there is no simple method to correct between empty and occupied stage conditions. This is investigated into more detail in [Chapter 7](#).

## 4.5 Conclusions

The propagation of sound within symphony orchestras (large ensembles) has been studied principally by the use of scale modelling. The results show that for the octave bands below 500 Hz, the orchestra does not significantly obstruct the sound on stage. This means that low frequency sound, in the 63 and 125 Hz octave bands, can propagate close to freely between players. The floor reflection will contribute to raise the level above the direct sound level for all players being more than 3 m apart at 63 and 125 Hz. The results from this study also indicate that sound levels on stage at 63, 125 and 250 Hz can be calculated analytically, as defined by the geometry of reflecting surfaces on stage, as long as the use of a point source is a valid assumption. The screening effect of the orchestra increases with frequency and for the octave bands above 500 Hz, the orchestra significantly attenuates the sound propagating within the orchestra. Measured sound levels at 2 kHz for source-receiver distances above



14 m show an attenuation of about 12 dB introduced by the orchestra. Linear relationships have been proposed for this behaviour, which will represent typical conditions. Such high levels of attenuation are found for players sitting on a flat floor.

This study has employed an omni-directional sound source whereas most musical instruments within a symphony orchestra become directional above 500 Hz. The directivity of real instruments will affect the level balance of direct sound, floor reflection and reflections from within the orchestra. With directivity of real musical instruments taken into account, some players could experience higher or lower degrees of attenuation compared to the scale model results. The scale model results therefore serve as average values for instrument groups as a whole.

With risers on the stage, sound levels between musicians are generally raised, but some exceptions are found: at 250 Hz the results show significantly lower levels between a player on a 0.95 m high riser and a player on the flat floor, compared to results for both players sitting on the flat floor, in particular for source-receiver distances of 3–10 m. Similar effects are seen at high frequencies for deep riser sections (2.6 m deep): the sound level at 1–2 kHz from players at the back of a deep riser has been found to be lower than sound levels from players on a flat floor at corresponding distances. The specific depth and height of each riser level therefore appears highly relevant for controlling sound levels between different instrument groups within the orchestra.

With normal orchestra configurations the string sections sit across the stage width on a flat floor, while woodwind, brass and percussion are on risers. On most stages, stage width is greater than stage depth. This results in string players at the outward extremes of the stage often experiencing the lowest mutual sound levels within the orchestra (within-orchestra sound levels). The outermost string players can however be placed on risers which will lead to improved sight-lines and direct sound propagation. The results do though show possible disadvantages with such a solution with a reduced contribution from the floor reflection by use of risers (particularly in the 250 Hz octave band). In addition for cellos and double basses, stage floor resonance may be significantly less when these instruments are on risers. With significant attenuation by the orchestra over the frequency range 500 Hz and above, only small surfaces may be sufficient to provide early reflections that will help compensate for low mutual sound levels between players. The degree to which within-orchestra attenuation can be compensated for by introducing reflections from stage enclosures is discussed in the following chapter.

## Chapter 5

# The effect of reflected sound back towards a symphony orchestra

### 5.1 Introduction

The results from Chapter 3 suggest that good acoustic conditions are identified by the players as being able to hear all other players clearly, well balance with sound from one's own instrument. Also, hearing the acoustic response from the main auditorium appears important for the players. In the same study, judgements of overall acoustic impression among the players were compared to objective measures of 12 purpose-built concert halls the players were visiting on a regular basis as well as other halls (excluding home venues). The results indicated that the most popular halls have a stage enclosure that generally can be described as narrow and high. On the contrary, the halls with a wide and low stage enclosure were among the least preferred halls.

For halls with narrow and high stage enclosures, the players explained their favourable impressions by the fulfilment of the criterion for good stage acoustic conditions described above. For the wide and low stage the players complained about problems hearing the others, muddy (unfocused) sound and high sound levels. The dimensions of the stage enclosure cannot be seen as the only factor behind the differences of perceived conditions, but objective measures based on stage dimensions show the most significant correlations with overall acoustic impression.

The judgements by the players varied significantly between individual players, only judgements of the least and most preferred halls were found to differ at a statistically significant level. It will therefore be instructive to discuss how overall dimensions and acoustic properties of the stage enclosure may relate to perceptual effects that appear relevant for perceived ensemble conditions. The perceptual effects studied include masking effects, the precedence and the cocktail-party effect. More orchestra specific conditions and localisation of reverberant sound are also included. How these perceptual effects may relate to level, arrival time and direction



of reflections have previously been studied through several controlled laboratory experiments by others.

Levels, delays and directions of reflections provided by a set of different enclosure widths and heights have been studied analytically. The investigation has been done analytically because of problems with low controllability of the different factors contributing to the acoustic conditions if studying real stage enclosures. How the differences found in levels, delays and directions may affect the perceptual effects positively or negatively towards the optimum conditions as defined by the players are then discussed. The chapter is organised into three main parts: the first part discusses the need for reflected sound on stage and how the level and delay of early reflections differ between a ceiling and side wall reflections the different perceptual effects studied. The second part relates the levels and delays of reflections from the stage enclosure to the perceptual effects included for this study. The third part discusses the relevance of scattering properties of the stage enclosure, how the results from part two agree with acoustic conditions for the audience, and how the architectural stage measures proposed in Chapter 3 may correspond with perceptual effects studied.

## 5.2 The need for early reflections back to the players

Early reflections back to the orchestra will contribute to raise the sound level for the players on stage. For studying the level of the early reflections, it is beneficial to first investigate to what degree raised sound levels on stage are needed. The need for raising sound levels origin from three main factors: differences in sound power levels between the different musical instruments, the physical separation between players and attenuation of sound introduced by the orchestra itself. These three factors are described below.

The sound power level ( $L_w$ ) of string, woodwind and brass instruments were investigated by Meyer (2004). The results showed that the brass instruments are typically 10 dB louder than the string instruments and 5 dB louder than the woodwinds. This suggests that sound levels are not uniform for individual players within the orchestra.

Most stages have a larger stage width compared to stage depth. Additionally, with the most common orchestra configuration woodwind, brass and percussion sit at the back half section of the stage on risers, while the string section sit across the full width of the stage at the front half of the stage on the flat floor. This leads to large distances between many of the players within the string section, while percussion, brass and woodwind are relatively closer to most other players.

The effect of other players (and other objects on stage like instruments and music stands) obstructing/attenuating sound was studied in Chapter 4. The sound within the orchestra with no stage enclosure present will consist of the direct sound, the floor reflection and reflections from other players and objects on stage (like music stands and instruments). This combined sound level has been referred to as the ‘within-orchestra sound level’ and denoted  $L_{dfo}$  – the combined level of the direct sound, the floor reflection and orchestra reflections.  $L_{dfo}$  does not

take sound power levels into account, only the obstruction and separation effect is included. Results from the scale model study mentioned above show that the obstruction effect by the orchestra is most significant above 500 Hz. For players being more than 14 m apart across the stage, the mutual sound level was attenuated by about 9 dB at 1 kHz and 12 dB at 2 kHz (in excess of inverse-square-law attenuation). Gade (1989b) found that a high frequency loss of the direct sound made the ensemble conditions more difficult for the players. How the within-orchestra sound levels vary within the orchestra with risers at back of the stage is illustrated in Figure 5.1.

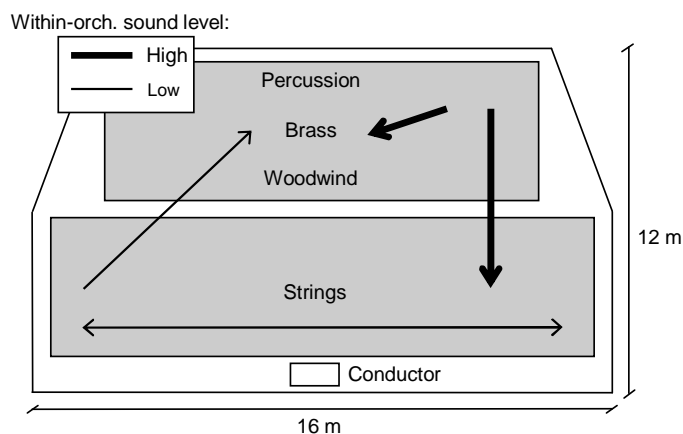


Figure 5.1: Within-orchestra sound levels between the different instrument groups.

The combined effect of these three factors appear to be that few players struggle to hear percussion and brass, while string players will struggle the most with hearing other players or one's own instrument – particularly being able to hear other string players at the opposite side of the stage. Subjective results support such a conclusion: in Chapter 3, percussion and brass were normally found too loud by most players within the orchestra, and string players responded they frequently struggle to other string players at the opposite side of the stage.

Alternative arrangements of a symphony orchestra will change the presence of compensating and competing reflections. For sound recordings of a symphony orchestra, Audun Strype has practised a reversed arrangement of the orchestra, where the string players are at the back of the stage, close to the rear stage wall, while the percussion players are located at the stage front. This results in the stage back wall providing compensating reflections for the string section instead of competing reflections from the percussion and brass. This arrangement has apparently resulted in improved balance between the different instrument groups; see Appendix F for more details. These experiences also suggest that percussion and brass instruments do not need much reinforcement of their sound provided by the stage enclosure (using a normal orchestra arrangement). French horn players though prefer reflecting surfaces behind them, as discussed in Chapter 3.

It is likely that the principal benefit of a stage enclosure for musicians is reflections back to the players to compensate for low within-orchestra levels. Reflections which perform this function will be called here 'compensating reflections'. These reflections appear to be most needed by string players. However introducing surfaces around the orchestra to provide compensating reflections is also likely to raise the overall level on stage; it is against this background that the compensating reflection has to be heard. If the level of sound from all instruments is

raised equally by the enclosure, there is no benefit for players. It is therefore also necessary to study reflections which will have a negative effect on the audibility of distant musicians on stage; these reflections are therefore called ‘competing reflections’. Installing risers on stage increases within-orchestra levels, so the need for compensating reflections will be influenced by the presence or absence of risers. The discussion in the following sections assumes that there are rear risers only on the stage. How ceiling and wall reflections can provide compensating reflections across the stage is first studied.

## 5.3 First order compensating ceiling and wall reflections

For studying the differences between overhead and side reflections for players sitting sideways across the stage on a flat floor, simplified situations have been studied analytically – simplified in terms of only looking at flat surfaces, only including 1<sup>st</sup> order specular reflections and assuming an omnidirectional source. The motivation for doing this is to study the differences between an overhead reflection (typically from ceiling or reflector) and side reflections (typically from walls) imposed by the geometrical differences alone. When studying levels, the sound is here considered stationary (steady-state levels).

Figure 5.2 shows cross-sectional views of a generic stage, sideways across the string players, where three different possible reflections are indicated: a ceiling reflection C and two side wall reflections  $W_1$  and  $W_2$ . With the reflecting surfaces at the sides of approximately 2.5–3 m height and with the top sections tilted about 15°, the wall reflections  $W_1$  and  $W_2$  will be close to unobstructed by the orchestra. For a discussion of how to provide unobstructed reflections from the sides of the orchestra taking into account the frequency response of the reflection (including cornice reflections), see Appendix C. Figure 5.2(a) shows a listening player S sitting on the far left side, who will receive sound from the different players across the stage, while Figure 5.2(b) shows a listening player M sitting in the middle of the stage. Only violin players are illustrated for simplicity (all illustrations of musicians in this chapter are taken from Meyer (2004)). An orchestra width of 16 m is used. String players are chosen since they will normally sit on a flat stage floor spread across the stage width. The direct sound and floor reflection level will be low between players on opposite sides since other players will block the propagation path as illustrated, particularly at high frequencies. For the players not sitting far away, the sound level will be considerably higher (due to shorter distance and fewer obstructions between them). The players sitting far away from each other would benefit from a reflection to raise the mutual sound level and compensate for the low within-orchestra sound level.

### 5.3.1 Level of compensating reflections

The levels of the early reflections (C,  $W_1$  and  $W_2$ ) have been calculated under the following assumptions: only 1<sup>st</sup> order specular reflections (off plane surfaces) are considered and

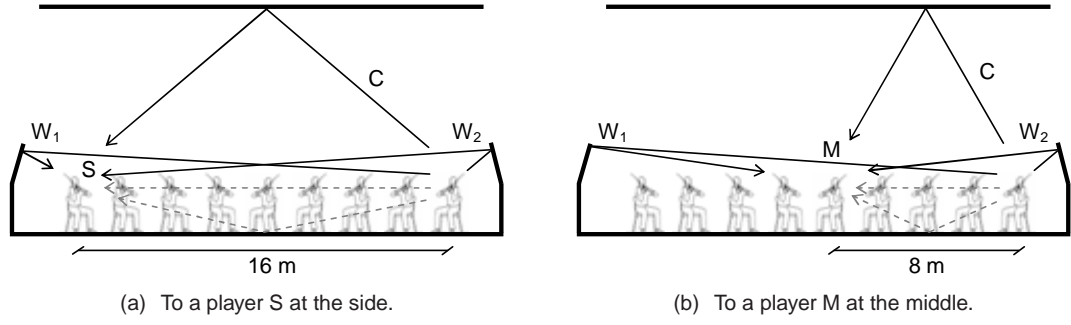


Figure 5.2: 1<sup>st</sup> order ceiling reflection (C) and side wall reflections ( $W_1$  and  $W_2$ ) sideways across the stage. From players across the stage to a player S on the far left side and a player M at the middle. Direct sound and floor reflection as dashed lines. Violinist illustration from Meyer (2004).

reflection levels are based on unobstructed sound paths. Higher order reflections are excluded because 1<sup>st</sup> order reflections will dominate under the given conditions.

The levels of the reflections C,  $W_1$  and  $W_2$  are shown in Figure 5.3. The levels are seen relative to the direct sound level at 1 m distance. The reflection levels are calculated for three different ceiling heights and two different widths between the side walls: the height  $H_{rb}$  is either 7, 13 or 19 m, while the side walls width  $W_{rs}$  is either 18 or 26 m. Estimated within-orchestra level at 1 kHz sideways on a flat floor is also included (according to results from Chapter 4). At the 1 kHz octave band, the attenuation introduced by the orchestra is highly significant.

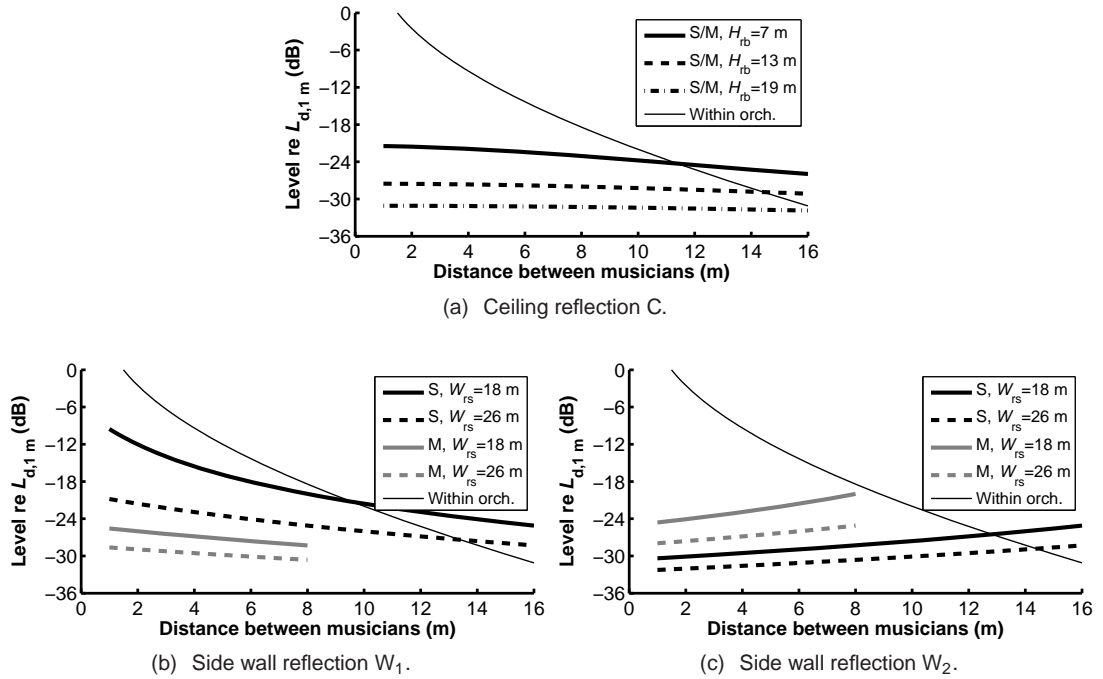


Figure 5.3: Level of specular unattenuated 1<sup>st</sup> order reflections of sound radiated from players S and M. The presented levels depend on source-receiver distance between the source and listening players sitting across the stage. Calculated for the ceiling reflection C and the side wall reflections  $W_1$  and  $W_2$  for different values of  $H_{rb}$  and  $W_{rs}$ . The within-orchestra sound level at 1 kHz is included.

The level of the ceiling reflection from players towards the side (up to 8 m away) to player M would be the same as for the player S, so levels presented in Figure 5.3(a) represent both cases. For the side wall reflections, the level will differ for players M and S for corresponding distances between players, so the resulting wall reflection levels in Figure 5.3 are split up for players M and S.

When comparing a low ceiling compared to narrow side walls, it will be relevant to study total sound levels for listeners across the stage with either a low ceiling or narrow side walls introduced. Figure 5.4 shows the total level of within-orchestra and reflection sound level for listeners across the stage with player S as source. The low ceiling was set at  $H_{rb} = 7$  m, while the side walls were set at ( $W_{rs} = 26$  m). From Figure 5.4 we see that for players 1–6 m from player S, the total level is mainly controlled by the within-orchestra sound level. For distances 6–16 m the reflection will contribute to compensate for the low within-orchestra sound level. The side walls will result in slightly higher total levels, especially at large distances: from players 16 m away at the opposite side of the stage, the side walls will raise the total level by about 3 dB more compared to the ceiling. If studying the detail of the reflection level of C,  $W_1$  and  $W_2$  across the stage in Figure 5.3, we see that reflection  $W_2$  has highest level from players farthest away and the variation of reflection level across the stage is largest for the wall reflections.

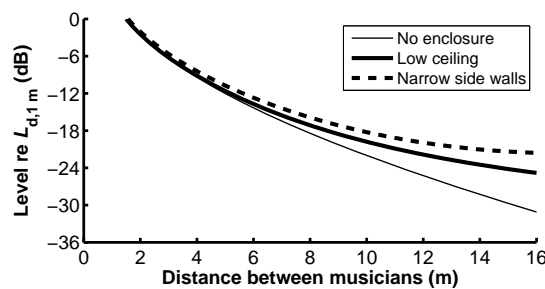


Figure 5.4: Total sound level for listeners across the stage for a player S at the side of the stage. Calculated for no enclosure ( $L_{dfo}$ ), low ceiling only ( $H_{rb} = 7$  m) and narrow side walls only ( $W_{rs} = 18$  m).

### 5.3.2 Delay of compensating reflections

The time delay of the ceiling and the wall reflections from players across the stage are shown in Figure 5.5. The delays presented in this figure are seen relative to the arrival of the direct sound, since the delay of the direct sound will vary with distance between the players. The delay of the direct sound itself may be highly relevant as well, as discussed in Section 5.4. The most significant difference between a ceiling reflection and side wall reflections is that the delay of the ceiling reflection will only vary within approximately 20 ms, whereas the delay will vary considerably more between the different players for the side walls. Or more precisely according to Figure 5.5(b): the delay of  $W_1$  will be constant from all players whereas the delay of  $W_2$  will vary significantly across the stage. From players close to the side wall the delay of  $W_2$  will be very small – down to 6 ms for players 1 m from the wall.

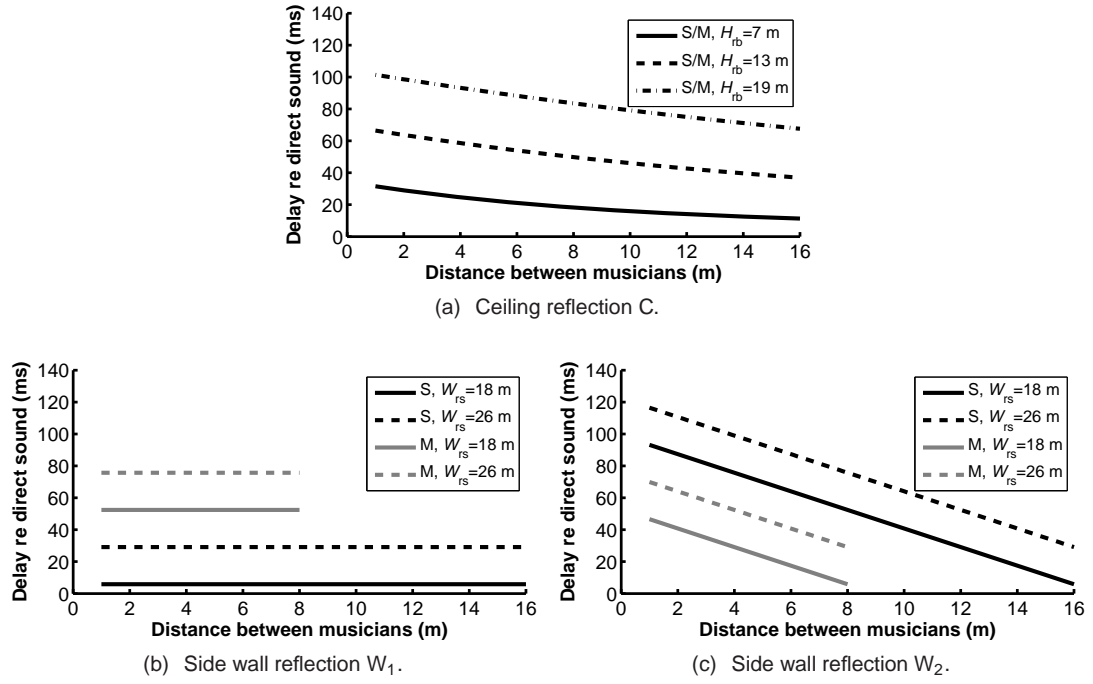


Figure 5.5: Delay of 1<sup>st</sup> order reflections of sound radiated from players S and M. The presented levels depend on source-receiver distance between the source and listening players sitting across the stage. Calculated for the ceiling reflection C and the side wall reflections  $W_1$  and  $W_2$  for different values of  $H_{rb}$  and  $W_{rs}$ .

### 5.3.3 Discussion of results

From this simplified analytical study we can conclude that either the ceiling or the side walls must be close to the orchestra for providing significant compensation of low within-orchestra sound levels across the stage. Achieving significant compensation (above 500 Hz) relies on the reflection paths not being obstructed by the players. With a large stage height ( $H_{rb} = 19$  m) or stage width ( $W_{rs} = 26$  m), the reflection level will be below the within-orchestra level between most of the players across the stage, and consequently providing little compensation. Such reflections at large distances from the orchestra could instead contribute to reduced temporal clarity, by introducing reflections being delayed more than 80 ms (Figure 5.5). For  $H_{rb} = 7$  m or  $W_{rs} = 18$  m, the reflection will start compensating for low within-orchestra levels for players sitting more than 6 m apart (Figure 5.4). This assumes the actual players sit on a flat stage floor across the stage, which is the case for the string players in most concert halls. If risers are being used there will be less need for a compensation for the within-orchestra sound levels.

When comparing the combined sound level of within-orchestra sound and 1<sup>st</sup> order reflections, a ceiling alone at  $H_{rb} = 7$  m or side walls alone at  $W_{rs} = 18$  m, result in minor differences: the side walls lead to the total level being about 3 dB higher between players on opposite sides of the stage compared to the ceiling (Figure 5.4). A 3 dB difference could be significant in terms of balance between the different instruments, but there may be other measures or mechanisms involved than steady-state sound level differences. When comparing time delays of the 1<sup>st</sup> reflections, more significant differences are seen between a ceiling and side reflections. It is

therefore relevant to study how these time arrival differences may affect the conditions for the players, in particular related to potential temporal masking effects.

## 5.4 Masking caused by delay of sound within the orchestra

If orchestra players struggle to hear particular instruments or one's own instrument, it will normally be due to the sound level of some other instruments masking the sound (taking precedence perceptually). Such masking mechanisms can take place due to time arrival differences and/or level differences, both studied by [Zwicker & Zwicker \(1991\)](#) and others in general cases (not the case of a concert hall platform). The masking effects relate to effects within cochlea, which suggest that the masking effects are difficult to adapt to or reduce through training. This section covers masking effects caused by time arrival differences, while level masking is discussed in Section 5.5.

Musical sounds are normally transient, not stationary. The orchestra rarely produces continuous sound at a constant level (as was assumed when comparing total sound levels in Section 5.3.1). Hence it is relevant to also study temporal masking effects. For the players, the onset of a note (the transient sound) contains relevant ensemble information. Several musical aspects can potentially be extracted from the onset of the notes, like timing, sound level and articulation. Beside [Zwicker & Zwicker \(1991\)](#), the mechanisms of temporal masking have also been studied by [Plack & Moore \(1990\)](#) and [Fastl & Zwicker \(2005\)](#). [Zwicker & Zwicker \(1991\)](#) found that the amount of temporal masking will be dependent on the duration of the masking note. For a sound lasting only 5 ms, the masking could last for typically 10–20 ms, whereas for a sound lasting 200 ms, it could mask other sounds for typically 25–50 ms after the masking sound source has been switched off, depending on the loudness and character of the competing sounds. Results from the orchestra collaboration (covered in Chapter 3) indicate that the string players often struggle to hear across the stage, while the sound level of the instruments at the back of the stage (percussion and brass) frequently become too loud for the string players (and the other players as well).

### 5.4.1 Synchronicity and temporal masking of sound within the orchestra

As described in Section 2.1, in order for the whole orchestra to sound synchronised for the audience the players at the back of the stage need to anticipate their onset of notes compared to the string players. For the same reason the whole string group must start their note at the same time. Figure 5.6 illustrates how sound from across the stage will be delayed as a consequence of how the players within a symphony orchestra synchronise relative to each other. The three players at the bottom (stage front) in Figure 5.6 are within the string section, while the two players on top (back of stage) are typically brass (or percussion). The figure indicates the physical distance between players and effective delays of direct sound, as experienced for a string player M at the middle of the stage and for a string player S at the



side of the stage. The string players M and S are presumed to start their notes simultaneously while the brass and percussion are playing ahead of the beat so that they are synchronised with each string player at their onset (hence 0 ms for players M and S). However for the string player M, sound from their colleagues at the side of the stage is delayed about 23 ms, whereas for player S, sound from their colleagues on the opposite side of the stage is delayed about 46 ms. Any sound from other instruments arriving before this 46 ms delay could contribute to mask the mutual sound between these players and will represent ‘competing sound’ or a ‘competing reflection’. For string players closer to each other, the delay of the direct sound will be reduced, but will still arrive after the direct sound from instruments at the back.

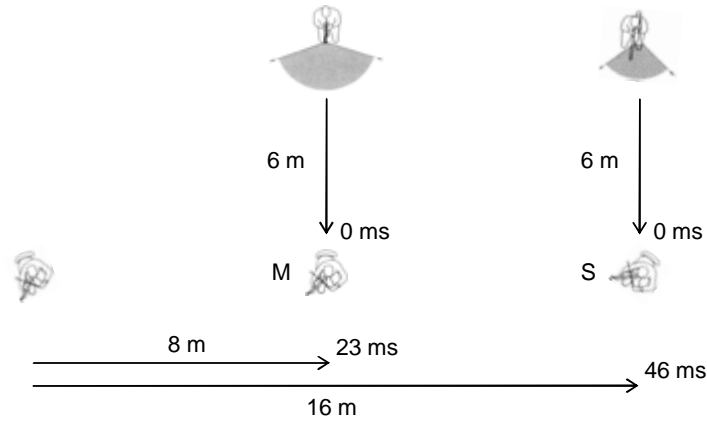


Figure 5.6: Delay of direct sound within the orchestra referring to absolute time. For a player S at the front side and a player M at the front middle of the stage. Musician illustrations from Meyer (2004).

If the string player at the left side synchronise visually with other string players being closer to players M and S, the delays presented in Figure 5.6 will be smaller. The delays presented will be most valid for individual or low number of instruments at the outer regions of the orchestra who visually synchronise together, like double basses and harp. Regardless of number of players synchronising, the sound from the sides of the orchestra will arrive after the sound from players at the back of the stage. This delay of sound from the sides appears significant for temporal masking effects, which will be studied in more detailed below.

## 5.4.2 Echograms within the orchestra

With respect to temporal masking it is relevant to study the echograms at typical locations on stage for sound from other players, in this case on the paths shown in Figure 5.6. This has been investigated analytically for two stage enclosures: a wide, low enclosure ( $H_{fb} = 7$  m and  $W_{fs} = 26$  m) and a narrow, high enclosure ( $H_{fb} = 18$  m and  $W_{fs} = 19$  m). The echograms shown in Figures 5.7 and 5.8 are based on results from Section 5.3. In both figures, the top echograms are from the player towards the back of the stage, while the bottom echograms are from the player at the far side. Differences of sound power level of the different instrument are not taken into account; the within-orchestra sound level described in Section 5.2 is here used. The time  $t = 0$  is the time for the simultaneous note from the strings and the arrival time of the note from the brass (playing ahead of the beat) at the front of the stage. Due to the shorter distance and fewer obstructions for sound from the player at the back, the estimated



within-orchestra sound level is higher from a player at the back compared to the player at the far side. (The within-orchestra sound level is estimated to approximately 4 dB higher for the player at the back with no obstruction of the direct sound.)

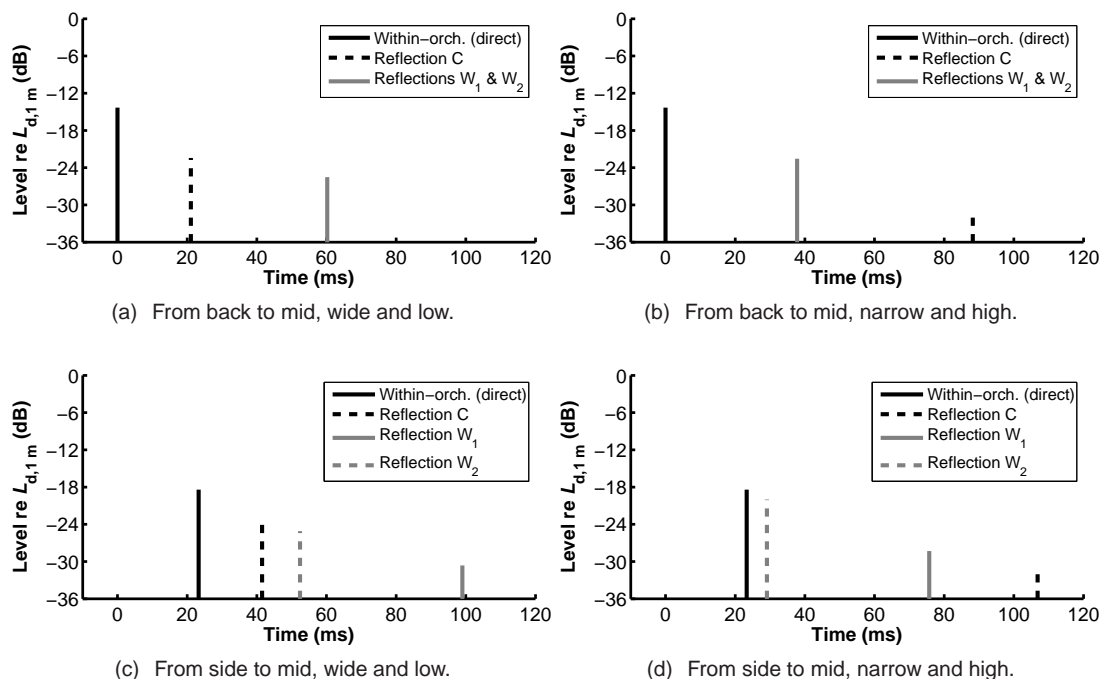


Figure 5.7: Estimated echograms to player M. The wide and low stage enclosure has  $W_{rs}=26$  m and  $H_{rb}=7$  m, while the narrow and high stage enclosure has  $W_{rs}=18$  m,  $H_{rb}=19$  m. The time  $t=0$  represents the onset of a note observed along the stage front line.

From Figure 5.7 for position M we see that the sound from the player at the back of the stage will lead in time and have a higher level compared to the sound from the player at the side. With a ceiling height  $H_{rb}$  of 7 m (the wide and low enclosure), the ceiling reflection from the player at the back will also arrive before the direct sound from the player at the side. With a higher ceiling ( $H_{rb}$  19 m), the ceiling reflection will arrive after the arrival of the direct sound from the player at the side. Additionally, the reflection from the side wall close to the player at the far the side will arrive shortly after the direct sound from this player.

Figure 5.8 shows corresponding responses for position S sitting at the right side of the stage. For the wide and low stage enclosure the reflections from the player at the back arrive delayed 15–20 ms. With the direct sound from the player on the opposite side arriving at about 46 ms, this means that the direct sound and two reflections from the player at the back will arrive before the direct sound from the player at the opposite side. The compensating reflection across the stage will arrive at about 57 ms. If the ceiling is raised above 7 m to reduce the level of competing reflections, the compensating reflection will arrive later – a ceiling height of 10 m would result in a delay of 65 ms (assuming the stage width is unchanged). If percussion and/or brass players lag in time compared to conditions in Figure 5.6 (the players don't fully anticipate), the reflections from percussion and brass will move closer to the string sound with respect to time. This may be beneficial for player M, but not for player S.

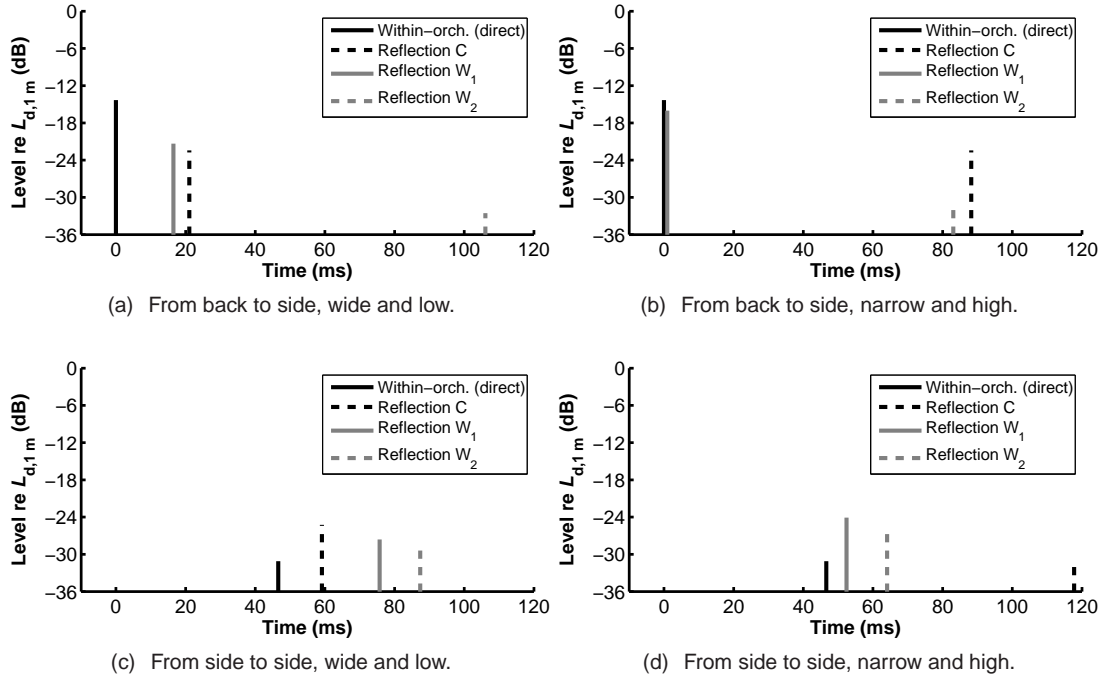


Figure 5.8: Estimated echograms to player S. The wide and low stage enclosure has  $W_{rs}=26$  m and  $H_{rb}=7$  m, while the narrow and high stage enclosure has  $W_{rs}=18$  m,  $H_{rb}=19$  m. The time  $t=0$  represents the onset of a note observed along the stage front line.

### 5.4.3 Discussion of results

When taking into account how the different instrument groups of a symphony orchestra synchronise relative to each other, the effect of location of reflecting surfaces close to the orchestra appear much more significant compared to only studying steady state sound levels. For the string players with a low ceiling above the orchestra, several competing sound events from instruments at the back of the stage will arrive before direct sound from other string players. The compensating reflections provided for the string players are within 60–90 ms with a wide and low stage enclosure. With a narrow and high stage enclosure, only the direct sound from players at the back of the stage will arrive before the mutual direct sound between the string players. The compensating reflections provided for the string players by such a stage enclosure arrive within 50–65 ms. These differences may be relevant for the orchestra as a whole, not only just the string players.

The differences between these two stage enclosures appear relevant for temporal masking effects and consequently perceived balance between different instruments. The presence of what could be seen as competing sound is reduced with a narrow and high stage enclosure. Perceived temporal clarity of sound may also be affected by the differences seen. The way the instrument groups synchronise together means that string players are used to delays of sound events up to approximately 45 ms based on the direct sound within the orchestra. Players at the back of the stage (percussion and brass) may be used to delays of up to approximately 60 ms (across a 16 m wide and 12 m wide stage). This would imply that any sound events within 60 ms may be perceived as the ‘direct’/‘immediate’ orchestra sound contributing to clarity of sound for players at the back, while string players have adapted to the orchestra

sound not deviating more than 45 ms. The compensating reflections arriving with larger delays with a wide and low stage enclosure may lead to reduced temporal clarity for the string players.

If the aural cues deviate significantly from the visual cues with respect to time, it could be disturbing for the players. If the perceived delay of the aural cue relative to the visual is consistent, it may be possible to adapt to it. For the players at the back, the delay of the string sound would be reasonably consistent if the stage/orchestra depth does not vary considerably between different stages. With the players at the back on risers, the within-orchestra sound level is improved (compared to players on flat floor) and early reflections are not likely to take perceptual precedence over the direct sound. For the string players, unattenuated early reflections may take precedence due to low within-orchestra sound levels. If the time arrivals of these early reflections are significantly above 45 ms, it can be confusing for the players to relate to excess time lag of sound from players at the opposite. The excess time lag will depend on the design of the stage enclosure and will not be consistent between different stages.

In Chapter 3, string players commented on excess delay of sound from string players on the opposite side, when being asked about problems related to listening to particular players. The reasons given for their most preferred stages also referred to the impression of hearing the whole string section as one united group (on stages having low values of  $W_{rs}$ ). This variation of perceived delay of sound across the string sections is among the main reason why symphony orchestras need to rehearse in venues they are not familiar with prior to a concert, according to Ihlen (2008). It appears therefore likely that the stage enclosure controls the perceived delay of aural cues. Stage enclosures with a large width between side walls and a high ceiling providing unattenuated specular reflections have the highest risk for leading to disturbing delays. Reducing the width between the side walls will provide compensating reflections without excess delay. Reducing the ceiling height will also reduce excess delays, but the levels of competing reflections will also be increased. By referring to temporal masking effects likely to affect perceived level balance of the different instrument groups, a preference is therefore found for side reflecting surfaces compared overhead reflecting surfaces. The following section investigates how level masking may affect perceived balance.

## **5.5 Hearing oneself and level masking based on instrument directivity**

The perceived level of sound from one's own instrument appears to be highly controlled by direct sound and bone-conducted sound (depending on instrument). The bone-conducted sound involves the vibrations going directly from the instrument to the inner ear through the player's body. According to laboratory experiments by Gade (1989b), early reflections as late as 50 ms are easily masked by the direct sound and bone conducted sound from one's own instrument. For this reason it is likely that introduction of early reflections on stage will raise the level of others' sound more than the level of one's own instrument, as suggested by Naylor

(1988). In cases where the players have problems with hearing themselves, lowering the level of others appear more effective than trying to raise the level of one's own instrument.

### 5.5.1 Competing sound from the instruments at the back of the stage

Normally the sound of percussion and brass appear to be loud enough for all players without any stage enclosure. The percussion and brass have a higher acoustic energy output level and the directivity of the trumpet and trombone result at higher frequencies in most of the sound from these instruments propagating in the direction in front of the players (at lower frequencies radiation is much closer to being omnidirectional). The direct sound level can be controlled to some degree by allowing a certain physical separation between the players, but the area available on stage often forces some players to sit close to the loud instruments. For this reason some orchestras have started using screens in front of the loud instruments to protect the nearby players against excess sound levels, as described among others by [Lee et al. \(2005\)](#), with the aim of both improving ensemble conditions and reducing risk of hearing impairment.

One issue already mentioned is that of a directional brass instrument creating excessive levels at the front of the stage. Early reflections provided by a stage enclosure will contribute to further raise sound levels. Figure 5.9 considers at what minimum height,  $h_{\min}$ , a ceiling will no longer reflect the main radiation sector from the trumpet, based on trumpet directivity at 1.5 kHz as published by [Meyer \(2004\)](#). The main radiation sector is defined by the angle where the sound level from the source is  $-6$  dB relative to on-axis level (straight in front of the trumpet). Since all notes being played on a trumpet and trombone will be radiated from the same bell physically, the directivity pattern at higher frequencies will be reasonably consistent between each note played as demonstrated by [Otondo & Rindel \(2004\)](#). Due to its smaller size, the trumpet will be less directional at the same frequency compared to the trombone, so the trumpet will have the largest sector.

Equation (5.1) gives the formula to calculate  $h_{\min}$ , where  $d$  is the floor distance between the trumpet and string player,  $\alpha$  is the angle (in degrees) between the horizontal direction and the  $-6$  dB direction upwards;  $h_r$  is the height above the stage floor of the trumpet riser;  $h_t$  is the height of the trumpet above the riser and  $h_e$  is the height of the string player's ear above the stage floor. With  $d=11$  m,  $\alpha=55^\circ$ ,  $h_r=1.0$  m,  $h_t=1.0$  m and  $h_e=1.2$  m,  $h_{\min}$  becomes 9.3 m – or 10 m as a rough figure. If using  $d=19$  m (diagonally across the stage),  $h_{\min}$  becomes 14.9 m. These results are based on the direction of  $-6$  dB level defining  $\alpha$ , and using the directivity of a trumpet at 1.5 kHz. With other relative levels defining  $\alpha$  or frequency,  $h_{\min}$  will have a different value. A 6 dB drop may be regarded as a significant reduction of reflection level, and 1.5 kHz is within the frequency range found important for perceived ensemble conditions ([Gade, 1989b](#)).

$$h_{\min} = 0.5 (d \cdot \tan(\alpha) + h_r + h_t + h_e) \quad \text{m} \quad (5.1)$$

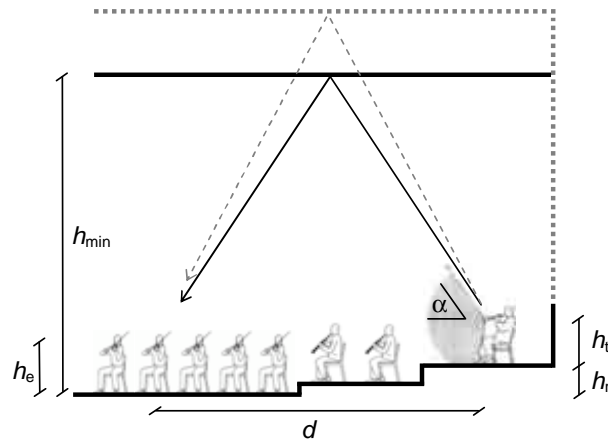


Figure 5.9: Ceiling reflection from trumpet at 1.5 kHz. Trumpet directivity and musician illustrations from Meyer (2004).

The wall behind the orchestra can also contribute to unnecessarily raise sound levels of percussion and brass, especially if the wall has a tilted section as indicated in Figure 5.10. Kahle & Katz (2004) found that adding sound absorbing materials on the back wall improved the conditions for the players. On the other hand results from the first orchestra collaboration of this project (Chapter 3) confirmed a well-known fact that most French horn players prefer having a reflecting surface behind them, since high frequency sound of French horns is projected backwards. This indicates a conflict of interest between some players within the orchestra.

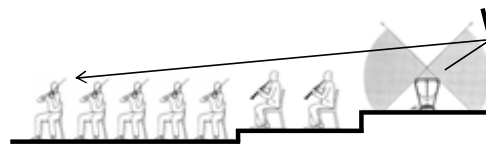


Figure 5.10: Back wall reflection from timpani at 90–200 Hz. Timpani directivity and musician illustrations from Meyer (2004).

Parallel side walls appear useful for providing compensating reflections back towards the strings, but can also contribute to raise the sound levels of percussion and brass (unnecessarily) for the string players, as illustrated in Figure 5.11. The back half of the side walls could be made diffusing or absorbing in a similar way as the back wall, splayed (as indicated in Figure 5.11) or curved, to reduce the level of competing reflections within the orchestra. If the brass players struggle to hear the string players it appears difficult to add reflection(s) of strings back to the brass players without adding (unnecessary) reflection(s) of brass towards strings. But by making the back half of the stage more absorbing or projecting the sound away from the stage area, the sound from one's own groups appears less likely to mask the string sound for the percussion and brass players.

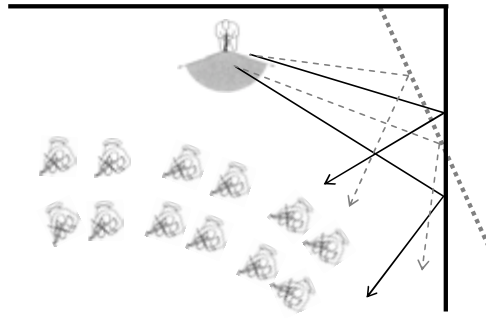


Figure 5.11: Side wall reflections from trumpet at 1.5 kHz. Trumpet directivity from Meyer (2004).

## 5.5.2 Other level masking mechanisms

The level masking could also take place in the frequency domain, especially with low frequency sound masking high frequency sound as described by Zwicker & Zwicker (1991). Zha & Fuchs (2002) and Adelman-Larsen *et al.* (2010) found improved conditions for the players by reducing the build-up of low frequency sound on stage. The build-up of sound within the stage enclosure is further discussed in Section 5.9.

As mentioned in Section 2.2.3 Meyer (1986) investigated how players of different instruments have different sensitivity to early reflections from different directions due to masking effects caused by the sound and directivity of their own instrument. His results suggest that violin players at 1–2 kHz are most sensitive to a reflection within line of sight or directly from above and less sensitive to a reflection diagonally from above. This was also the case for woodwind players at 2 kHz. At 1 kHz the woodwind players were most sensitive to reflections arriving from the sides and above. This suggests that the balance of self to others could be affected by the direction of the early reflections. From these results, a low ceiling could lead to violin and woodwind players hearing more of their own instrument. Additionally the reflection from the players at the far sides of the stage will arrive diagonally from above with a low ceiling, and more in the horizontal plane for a side wall reflection. Hence a wide and low stage enclosure could result in string players at the middle of the stage hearing themselves and woodwinds too much while struggling to hear the string players at the sides.

## 5.5.3 Discussion of results

This section has focused on ways to reduce competing reflections from instruments likely to be already loud enough without any stage enclosure. Percussion and brass often fall into this category. By reducing the levels of competing reflections of these instruments, other instruments will become more audible on stage. For a ceiling height of less than approximately 10–15 m above the stage floor, the direct sound from trumpets is reflected down towards the players at the front of the stage at a significant level. The level of such reflections will depend on the finer details (shape and acoustic properties) of overhead reflectors/ceiling, but a low height means there is significant likelihood of competing overhead reflections from brass (and percussion). In Chapter 3,  $H_{tb}$  above 12.8 m was found to be a good indication of a stage

enclosure providing good acoustic conditions for the players. This height limit is thus supported by both analytical and experimental results. The results of [Andersson \(2007\)](#) also suggest that removing reflecting surfaces above the orchestra that reflect brass and percussion down towards the string players has positive effects. For string and woodwind players a low and wide stage enclosure can result in the sound level of one's own instrument being too high, while sound from players at the sides of the orchestra tends to become inaudible. A reflecting back wall close to the orchestra (often behind percussion) could result in similar negative effects, though such a reflection appears useful for the French horn players. To summarise, considering stage dimensions with respect to perceptual masking effects suggest a narrow, high and moderately deep enclosure will provide the best perceived balance between the instrument groups. With regard to being able to separate the sound from different instruments, the following section discusses the relevance of the cocktail-party effect on stage.

## 5.6 Cocktail-party effect and spatial separation of instruments

[Meyer \(1986\)](#), [Andersson \(2007\)](#) and [Guthrie \(2008\)](#) have discussed the relevance of the cocktail-party effect ([Cherry \(1953\)](#), [Bronkhorst \(2000\)](#), [Kidd \*et al.\* \(2005\)](#)) regarding ensemble playing. The cocktail-party effect can be described as an improved ability to focus on one source in multiple-source environment. According to [Hawley & Litovsky \(2004\)](#), the ability to focus on one source is enhanced by spatial cues and fundamental frequency differences. The results from the orchestra collaboration (Chapter 3) support such a hypothesis, where the ability to focus (mentally) on particular instruments appears to be related to spatial separation.

With low direct sound levels within the orchestra, the early reflections on stage could take temporal precedence as discussed in Section 5.4 as well as spatial precedence over the direct sound. The situation where a reflection confuses or changes the perceived direction of a sound source is referred to as an image shift. Normally, a reflection will fuse better with the direct sound if it arrives from a direction close to that of the direct sound as found by [Litovsky \*et al.\* \(1999\)](#) and [Seraphim \(1963\)](#). The risk of an image shift is highest for players far apart across the stage on a flat floor. Figures 5.8(c) and 5.8(d) show reflections being more than 6 dB higher than the within-orchestra sound level. For an early lateral reflection at an azimuth of 40°, [Barron \(1971\)](#) found that an image shift can occur when the reflection level (delayed 10–40 ms after the direct sound) has a level about 2–3 dB higher than the direct sound.

By having compensating reflections for the string players arriving from the sides, the sound from strings relative to sound from percussion and brass will have a significant spatial separation. With reflecting surfaces from above, spatial cues from above will be introduced from all instruments within the orchestra if the complete orchestra is covered by such reflecting surfaces. This may suggest that focusing on particular instruments will be easier on a narrow and high stage enclosure.



Rodgers (1981) carried out research that indicated that comb filtering could contribute to confuse our directional hearing. Halmrast (2000) found that players disliked acoustic conditions on stage where comb filtering occurred for sound travelling across the stage. In Halmrast's study the players reported negative effects on timbre where comb filtering occurred. But comb filtering could potentially also contribute to difficulties with sound localisation (as indicated by results by Rodgers) and consequently separating particular instruments spatially. Comb filtering will also lead to the ratio between the direct sound and total reflected sound being low within certain frequency bands, which could be a good objective measure related to perceived clarity of sound according to Griesinger (2007). See Appendix D for more details on how comb filtering might be related to the width and the height of the stage enclosure.

So far in this chapter, focus has been on perceptual effects relating to level balance and separation of the different instruments. The two following sections discusses other effects that appear relevant for being able to hear all other players clearly, as well as hearing the acoustic response from the main auditorium – namely low frequency effects, diffusion of reflections and late arriving reflections/reverberant sound within the stage enclosure.

## 5.7 Low frequency enhancement of double bass

According to results in Chapter 3, several players commented on their need to hear the double basses. For ensemble hearing (in general), the bass is often essential for definition of temporal cues and rhythm. Therefore, hearing the double bass sufficiently clearly may be an critical factor for the ability to hear the other players. The mid frequency range sound from the double bass may easily be masked by other instruments, while the low frequencies will not be masked.

All four instruments of the string section (violin, viola, cello and double bass) lack a resonance in their main body to support the deepest notes played on the instrument, as demonstrated by Askenfelt (1986). This problem is most significant for the double bass – the other low frequency instruments (like bassoon, timpani) do not exhibit similar problems. If the double basses are close to a hard reflecting surface, the reflection off the surface will at lower frequencies be in phase with the direct sound and the total sound level can theoretically be raised by 6 dB by one reflecting surface.

Raised levels at low frequencies can be beneficial both for the players themselves and the rest of the orchestra (with regard to temporal cues mentioned above). The stage floor will serve as such a reflecting surface, but a side wall can serve as an additional reflecting surface to raise the low frequency level further. (The latter would require the double bass to be located on the side of the orchestra.) Lee (1982) found a theoretical boost of about 5 dB at 41 Hz when putting the double basses 1 m from a reflecting wall, but a reduction of 2.5 dB at 110 Hz. Unpublished work (Halmrast, 1995) (also see Halmrast (2000)) showed that players appreciated the introduction of vertical reflecting surfaces close to the double bass, on a stage which was originally very wide. Qualified listeners among the audience commented on experience a fuller tone of the double bass with this configuration. Raising the low frequency levels by introducing very early coherent reflections rather than raising the reverberation time at



low frequencies, could be beneficial for achieving a full tone while maintaining temporal clarity of sound on stage (as well as in the audience area). Such conditions can also contribute to better conditions for amplified music in auditorium. Results by [Zha & Fuchs \(2002\)](#) indicate that perceived clarity of sound on stages relate to reverberant sound at low frequencies – excessive acoustic response at low frequencies was found to have negative effects on how the players perceive the acoustic conditions. Similar results were found for amplified rock musicians by [Adelman-Larsen et al. \(2010\)](#).

## 5.8 Diffusion and scattering

All calculations above have been carried out assuming flat surfaces. If scattering reflectors are introduced the level of the specular reflection is reduced and the echogram becomes more smeared out in time. This could be positive with regard to lowering the level competing reflections – for instance from the back wall behind percussion and brass. Diffusion can also lower the risk for later arriving reflections contributing to reduced temporal clarity (as discussed in Section 5.4.3). With regard to late sound within the stage enclosure, diffusion can be beneficial for directing a portion of the sound energy away from the stage enclosure, and instead project some of the acoustic response from the main auditorium down towards the players. On the other hand, adding scattering means that the level of beneficial compensating reflections may be reduced. It could also lead to the directional cues becoming more ambiguous in the absence of a strong direct sound, which potentially could lead to problems with spatially separating different instruments.

In [Halmrast \(2000\)](#) and [Halmrast \(1995\)](#), introducing an overhead reflector array above the orchestra was found to lead to negative timbre colouration effects. When introducing vertical reflectors at the sides instead, similar negative effects were not found. The negative colouration effects were associated with the non-scattering properties of overhead reflector array studied as well as the delay of the reflections introduced. These results support the hypothesis that narrow side walls will lead to better acoustic conditions for the players, compared to a low ceiling/reflector. It also suggests that the scattering properties of surfaces introduced are less critical with side walls close to the orchestra.

With all players at the outer regions of the orchestra being on risers (string player as well), the need for early (compensating) reflections will be reduced. In such a case the side walls could be made diffusing, lowering the level of the compensating reflections as well as reducing the risk of unfavourable effects of these reflections. This appears most needed for a large distance between the side walls, referring to temporal clarity as discussed above.

## 5.9 Late reflections and reverberant sound

The sound of the orchestra heard on stage is very different from that for the audience. The players on stage will mostly hear their own instrument and instruments not far away from

them. Due to distance attenuation and the orchestra screening effect, low sound levels occur for sound from players at greater distances (typically outside a 4 m radius). This will lead to a skewed balance of the orchestra sound, as indicated in Figure 5.4, where level differences based on the within-orchestra sound alone are above 30 dB. Compensating reflections will contribute to improve this skewed balance, but only to a certain degree. In addition, what the performers hear of their own instrument is, due to instrument directivity that varies with frequency, as well as bone conducted sound, is very different to the sound heard by someone nearby.

In the audience area, all instruments are at a comparable distance from the listener with reasonable free sight-lines to all instruments (except for listeners for instance very close to the orchestra). This leads to the level balance of different instruments being perceived differently in the audience area compared to on stage, particularly if based on the direct sound levels alone. The late reflections and reverberant sound may provide some compensation for the skewed level balance on stage, which will here be discussed.

Results from Chapter 3 show that players often describe good acoustic conditions in terms of 'projection' and/or 'bloom'. Good 'projection' appears to relate to hearing an acoustic response localised from the main auditorium/audience area that creates an impression of reaching through to the audience, giving evidence of satisfactory communication. Many of the orchestral instruments rely on being supported by the room acoustically to achieve their preferred tone colour; such an acoustic support is often referred to by the players as 'bloom'. From Chapter 3, some of the players responded they use the reverberant sound they hear from the main auditorium for artistic purposes. It also appears to enable the players to make artistic judgements with greater confidence. Results of Brixen & Wolter (2006) and Lokki *et al.* (2009) agree well with such findings relating to late sound: musicians of a symphony orchestra as well as singers reported improved conditions on stage when reverberated sound of their own sound was introduced back to them by means of an electro-acoustic system.

The design of the stage enclosure will affect how audible the late or reverberant sound from the main auditorium will be on stage. The levels of both early reflections and reverberant sound within the stage enclosure itself are likely to be significant here. If the stage enclosure and the main auditorium could be treated as two acoustically coupled spaces, the players will hear a reverberant sound that may differ significantly from the main auditorium. This would potentially lead to players experiencing a lack of 'projection' – the reverberant sound is not localised from the main auditorium/audience area. Other negative effects of an enclosed stage may be excessively high total sound levels on stage, and more difficulties locating/separating the sound from the different instruments (as discussed in Section 5.6). These considerations would suggest that a stage enclosure should provide beneficial compensating reflections and otherwise expose the orchestra as much as possible to the rest of the concert hall volume. The location of reflecting surfaces could affect the build-up of later arriving reflections and reverberant sound. Results from Chapter 3 show that all the six most preferred halls (out of twelve) have an exposed stage – the stage is acoustically highly integrated with the main auditorium. To what degree the acoustical integration between stage and main auditorium may be assessed objectively is investigated and discussed in Chapters 6 and 7.

Figure 5.12 compares possible higher order reflections from a ceiling and side walls. Higher order ceiling reflections are possible on stage since the orchestra will obstruct the sound less significantly vertically compared to horizontally. If the side walls have tilted sections, as indicated in Figure 5.12(a), the higher order side wall reflections are likely to be suppressed due to the need to pass through the orchestra. With vertical side walls, as indicated in Figure 5.12(b), higher order side wall reflections can propagate via the ceiling unattenuated. These observations suggest that tilted side wall sections close to the orchestra can provide compensating reflections without generating significant higher order reflections. [Kahle & Katz \(2004\)](#) and [Andersson \(2007\)](#) both mention the advantages of reducing the reverberant sound within a stage enclosure. In addition, the tilted side walls may be beneficial for projecting late reflections from the main auditorium down towards the players, making the acoustic response from the main auditorium more audible (and raising the value of  $G$  on stage). Overhead reflecting surfaces could also be tilted vertically to achieve the same way of projection of late sound for the players (as well as early reflections for the audience). Such angling of the overhead surfaces will also reduce the level of competing reflections.

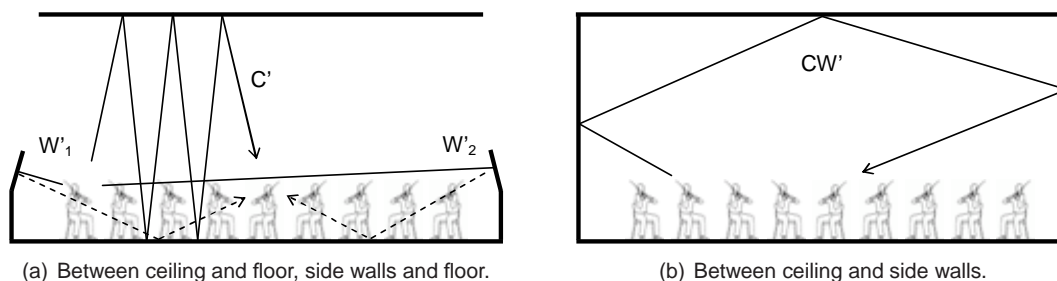


Figure 5.12: Higher order reflections on stage. Violinist illustration from [Meyer \(2004\)](#).

The two remaining sections cover findings regarding stage enclosure design from the audience's point of view, and how the architectural measures proposed in Chapter 3 may correspond with the perceptual effects studied.

## 5.10 The stage enclosure's effect on conditions for the conductor and the audience

[Meyer \(2008\)](#) has studied acoustic conditions for the conductor for the case of the percussion, brass and woodwind instruments being on risers. He found that because of the different distances of instruments from the conductor, the balance situation for the conductor (like for the orchestra) is distinctly different to that in the audience area. His results showed that reflections from above the orchestra, especially above the strings, can make it difficult for the conductor to get the right impression of the balance of the orchestra, while side walls reflections are considered beneficial. The exception to this is overhead reflectors that favour the woodwind, since for the conductor this group is easily masked by the strings and brass. Meyer also found that a large volume surrounding the orchestra (an exposed stage) enables the conductor to

get an impression of the late sound of the orchestra, which is useful for getting an impression of the total sound of the full orchestra.

Griesinger (2006) found that an excessive level of early reflections (like from within the stage enclosure) could create the impression of a remote and 'muddy' sound for the listener. In some halls the sound level for the audience might suffer if there are no reflecting surfaces above the orchestra. Such an overhead reflector (system) can be designed to project early sound mainly towards the audience, not back towards the orchestra. Such an arrangement of a reflector system will also direct late sound from the main auditorium down towards the orchestra, which appears beneficial for the players (see Section 5.9). Cremer & Müller (1982) found that maximum 30 % of the space above the orchestra should be covered by reflectors for the audience's point of view, whereas Beranek (1992) set this limit to 50 %. If comparing these findings to what has been found as beneficial stage enclosure design for a symphony orchestra in this chapter, there are no strong contradictions found.

## 5.11 Relevance of architectural measures

The results from the studies within this chapter support the findings in Chapter 3 with regard stage enclosure dimensions being relevant for perceived conditions on stage. In Chapter 3 significant correlations were found between the proposed architectural measures and perceived acoustic conditions by the players. The significant correlations appear to be related to direction of reflecting surfaces being taken into account, and that the measures give a sufficiently valid indication of acoustic conditions with the orchestra present.

Based on these findings, the five architectural measures proposed in Chapter 3 can have the following relations to perceptual effects and perceived acoustic conditions:

$W_{rs}$  (the distance between reflecting surfaces at the sides): a low value will indicate compensating reflections for players across the stage at significant level. This appears to contribute positively to avoid negative level and temporal masking effects, avoid perceived excess delay for the string players on opposite sides of the stage (precedence effect) and increase the spatial separation of reflected sound on stage (cocktail-party effect). A low value will also increase the sound level of double basses at low frequencies.

$H_{rb}$  (the distance between stage floor and overhead surfaces reflecting brass instruments): a high value will indicate low levels of competing reflections from brass and percussion down towards woodwind and string players. This appears to contribute positively to avoid negative level and temporal masking effects. Overhead reflecting surfaces also appear as an important contributor to a build-up of reverberant sound on stage. A high value of  $H_{rb}$  could therefore also indicate good clarity of sound and that the reverberant sound from the main auditorium will take perceptual precedence over the reverberant sound within the stage itself. A high value could also indicate overall sound levels not being experienced as too high.

$D$  (the distance between the back end of the stage accessible to the orchestra and the average stage front): a high value will contribute positively regarding masking effects, like  $H_{rb}$ , but French horns players appear to prefer a reflecting surface behind them at moderate distance. A moderate value of  $D$  therefore appears as the best compromise.

$H_{rb}/W_{rs}$ : since  $W_{rs}$  should not be too large, and  $H_{rb}$  not too small, a large value of  $H_{rb}/W_{rs}$  would indicate good acoustic conditions and partially monitor the different aspects monitored by  $W_{rs}$  and  $H_{rb}$ .

$D/W_{rs}$ : similar to  $H_{rb}/W_{rs}$ .

The height to reflecting surfaces reflecting sound from the strings ( $H_{rs}$ ) is not included among the proposed measures since such reflecting surfaces have not been found clearly advantageous nor disadvantageous. Such reflecting surfaces will introduce compensating reflections for the string players and may be beneficial, but appear to also lead to negative effects like the balance of one's own instrument and the others (as discussed in Section 5.5.2) and the orchestra balance for the conductor (covered in Section 5.10).

## 5.12 Conclusions

This chapter has studied how musicians within a symphony orchestra may perceive the acoustic conditions provided by a stage enclosure with varying width, height and depth. With regard to perceived conditions the focus has been on what are found most important for the players: the ability to hear all other players clearly, well balanced with sound from one's own instrument and reverberant response from the main auditorium. The perceptual effects that appear highly relevant for these impressions are masking effects, the precedence effect and the cocktail-party effect. The relations between such perceptual effects and characteristics of a stage enclosure are complex and difficult to detect clearly. This chapter has investigated evidence of how the dimensions of the stage enclosure may relate to these three perceptual effects. This has been done taking into account sound source level differences within the orchestra, how the orchestra itself attenuate sound between players and how the players synchronise relative to each other.

Based on the instrument sound source levels, orchestra attenuation effect and how the players synchronise, communication between players across the stage on a flat floor (like between the different string sections) appears most problematic. If introducing a large reflective surface above the orchestra, reflections from all the instruments including those often reported as too loud will be introduced. Reflections compensating for low within-orchestra sound levels will be introduced, but also reflected sound of the loud instruments will be introduced – competing with the compensating reflections. By referring to masking effects, both in level and time, as well as the cocktail-party effect, the introduction of an overhead reflecting surface covering the whole orchestra does not appear to effectively aid the communication within the orchestra. The reflected sound provided by an overhead surface can also result in a reverberant acoustic response at a significant level that can the reverberant response from the main auditorium. On

the contrary, if introducing reflecting surfaces at the sides close to the orchestra (particularly with approximately 2.5–3 m height and tilted top sections), the time arrival and direction of these reflections appear to better aid the ensemble conditions for the players compared to an overhead reflecting surface. Through careful design, the negative effects of overhead reflecting surfaces may be reduced but not fully result in the same perceived conditions compared to side reflecting surfaces. The results regarding location of reflecting surfaces close to the orchestra support the finding from the orchestra collaboration (Chapter 3), that stage enclosures generally described as narrow and high and largely exposed to the main auditorium provide the most beneficial acoustic conditions for the players. With regard to stage depth, a moderate depth appears the best compromise regarding competing sound and providing reflections back to the French horn players.

This chapter has focused on reflecting surfaces at the sides of the string players and above the orchestra in general. To what degree overhead reflectors above the string and/or woodwind section only can replace reflecting surfaces at the sides has not been studied in detail. But such reflecting surfaces can make the stage less exposed to the response from the main auditorium and make sound from one's own instrument too loud. Results regarding conditions for the conductor suggest that reflectors above the string players can make the strings too loud at the conductor's position, while overhead reflectors for the woodwind only may be beneficial.

When referring to what dimensions and characteristics of the stage enclosure that has by others been found beneficial for the conductor and the audience, there are indications of a narrow and high stage enclosure largely exposed to the main auditorium also having several beneficial effects for both the conductor and the audience.



## Chapter 6

# Computer modelling of stage enclosures including a full symphony orchestra

### 6.1 Introduction

When investigating objective acoustic conditions for symphony orchestras in concert hall stages, there will normally be significant differences between the conditions the players experience and what can be measured by use of acoustic test equipment on the stages with no orchestra present. The results from the subjective studies covered in Chapter 3 indicate that musicians' ability to hear each other clearly is a crucial requirement. However objective testing in the same conditions as experienced by players is often difficult due to the absence of an orchestra during physical tests and due to the directivity of instruments. An orchestra significantly attenuates sound passing through it. Most musical instruments within the orchestra are far from omnidirectional at frequencies above 500 Hz, whereas acoustic test equipment for concert halls normally consists of an omnidirectional loudspeaker and microphone.

Carrying out measurements of the objective behaviour on stages with a full symphony orchestra (or equivalent group of people) present, will in most cases be very expensive. Scale modelling and computer modelling are attractive options for investigating objective acoustic conditions on concert hall stages, because the presence of the orchestra can be included. For scale modelling the directivity of the real sound sources on stage will still represent a problem, whereas for computer modelling the directivity of musical instruments can be represented. The obstruction effect of the orchestra is affected by diffraction and screening effects that will be included in a physical scale model, whereas computer models normally have problems representing diffraction effects accurately.



This chapter studies how the obstruction and absorption of sound by the orchestra can be modelled in a computer model, using CATT-Acoustic. Verification of the computer modelling has been done by scale modelling. The following studies within this chapter focus on applying the developed orchestra model to investigate impulse responses within the orchestra under different stage enclosure conditions. The resulting impulse responses are assessed with regard to arrival time and level of ‘compensating’ and ‘competing’ reflections, and build-up of late/reverberant sound within the stage enclosure itself. These factors were in Chapter 5 found to be relevant for perceived ensemble conditions. The acoustic measures  $G$ ,  $G_l$  and  $C_{80}$  are also included as means of indication of sound levels and temporal clarity for the enclosures studied.

For verification of the orchestra model, two different cases have been compared: the sound levels within the orchestra with no stage enclosure present (‘within-orchestra sound levels’), and the early part of impulse responses (0–200 ms) was investigated across the orchestra with a stage enclosure on a generic concert hall stage. The resulting representation of the orchestra in the computer model was used to study how the sound level and impulse responses within the orchestra are affected by having reflecting surfaces above or at the sides of the orchestra. Additionally a set of six different stage enclosure designs have been compared with regard to impulse responses and late sound level,  $G_l$ , within the orchestra. For the six stage designs, the design of the audience part of the hall is kept constant, leaving the stage enclosure design as the only varying architectural element.

The effects of the orchestra on stage and directivity of musical instruments are greatest at high frequencies. The study of sound levels on stage here has concentrated on the frequency range of 1–2 kHz, while studies of impulse responses have been studied at 2 kHz. These octave bands are also within the frequency range Marshall & Meyer (1985) and Gade (1989b) found to be most important for ensemble conditions, and conveniently it is at high frequencies that computer modelling based on ray tracing is likely to be most valid. The results from scale model investigations of sound propagation within a symphony orchestra (Chapter 4) show that wave effects are no longer present at the 1 and 2 kHz octave bands. Results by Zha & Fuchs (2002) and Adelman-Larsen *et al.* (2010) showed that the room acoustic low frequency response is relevant for how the musicians perceive the conditions on stage. This suggests that low frequency acoustic responses may also be relevant for the performers. However, the focus is here mainly effects related to the presence of a symphony orchestra being present on stage: the validity of the model developed for representing a symphony orchestra, build-up of reverberant sound within the stage enclosure, as well as how low within-orchestra sound levels are compensated for by the stage enclosure. The results from the scale modelling (see Chapter 4 for more details) indicate that for the octave bands 63–250 Hz, the orchestra is close to being transparent and the interference effects between the direct sound and the floor reflection largely control measured levels. Studies of low frequency behaviour on stage are therefore not included in this study.

## 6.2 Computer modelling methods

In Section 4.3 it is shown that at low frequencies sound passes through the orchestra (players, instruments and music stands) with little attenuation due to screening and diffraction. At higher frequencies the orchestra provides significant obstructions for the sound propagating across the stage (within the orchestra). The players are typically 0.5 m wide, comparable to the wavelength at 700 Hz. We can therefore expect the transition range between diffraction and obstruction to be at around this frequency. This is confirmed by scale modelling investigations; see Chapter 4 for more details. In the computer model, the sound waves are represented as rays. To mimic diffraction phenomena in the computer model, the surfaces representing the orchestra have been modelled as semi-transparent, being most transparent at low frequencies. The orchestra was modelled as a series of 'benches', see Figure 6.1 for more details. Phase information of the sound waves is omitted in the computer model. Results from scale model investigations of this project (Chapter 4) suggest that the reflections within the orchestra itself contribute to reduce interference effects between the direct sound and the floor reflection, leading to phase information being less relevant for total within-orchestra sound levels.

Transparency is set by a transmission coefficient,  $\tau$ , and defined independently for each octave band in the modelling software used. This transmission coefficient is a property of the surface in addition to the absorption coefficient,  $\alpha$ , and the scattering coefficient (for assigning diffusion),  $s$ . The range of  $\tau$  is 0–1, where  $\tau = 0$  represents no transparency (only reflection or absorption at the surface) and  $\tau = 1$  represents a fully transparent surface (no reflection, only absorption at the surface).

The computer modelling was carried out using CATT-Acoustic version 8.0. According to the CATT-Acoustic User's Manual (CATT-Acoustic, 2008), the direct sound ray in the modelling software used goes deterministically through a maximum of one semitransparent surface and in passing through this surface is attenuated by  $(1 - \alpha) \cdot \tau$ . First order reflections are correspondingly attenuated by  $(1 - \alpha) \cdot (1 - \tau)$ . Second and higher order transmissions (sound going through more than one semi-transparent surface) are random depending on the value of  $\tau$ . Within the orchestra the direct sound will need to pass through more than one transparent surface, so the level of the direct sound will be statistical varying in the modelling software used, due to the way higher order transmissions are modelled. The computer simulation was configured to automatically select the number of rays used and to include surface and edge diffusion.

To test the validity of this orchestra modelling in the modelling software used, comparable conditions were created in both the computer model and a 1:25 scale model. Two different cases were studied: the within-orchestra sound level with a flat floor and no stage enclosure surrounding the orchestra, and impulse responses across the stage for a generic stage enclosure.

## 6.3 Validation of within-orchestra sound levels

In Chapter 4, the sound levels within a symphony orchestra (with no stage enclosure present) were studied using a 1:25 scale model. The results from this scale model investigation have been compared with full scale measurements to yield reasonably good agreement at 500–2000 Hz. For studying the validity of the computer representation of a symphony orchestra, results from the computer modelling were compared to this scale model investigation. Comparable orchestra configuration and transducer positions were used in both models – the sound level within the orchestra was studied along a path across the stage front. The path of most significant obstruction will normally be across the stage sideways at the front part of the stage on a flat floor (no risers), since it is the longest path within the orchestra and there is no change of floor level. This path will typically represent the path between violins and double basses on stage.

In the computer model the orchestra has been modelled in a very simplified manner. It is represented by ‘benches’ placed on stage, in a staggered pattern relative to each other to avoid (as much as possible) free paths with no obstruction within the orchestra. Typically two musicians are represented as one horizontal flat surface (1.5 m long, 0.5 m deep and 0.5 m above the floor) and one vertical flat surface (1.5 m long, 0.6 m high with bottom edge 0.5 m above the floor and 0.25 m behind the horizontal surface). Figure 6.1 shows the stage configuration corresponding with the scale model investigation with these benches on stage to represent the orchestra. By assigning high scattering coefficients to these surfaces, the actual shape and angle of the benches will have little influence on the results. Figure 6.1 also shows the source and receiver area used for investigating sound levels across the stage. The receivers were kept at a minimum distance of approximately 0.5 m from any of the orchestra surfaces, since receivers being very close to a surface can produce misleading results in the modelling software used (according to [CATT-Acoustic \(2008\)](#)).

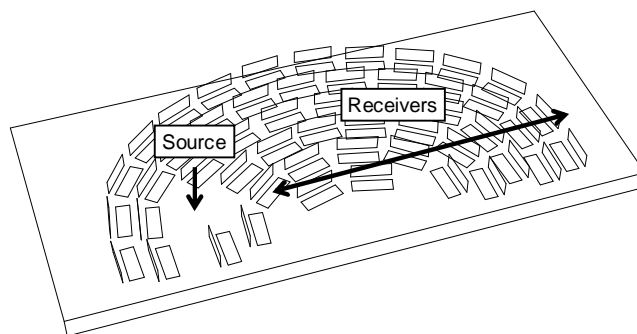


Figure 6.1: Measurement setup in the computer model for measuring the orchestra obstruction effect.

To find the absorption ( $\alpha$ ), scattering ( $s$ ) and transparency ( $\tau$ ) coefficients for these benches, initial values were chosen based on a rough physical understanding of the geometry and absorbing properties of materials within the orchestra, mainly clothes/fabric. The results based on these initial values were compared with the scale model results and several iterations of modifying the coefficients and re-running the computer simulations were repeated till the agreement was sufficiently good. The absorption coefficients were set similar to a fabric absorber. The scattering coefficients were as mentioned initially set high to minimise the effect

of the simplified geometry of the benches. The transparency was initially set to 0.50 at 500 Hz, given that this octave band would roughly represent the transition between transparency and obstruction. The transparency was set to decrease for each of the frequency band above 500 Hz. Table 6.1 shows the final coefficients used for the orchestra surfaces (benches) in the modelling software used. Due to the statistical behaviour of sound propagating through several semi-transparent surfaces in the modelling software used, ten repeated simulations were carried out and average (arithmetic) values were used for the final results.

Table 6.1: Coefficients used in the computer model for the surfaces representing the orchestra.

Parameter	500	1000	2000
Absorption ( $\alpha$ )	0.40	0.65	0.75
Scattering (s)	0.80	0.80	0.80
Transparency ( $\tau$ )	0.70	0.60	0.45

The orchestra screening effect has been studied in terms of a level difference,  $\Delta L$ , between within-orchestra sound levels,  $L_{\text{dfo}}$ , and sound levels on empty stage,  $L_{\text{df,e}}$  ( $\Delta L = L_{\text{dfo}} - L_{\text{df,e}}$ ).  $L_{\text{dfo}}$  is the combined level of direct sound, floor reflection and early reflections within the orchestra.  $L_{\text{df,e}}$  is the analytical unattenuated combined sound level of direct sound and floor reflection based on energy summing (applying the inverse-square law). The effect of the orchestra is presented as the within-orchestra sound level compared to  $L_{\text{df,e}}$  at corresponding distances.

### 6.3.1 Results and discussion

The corresponding results from the computer model for the octave bands 500–2000 Hz are shown in Figure 6.2(a). The shaded areas are defined by the range of results for the ten individual simulations whereas the solid line represents the average (arithmetic) result. Figure 6.2(b) shows the difference of results for  $\Delta L$  between the two models, given as  $\Delta L_{\text{c}} - \Delta L_{\text{s}}$ . We see that the agreement is best for the source-receiver distances 3–5 and 9–15 m. The large deviations 3–5 and at 16 m are most likely caused by the number surfaces obstructing the direct sound being either too low or too high in the computer model, and that significant wave interference effects at short distances are not represented in the computer model. At 16 m distance the direct sound must pass through several semi-transparent surfaces and the standard deviation of resulting levels become high due to the statistical behaviour of higher order transmissions in the computer model used (as seen for the result at 500 Hz). For distances 9–15 m the root-mean-square (RMS) value of the differences between computer and scale model is 1.5, 1.3 and 0.7 dB at 500, 1000 and 2000 Hz respectively. At 1 and 2 kHz values of  $\Delta L$  in the computer model vary within a range of 3 dB at 12–15 m relative to the scale model results.

The results suggest that it is difficult to get good agreement with the scale model results over the complete source-receiver distance range, 3–16 m, due to how the modelling software used treats semi-transparent surfaces. The number of surfaces the direct sound needs to pass through appears to significantly control the sound level and the variations of results between repeated simulations. If the direct sound has to pass through more than three semi-transparent

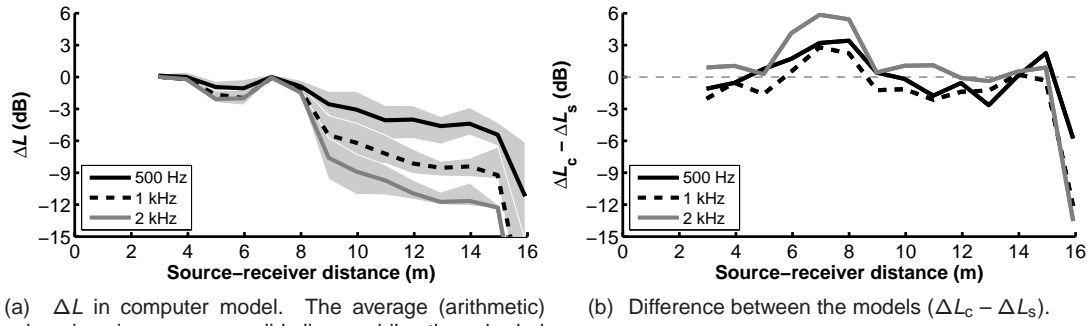


Figure 6.2: Results for  $\Delta L$  in computer model,  $\Delta L_c$ , relative to scale model,  $\Delta L_s$ , at the octave bands 500–2000 Hz.

surfaces, the within-orchestra sound level is apparently underestimated. This suggests that the arrangement and the acoustic properties of the benches must be set to optimise agreement for the source-receiver distances of interest (or a better density of benches may exist which will extend the range a valid source-receiver distances). With a focus on investigating how early reflections can compensate for low within-orchestra sound levels at higher frequencies, investigations for source-receiver distances within 12–15 m will be most relevant and for this range the computer model results have proven sufficiently valid comparing with the scale modelling results.

## 6.4 Validation of early part impulse responses

To study the validity of the computer prediction of the early part of impulse responses on stage, results were compared with scale model measurements in a generic concert hall model. The scale model (1:25 scale) of a generic concert hall contained detachable wall and ceiling panels to vary the scattering properties of these surfaces. For the specific task of comparing impulse responses to the computer model, the stage enclosure was set up with no scattering surfaces and with the orchestra on a flat floor. This made it easier to configure the computer model with acoustic properties corresponding with the scale model.

Figure 6.3 shows the stage in the scale model while Figure 6.4 shows the corresponding computer model. The source and receiver positions were duplicated in the computer model. To find the acoustic properties ( $\alpha$  and  $s$ ) for the surfaces of the scale model, the acoustic properties were varied between repeated simulations without the orchestra present in the computer model, until a reasonable agreement was reached with scale model results. Table 6.2 shows the acoustic properties used in the computer model for the different surfaces in the scale model. The surfaces surrounding the stage will be the dominating surfaces for the early response on stage. The benches on stage were arranged as described in Section 6.3 and it was ensured that the direct sound did not pass through more than three semi-transparent surfaces.

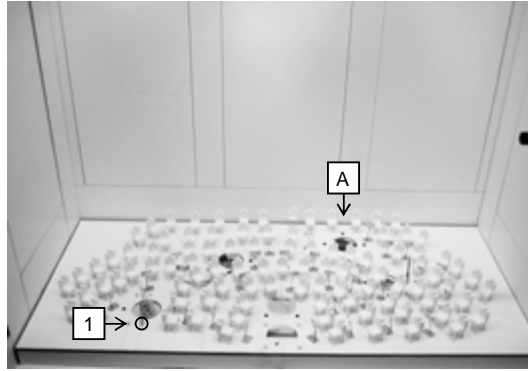


Figure 6.3: Scale model of a generic concert hall stage, scale 1:25. The stage is surrounded by flat surfaces and no risers on stage.

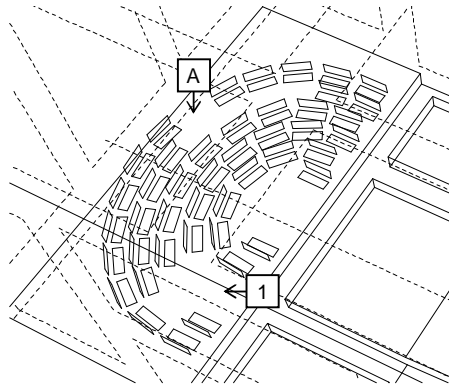


Figure 6.4: The generic concert hall scale model implemented in the computer model.

Table 6.2: Coefficients used in the computer model of the generic concert hall scale model.

Surface	Absorption ( $\alpha$ )		Scattering (s)	
	1 kHz	2 kHz	1 kHz	2 kHz
Flat hard surfaces (stage encl.)	0.04	0.04	0.08	0.08
Diffusing panels (main hall)	0.08	0.08	0.85	0.90
Audience (main hall)	0.87	0.85	0.70	0.75

The resulting impulse responses (within 0–200 ms relative to arrival of the direct sound) have been plotted as normalised sound levels (maximum level = 0 dB) together with an integrated response, mimicking the temporal integration in the human auditory system as used by [Cremer \(1989\)](#). The integrated response was calculated as the convolution between the impulse response squared and an exponentially decaying function (representing the ear integration with a time constant  $\tau_e$ ). The expression for finding the resulting response is shown in Equation (6.1). For the 2 kHz octave band a time constant,  $\tau_e$ , of 10 ms was used.

$$i(t) = h(t)^2 * e^{-t/\tau_e} \quad \text{dB} \quad (6.1)$$

## 6.4.1 Results and discussion

Figure 6.5 shows the resulting responses in the scale model and computer model from source position A to receiver position 1 (source-receiver distance 11.4 m). In general when comparing the impulse responses, there are minor differences to be seen between the two models for individual reflections, but the resulting integrated responses look very similar and the reflection patterns as a whole are similar. This good agreement of integrated responses suggests that such responses can be used to study the effect of different stage enclosures using the computer simulation model. Resulting responses using other source and receiver positions also showed good agreement.

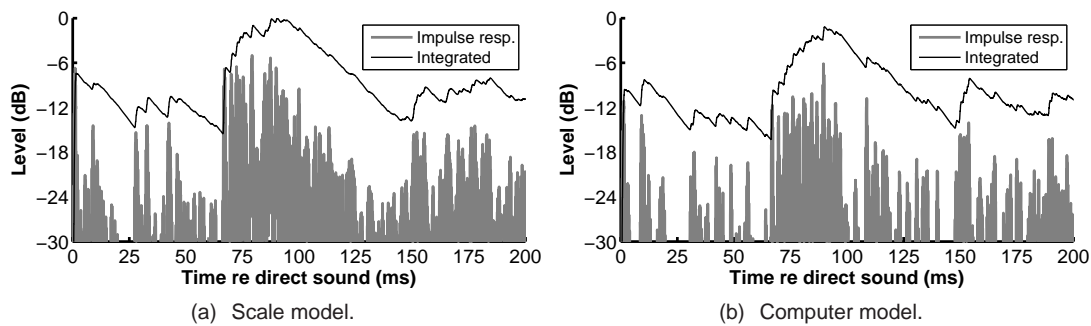


Figure 6.5: Impulse responses (normalised) in scale and computer model at 2 kHz with orchestra present. Integrated response,  $\tau_e = 10$  ms.

The good agreements in both within-orchestra sound levels and impulse responses mean that acoustic responses on stage with orchestra present can be studied in details by the developed representation of a symphony orchestra. The following sections apply the developed model to study (objectively) the effect of the stage enclosure for acoustic responses on stage within the orchestra. The resulting responses are in particular studied across the front part of the stage, compared with responses from the back of the stage towards the front part. From Chapter 5, such comparisons appear relevant for the perceived balance between the different instrument groups.

## 6.5 Comparison of overhead and side reflections

Results from the collaboration with eight professional symphony orchestras (Chapter 3) suggest that hearing across the stage can be difficult for the string section (in the absence of risers), while players at the back of the stage on risers are frequently too loud for the string players (and woodwind and brass players). This assumes a stage configuration where the rear part of the orchestra is on risers only. (With the outmost tiers of the string section on risers as well, the need for compensation for low within-orchestra levels is likely to be to a certain extent reduced.) Based on this we could think in terms of the stage enclosure providing ‘compensating’ early reflection(s) for players far apart who experience low within-orchestra sound levels. The effect of the compensating early reflection(s) depends on the presence of any ‘competing’ direct sound and early reflections from instruments having high within-



orchestra sound level in the first place. Results from Chapters 3 and 5 suggest that surfaces at the sides of the stage are better for providing compensating early reflections compared to overhead surfaces. To further investigate this hypothesis, it will be interesting to study how the location and type of reflecting surface affects the compensation for low within-orchestra sound levels across the stage, and also observe the presence of competing reflections as well as the build-up of a late acoustic response on stage.

To investigate the presence of compensating and competing reflections on stage, computer models of four different simple stage enclosures were created without any auditorium attached:

- Overhead reflector only, flat and solid reflector.
- Overhead reflector only, perforated scattering reflector.
- Side walls only, straight walls.
- Side walls only, tilted top section on walls.

The four different stage enclosures were modelled with the orchestra on risers as shown in Figure 6.6. Details on the four different reflective surfaces used in the models at 1 and 2 kHz are:

- Overhead reflectors: 7 m above stage floor. With flat and solid or flat and perforated scattering surface,  $\alpha = 0.04$ ,  $s = 0.10$  or  $0.70$ ,  $\tau = 0$  or  $0.40$ .
- Straight side walls: 2.5 m high,  $\alpha = 0.04$ ,  $s = 0.10$ .
- Tilted side walls: Tilted from height of 1.5 to 2.5 m at  $19^\circ$  vertical angle,  $\alpha = 0.04$ ,  $s = 0.10$ .

A tilt of  $19^\circ$  for the top tilted side walls allows a geometrical reflection via both tilted panels for players on opposite sides of the stage as illustrated in Figure 6.7. The tilt of side walls will be most significant at higher frequencies, typically from the 1 kHz octave band and above. The side walls will reflect 1<sup>st</sup> order reflection between the players as well (as indicated in Figure 6.7).

Total sound levels,  $G$ , were studied sideways on the front half of the stage to study how low within-orchestra sound levels are compensated for, particularly for players far apart. (For impulse responses regarding compensating reflections, see Section 6.6). To get an impression of potential competing reflections and higher order reflections, impulse responses were calculated for a source at the back of stage and a receiver at the front of the stage. To obtain within-orchestra sound levels and see the effect of the compensation provided by the reflecting surface(s), the condition with no reflecting surfaces was modelled. The results from this modelling exercise were also used to see how the presence of higher order reflections and a reverberant field are affected by the locations and types of reflective surface close to the orchestra. To judge the differences between these four configurations, the total sound level  $G$  (Strength) for players sitting across the stage was evaluated to see how low within-orchestra sound levels are being compensated for (to improve the cross-communication on stage).



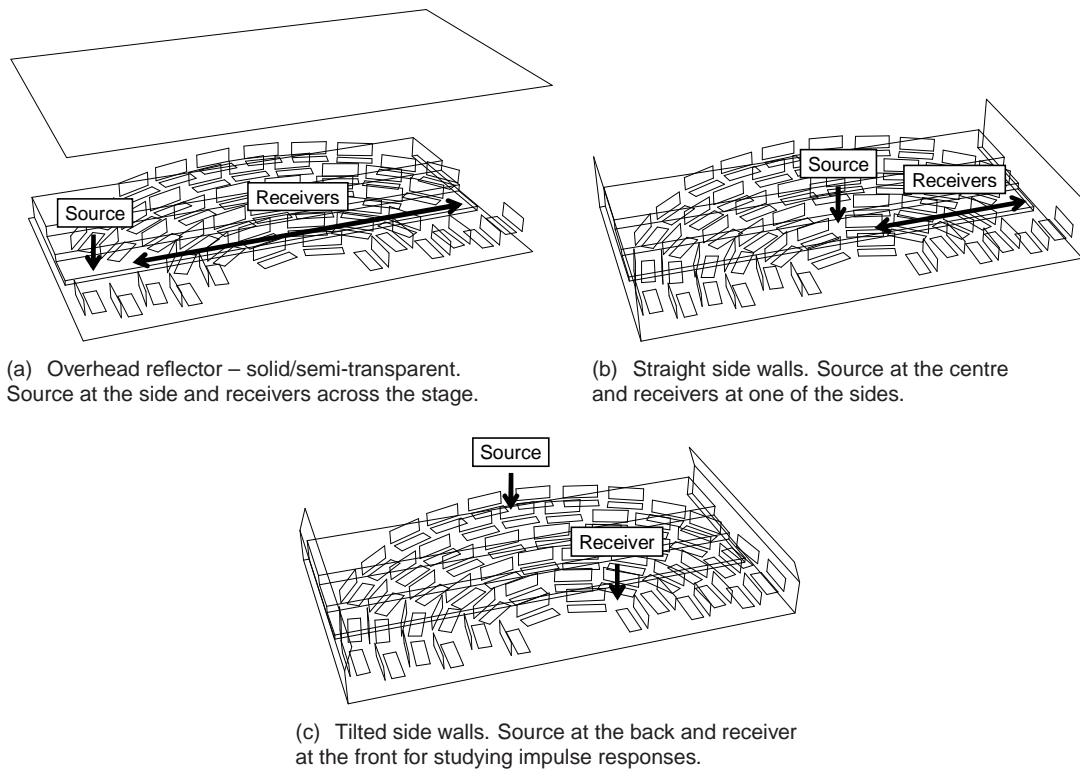


Figure 6.6: Models for comparing overhead and side reflecting surfaces. The three different source and receiver configurations (used for all the four different test configurations) are shown for each of the figures.

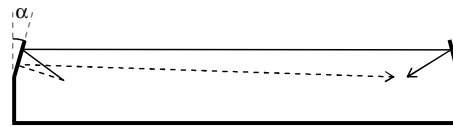


Figure 6.7: 1<sup>st</sup> and 2<sup>nd</sup> order reflections set up by tilted side walls.

The configuration for investigating  $G$  across the stage with the source at the side of the stage is shown in Figure 6.6(a). Simulations were also done for the source at the middle of the stage as shown in Figure 6.6(b). The impulse response was calculated from a player at the back centre of stage to a player 7 m in front of that player as shown in Figure 6.6(c), typically from the percussion/brass section to the string section. An omnidirectional source was here used for general considerations. Simulations were also done without orchestra present to compare responses with and without orchestra present. As for the impulse responses in Section 6.4, the impulse responses were temporally integrated to mimic the temporal integration being part of the human auditory system. The integrated responses can also represent temporal masking curves (as described by Zwicker & Zwicker (1991)). Here a time constant,  $\tau_e$ , of 4 ms was used, since the notes played by the instruments at the back of the stage (typically percussion or brass) will often have a short rise time and often shorter duration compared to for instance strings.

The modelling process was similar to the investigations in Section 6.3: the receiver positions being very close to the surfaces representing the orchestra (the benches) were omitted, and simulation of each configuration was repeated ten times to obtain average (arithmetic) values

of  $G$ . The simulation of the impulse responses were also repeated, but only one single simulation is presented in the results.

### 6.5.1 Results for sound level across the stage

Figure 6.8 shows results for  $G$  between players across the stage with the initial within-orchestra sound level and the corresponding levels for the four different configurations. Figure 6.8(a) is for the source on the side, while 6.8(b) is for the source at the middle of the stage. For players not far from each other, 1–6 m apart, sound levels are almost unchanged with the four different configurations due to dominating direct sound level. For a source-receiver distance of 8 m the within-orchestra level is low. This could be caused by problems similar to those experienced in Section 6.3 in this distance range. For players more than 8 m apart, the introduction of reflecting surfaces around the orchestra starts to result in significant compensation for low within-orchestra sound levels. For source-receiver distances above 12 m there are clear differences between the four configurations: the straight side walls and the scattering perforated ceiling show the least compensation, while the solid reflective ceiling and the tilted side walls contribute to raise the sound level the most for players far apart.

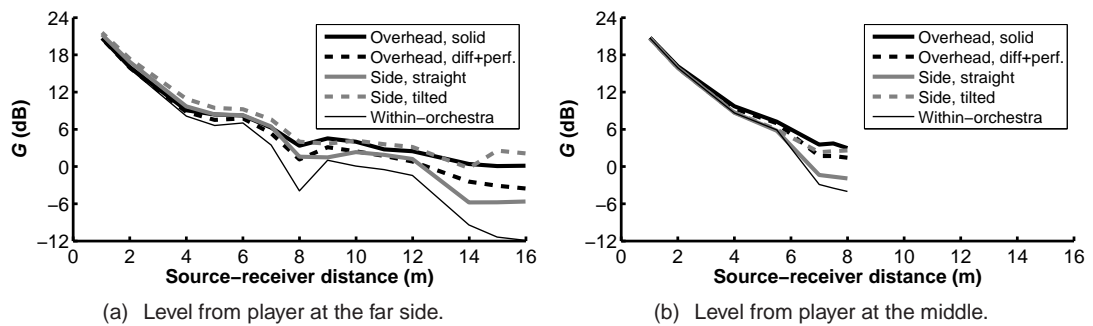


Figure 6.8: Results for  $G$  across the stage, average value 1–2 kHz.

For players on opposite sides of the stage (16 m apart), the variation in levels vary approximately 8 dB for the four different configurations. The tilted side walls configuration results in the highest compensation for players being 15–16 m apart, about 2 dB higher than the solid overhead reflector. For a player at the middle of the stage the differences are less significant, though the straight side walls configuration shows significantly lower compensation for the sound level from players 6–8 m to the side – the compensation relative to the within-orchestra level is only about 2 dB.

The standard deviation,  $\sigma$ , of  $G$  for the ten repeated simulations was below 1.5 dB for all source-receiver distances and the four different configurations involved. The whole simulation process was also repeated several times (also by varying source and receiver positions), giving consistent results.

## 6.5.2 Results for impulse responses

Figure 6.9 shows the resulting impulse responses from the back of the stage to the front of the stage. The presented responses are with the source at the back of the stage and receiver at front of the stage, as illustrated in Figure 6.6(c). The motivation for such a configuration is to study the presence of competing reflections from instruments at the back of the stage (percussion and brass) as well as the build-up of reverberant sound. The dB-scale in Figure 6.9 is fixed (not normalised) for each plot and with the time delay seen relative to the arrival of the direct sound. With the players at the back on risers, the direct sound will be unattenuated in the model used. In reality we may expect there to be some obstructions, but not as significant compared to players on the flat floor.

From the resulting responses in Figures 6.9(a) and 6.9(b), there appear to be many free paths for sound reflecting between the floor and the overhead reflecting surfaces. These free paths result in high levels of competing reflections (arriving 15–30 ms after the direct sound), as well as a reverberant field building up within the stage enclosure itself. Higher order reflections from the side walls in Figures 6.9(c) and 6.9(d) appear to be more attenuated, in particular with the tilted side walls, where no reflections at a significantly high level arrive 50 ms after the arrival of the direct sound. Due to the unobstructed direct sound, the total sound level for this situation show only small differences between the four configurations:  $G$  averaged within the octave bands 1 and 2 kHz is 6.2, 4.9, 4.2 and 3.2 dB respectively for Figures 6.9(a)–6.9(d). This represents a variation within 3.0 dB. For configurations without orchestra present, the corresponding levels are 7.8, 7.1, 6.7 and 6.0 dB – a variation within 1.8 dB.

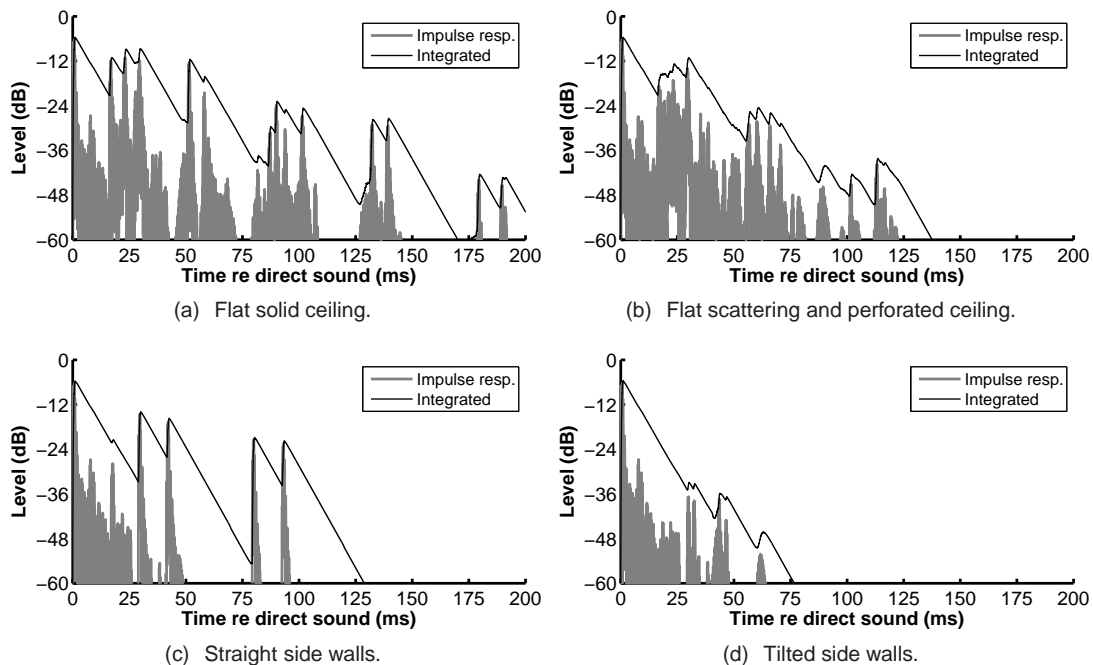


Figure 6.9: Impulse responses at 2 kHz from player at the back to player at front of the stage with musicians present. Integrated response,  $\tau_e = 4$  ms.

### 6.5.3 Discussion

The results are here discussed with respect to compensation of low within-orchestra levels for players sideways on stage, the presence of competing reflections from instruments at the back of the stage, and finally the build-up of reverberant sound.

In terms of total sound levels, the four different stage arrangements of reflecting surfaces close to the orchestra result in the most significant differences for players being far apart. If not providing a free path for the reflection surface(s) introduced or making the introduced reflecting surface scattering and/or perforated could lead to a lack of compensation for low within-orchestra levels at high frequencies. The tilted side walls resulted in the highest compensation, while the straight side walls resulted in the lowest compensation. This could be caused by the angling of the top sections – configured to set up both 1<sup>st</sup> and 2<sup>nd</sup> reflections as indicated in Figure 6.7. The presence of the straight side walls may be useful at low frequencies (below 500 Hz) even if the compensation effect at higher frequencies appears to be low – for instance enhancing the low frequencies for the double bass as discussed in Chapter 5. From a player at the back of the stage the sound level will be lowest for tilted side walls. With tilted side walls, resulting  $G$  is 3 dB lower compared to a solid overhead reflector.

These differences of total sound level may be seen as small, but the 8 dB difference in the level compensation that was found for players on opposite sides of the stage is likely to be significant relating to perceptual masking mechanisms. Such raised levels could contribute to improved level balance between instruments at the sides versus instruments at a shorter distance or at the back of the stage.

The simulated impulse responses from the back of the stage (omnidirectional source) indicate that the overhead reflectors will introduce more competing reflections than the side walls. Additionally the overhead reflectors appear to set up a reverberant sound field within the stage enclosure itself. This could be significant for temporal masking effects and clarity, and to what degree the players are able to hear the reverberant sound from the main auditorium as discussed in Chapter 5. Adding diffusion to the overhead reflector lowers the build-up of sound, but still the level of reflected sound is much higher compared to the tilted side walls configuration. The differences seen from the impulse responses, particularly how reverberant sound builds up on stage, may be more significant than what can be seen for the total sound level,  $G$ .

When comparing total sound level with orchestra present or absent with the sound source at the back of the stage, the differences seen between the four different configurations are reduced with the orchestra absent. This suggests it will be more difficult to discriminate between different acoustic conditions on stage without the orchestra being present.

## 6.6 Comparison of six different stage enclosure designs

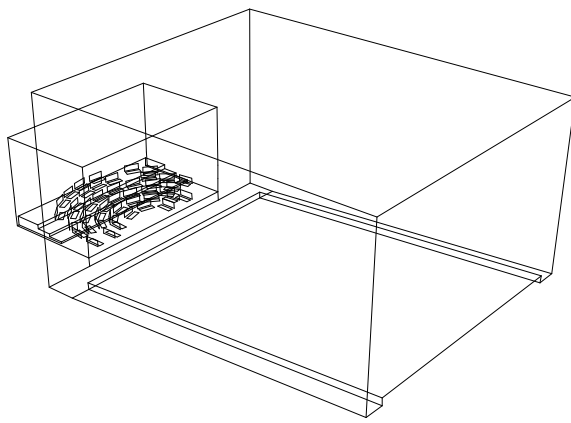
The previous section only studied one or two reflecting surfaces containing the stage enclosure, either above the orchestra or at the sides. For real stage enclosures there will be an interplay between the ceiling/overhead reflector, back and side walls. To further study how the stage enclosure could affect the presence of compensating and competing reflections for the balance between different players within the orchestra, six different stage enclosures were created with the same audience section of the hall.

The decision on which designs to test was based on the findings above with regard to differences between narrow side walls and low ceiling, as well as choosing some typical designs seen in concert halls globally and halls that were covered in detail in this project. The stage designs will not be directly comparable to real halls, due to the simplifications of the geometries, but will represent some general types of stage enclosure that are common for real purpose-built concert halls. The designs can be divided into two major categories: narrow and wide stage enclosures. Other generic design variations were stage ceiling height and to which degree the stage area is exposed to the rest of the hall. The design of the auditorium part of the model was chosen to be a simple shoe-box hall design with raked seating and the walls and ceiling very scattering to create a diffuse reverberant sound returning back to the stage from the audience section (contributing to reduce the influence of the architectural design of the main hall as well). Figure 6.10 shows the six different stages studied (with the narrow stage enclosures on the left column and the wide stage enclosure on the right column).

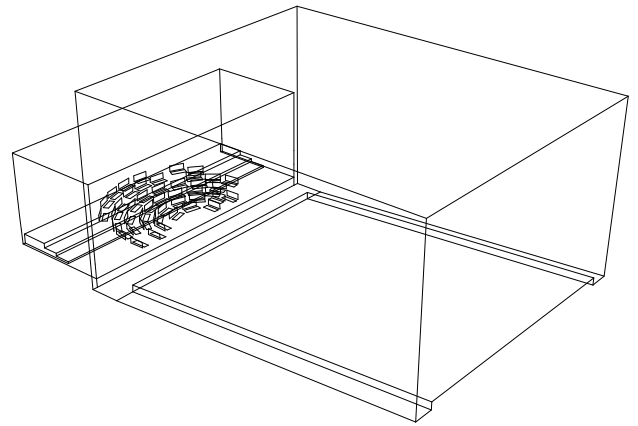
The acoustic conditions with these six different enclosures have been assessed similar to the method in Section 6.5: The presence of compensating reflections for string players sitting far apart across the front half of the stage – and the presence of competing reflections from instruments towards the back, experienced among string players at the side. These conditions were studied through simulated impulse responses across the stage. For an indication of the level of reverberant sound level on stage and temporal clarity of sound, the acoustic measures  $C_{80}$  and  $G_I$  were also studied.

Details on the three narrow stage enclosures:

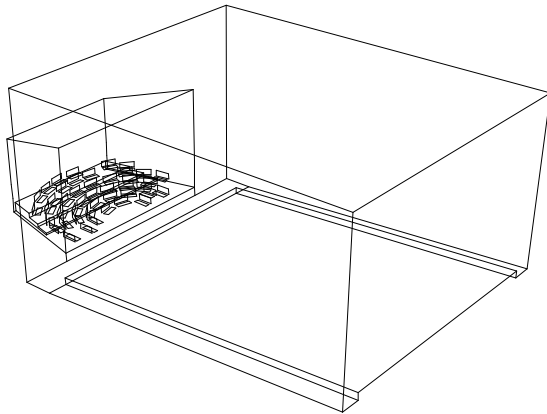
- Narrow and low (NL): 18 m wide stage at front, flat horizontal ceiling at 9.3 m above stage floor, enclosed stage with non-scattering surfaces.
- Narrow and low with splayed walls and ceiling (NLS): 19° splayed side walls, 18 m wide at front, ceiling angled 14° with average height 9.3 m, enclosed stage with non-scattering surfaces.
- Narrow and high (NH): 18 m wide stage at front, ceiling 18 m above stage, non-scattering walls 3 m high surrounding the orchestra with top section tilted 19° vertically, back wall on stage not tilted, exposed stage with scattering surfaces.



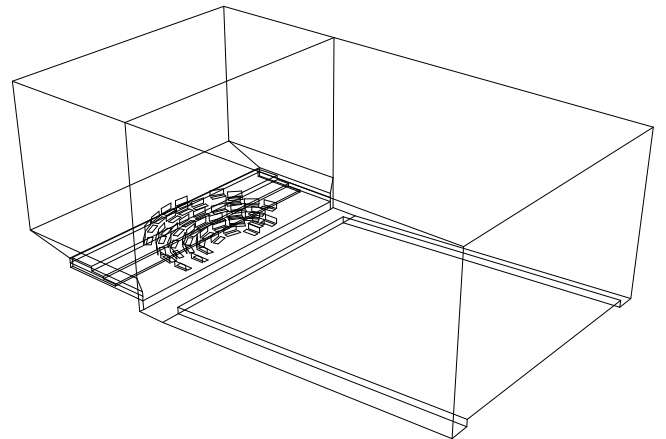
(a) Narrow and low (NL).



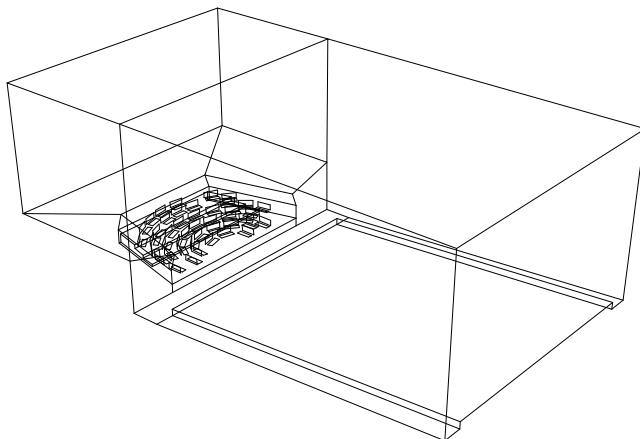
(b) Wide and low (WL).



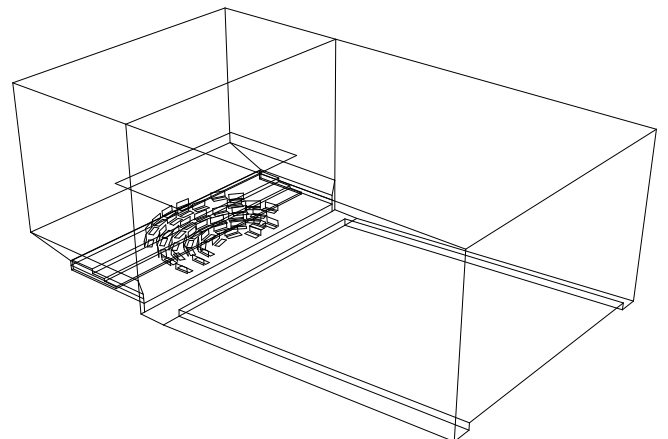
(c) Narrow and low, splayed walls & ceiling (NLS).



(d) Wide and high, exposed (WH).



(e) Narrow and high, exposed (NH).



(f) Wide and high, exposed, overhead reflector (WHR).

Figure 6.10: Models of six different stage enclosures attached to same generic audience section.

#### Details on the three wide stage enclosures:

- Wide and low (WL): 27 m wide stage, stage ceiling 9.3 m high, enclosed stage with non-scattering surfaces.
- Wide and high (WH): 27 m wide stage, ceiling 18 m high, exposed stage with scattering surfaces.
- Wide and high with reflector (WHR): 27 m wide stage, ceiling 18 m high with reflector at 7 m, exposed stage with scattering surfaces. Partially open, 40 % open, overhead reflector.

Acoustic characteristics of surfaces used in the models at 1–2 kHz:

- Non-scattering stage walls & ceiling:  $\alpha = 0.10$ ,  $s = 0.10$ .
- Scattering stage walls & ceiling:  $\alpha = 0.10$ ,  $s = 0.70$ .
- Partially open overhead reflector:  $\alpha = 0.04$ ,  $s = 0.70$ ,  $\tau = 0.40$ .
- Hall walls & ceiling:  $\alpha = 0.20$ ,  $s = 0.99$ .
- Audience:  $\alpha = 0.80$ ,  $s = 0.70$ .

All the stages had a depth of 10 m. The orchestra was of fixed size determined by the smallest stage. The stage areas varied as follows: 155 m<sup>2</sup> for NLS and NH, 180 m<sup>2</sup> for NL and 269 m<sup>2</sup> for the wide stages. All six stages studied included risers, covering the back half of the stage. The string section was always on the flat floor. The risers had three different levels with heights above the stage floor of 0.2, 0.5 and 0.95 m respectively. The two lowest riser levels were 1.6 m deep, while the highest level was 2.6 m deep. The hall section for the audience was set at 35 m long, 29 m wide, 18 m high at front and 16 m high at the back (3.5° rake for the audience section).

Two different source positions were used: one among the violins 1.5 m from stage front and 6 m off the centre line (stage right), and one among the brass section 8 m from the stage front and 4 m off the centre line (stage left). A set of four receivers were selected, typically among the double bass section in an area 0.5–1.5 m from the stage front and 6–8 m off the centre line (stage left), as shown in Figure 6.11. This resulting in source-receiver distance within 12–14 m from violin to double bass, and within 7–8 m from trumpet to double bass. For the violin source an omnidirectional source was used, since the directivity of a violin will vary considerably between each note played. A trumpet was used as a source at the back of the stage since loud brass instruments may more frequently be a problem compared to the percussion instruments, and the directivity of a trumpet appears be consistent for all notes played as described by [Otondo & Rindel \(2004\)](#). The directivity of the trumpet source was set as described in a PTB report ([PTB, 2008](#)). The trumpet was not pointed straight towards the double bass, but towards a point about 2 m from the centre line and along the front of the stage. The sound power level of the trumpet was set 14 dB higher than the violin based on results from [Meyer \(2004\)](#). Such individual sound power levels will not be relevant in real orchestra since several instruments play together as groups, but for simplicity individual levels were used for this investigation. For studying the stage enclosure's effect on conditions for the audience, conditions at five receiver positions within the audience area (source-receiver distance within 10–20 m) were also studied.

For these six stage enclosures the early impulse responses (0–200 ms) at 2 kHz were calculated for the two paths across the orchestra (as indicated in Figure 6.11). Responses at both 1 and 2 kHz were calculated, but only those at 2 kHz are presented, since the results for the two different octave bands are very similar, and the differences between the different enclosures are clearer at 2 kHz. The impulse responses were studied for the four receivers, but only one of these positions is presented in the results: a position 7 m to the side and 0.75 m from the stage front. The source-receiver distance was 13 m from first violin to double



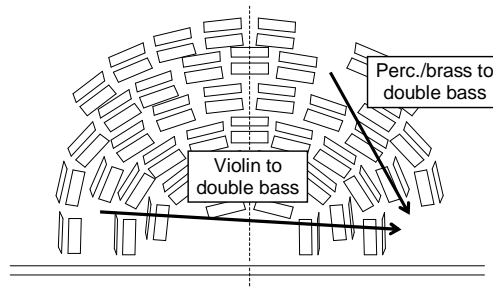


Figure 6.11: Direct sound paths on the six stages studied.

bass across the stage, while 7.7 m from trumpet to double bass using this receiver position. The impulse responses are plotted similar to responses plotted in Section 6.5, with a time constant  $\tau_s = 10$  ms from the violin and  $\tau_s = 4$  ms from the trumpet (as a rough representation of temporal integration and masking effects).

Impulse responses and the acoustic measure  $G_l$  (based on  $G$  and  $C_{80}$ ) and  $C_{80}$  have been obtained with and without an orchestra on stage. Results from the collaboration with eight professional symphony orchestras (Chapter 3) indicate that values of  $G_l$  and  $C_{80}$  on stage are relevant for the player's overall impression of acoustic conditions. Regarding the impulse responses the results presented with orchestra present include both direct sound path studies, while only the results along the path from violin to double bass are presented without the orchestra. For  $G_l$  and  $C_{80}$  results are presented for orchestra both present and absent for studying the effect of not including a full orchestra on stage.

### 6.6.1 Resulting impulse responses, violin to double bass

The left column of Figure 6.12 shows impulse responses at 2 kHz from violin to double bass for the narrow stages studied. The levels presented are only for relative comparisons. The most significant differences between these three stage designs are that the narrow and high stage enclosure shows the highest reflection levels 0–40 ms, while lower levels beyond 50 ms. The first compensation reflection for low within-orchestra levels arrives at 12 ms for the narrow and high (NH) stage enclosure, while the first significant compensating reflection arrives at about 25 ms for the narrow and low stages (NL and NLS). The narrow and low stage with parallel side walls and flat ceiling show the highest levels beyond 75 ms – apparently the splay of side walls and ceiling help reducing the reflection levels beyond 75 ms. Within 0–50 ms the narrow and low stages show comparable responses.

The right column of Figure 6.12 shows the corresponding impulse responses for the wide stage enclosures studied. The wide and low stages show the highest levels of reflections – especially the integrated level which reach a peak at about 75 ms. By making the stage ceiling absorbing these reflections are significantly reduced (integrated level within 25–75 ms reduced approximately 12 dB), confirming that the low ceiling is the major contributor to the high accumulated levels within 50–100 ms. The wide and high stage show low levels as would be expected – in the time region 0–50 ms there are a just a few reflections. The first



compensating reflection arrives at about 25 ms for the wide and low enclosure (WL), whereas for the wide and high stage (WH) such a reflection does not arrive before after about 40 ms. Adding the reflector above the stage (WHR) reduces this delay to approximately 15 ms, but the level of this reflection is not high due to the scattering and transparent properties of the partially open overhead reflector.

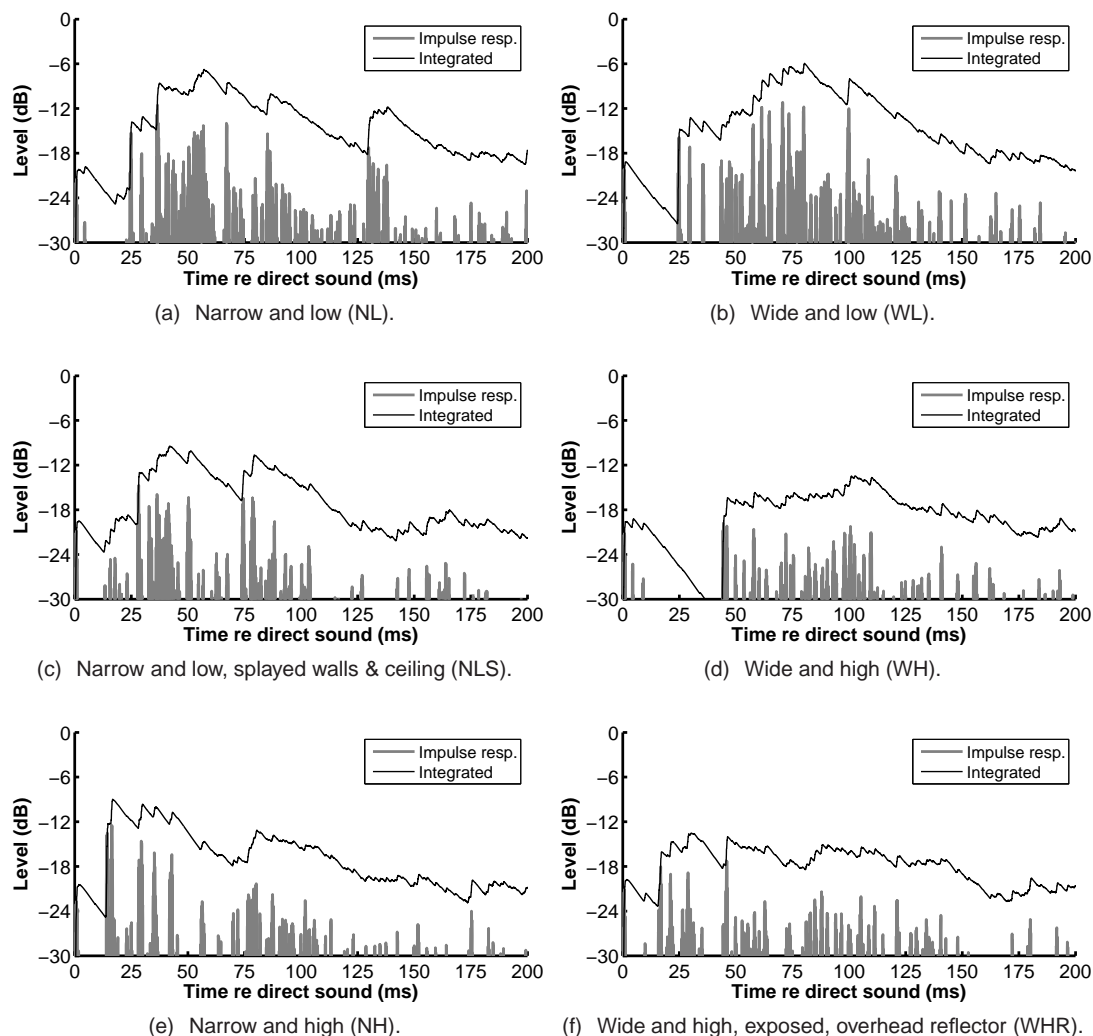


Figure 6.12: Impulse responses at 2 kHz from violin to double bass. Integrated response,  $\tau_e = 10$  ms.

## 6.6.2 Resulting impulse responses, trumpet to double bass

Figure 6.13 shows corresponding impulse responses from trumpet to double bass for the six different stage enclosures. When compared with the responses across the strings, the most obvious differences are the much higher direct (within-orchestra) sound level and lower level of late reflections. For the narrow enclosures (left column in Figure 6.13) the levels within 0–10 ms are very comparable, but beyond 10 ms the narrow and high enclosure shows the lowest levels. For the two narrow and low stages, the first competing reflection arrives at about 25 ms. The reflections arriving within 25–50 ms result in a build-up of integrated sound up to 50 ms. For the narrow and high enclosures there are no significant competing reflections seen within 25–70 ms. There will be a reflection off the side wall, but due to the short time delay

relative to the direct sound this reflection does not contribute to raise the integrated response. As for the response from violin to double bass, the effect of the splayed side walls and ceiling is reduced reflection levels, in this case beyond 50 ms.

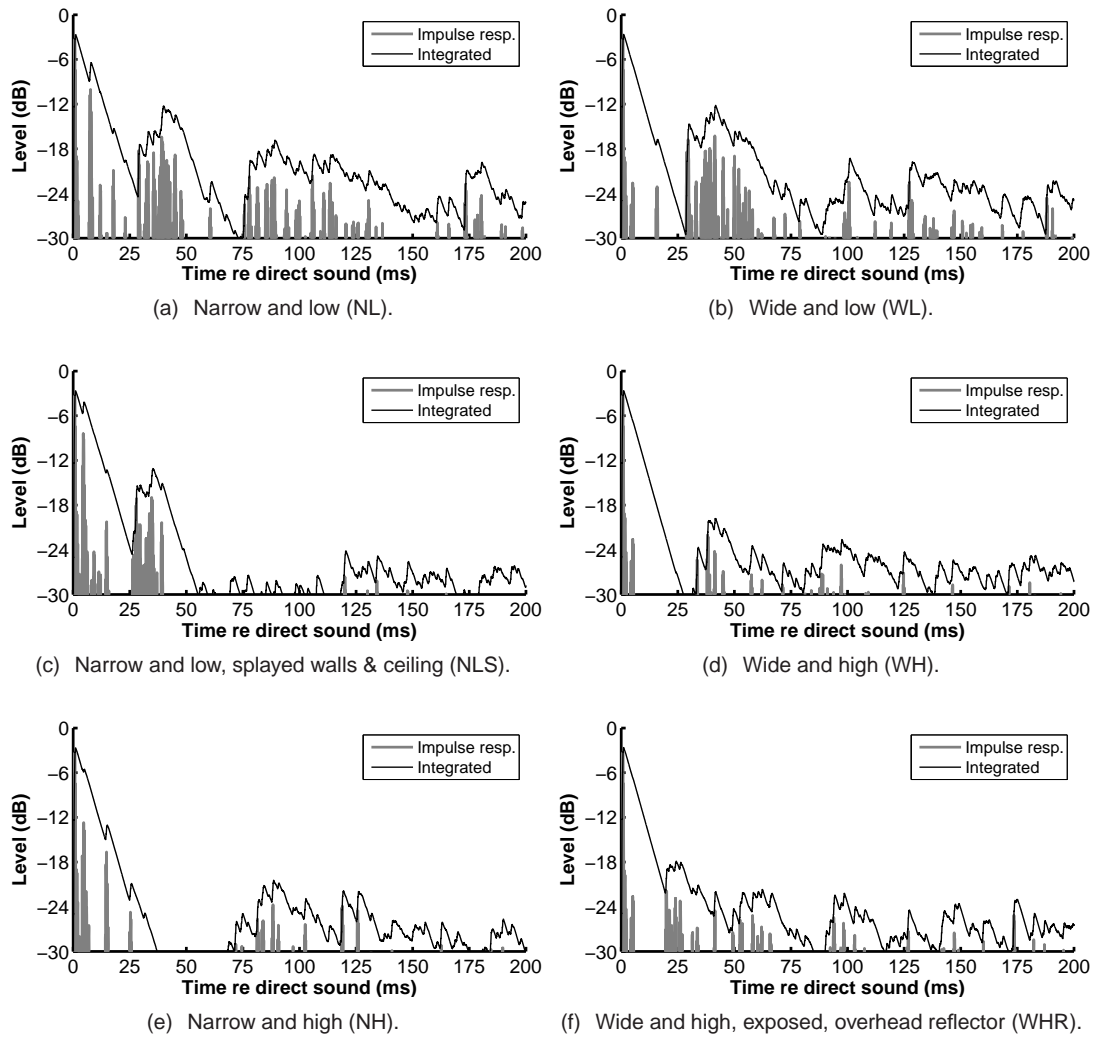


Figure 6.13: Impulse responses at 2 kHz from trumpet to double bass. Integrated response,  $\tau_e = 4$  ms.

When studying the wide stage enclosures in Figure 6.13 (right column), the wide enclosures show virtually the same level 0–10 ms as the narrow stages, while the wide and low enclosure shows the highest levels 25–60 ms. The first competing reflection arrives at about 25 ms for the wide and low stage, with several reflections arriving 25–60 ms. This is very similar to the narrow and low stages, and is most likely caused by the low ceiling and multiple reflections between the ceiling and floor, and cornice reflections at the wall and ceiling. The wide and high enclosures show levels similar to the narrow and high enclosure, but the levels of reflections within 25–70 ms are considerably lower for the narrow and high enclosure.

### 6.6.3 Resulting impulse responses without orchestra, violin to double bass

Figure 6.14 shows the corresponding impulse responses with orchestra absent, from violin to double bass. With the orchestra absent the most significant difference is the considerably higher levels within 0–10 ms compared to the orchestra present (shown in Figure 6.12). In addition, the overall shapes of the integrated curves for the six different enclosures are more comparable with the orchestra absent.

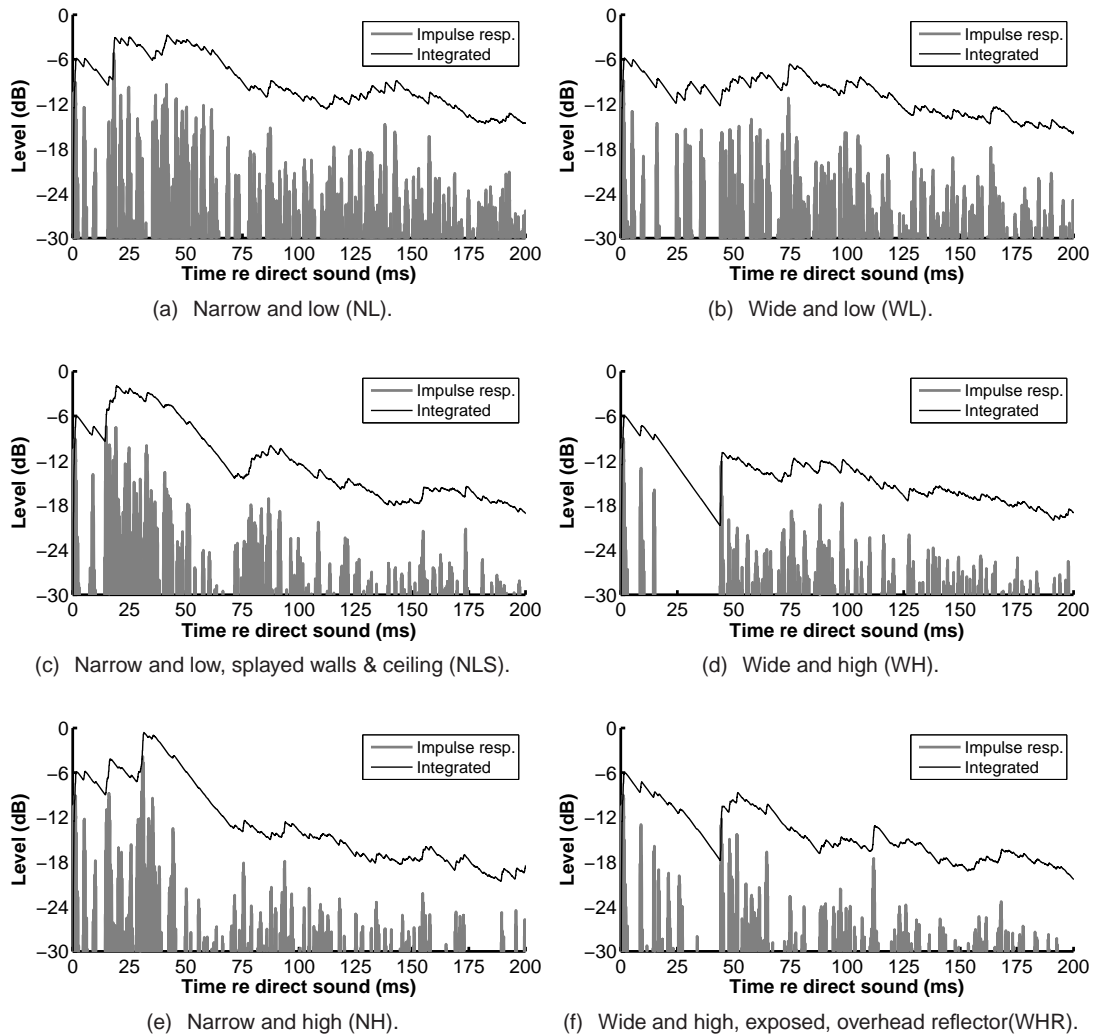


Figure 6.14: Impulse responses at 2 kHz from violin to double bass, with orchestra absent. Integrated response,  $\tau_e = 10$  ms.

## 6.6.4 Results for acoustic measures

Figure 6.15 shows the calculated level of late sound,  $G_l$ , on stage for the six different stage enclosures. From Figure 6.15(a) we see that stage enclosures NL and WL contribute to raise the late sound level on stage compared to the four other enclosures. Values of  $G_l$  in the audience area are consistently approximately 1 dB, with NLS showing the highest level. When comparing  $G_l$  on empty stage compared to in the audience area, NLS, NH, WHR and WH show an increase of approximately 3 dB on stage, whereas NL and WL show an increase of 6–7 dB.

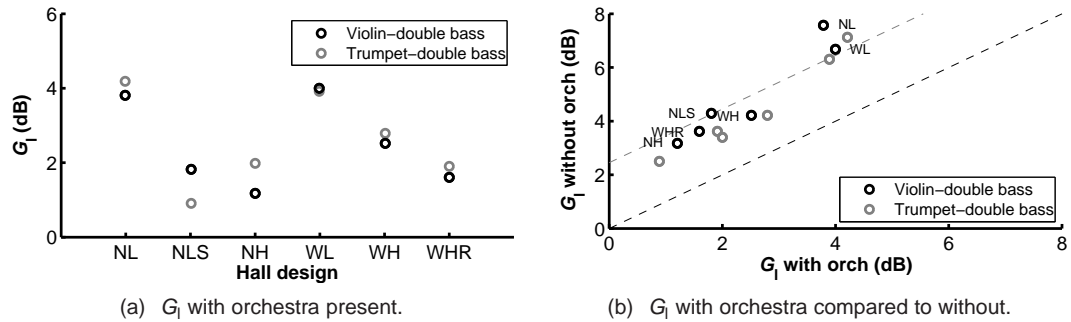


Figure 6.15: Late sound level,  $G_l$ , on stage between violin–double bass and trumpet–double bass. Only violin–double bass results are labelled with enclosure design.

From violin to double bass  $G_l$  is on average approximately 2.5 dB higher with an orchestra absent (indicated with the grey dashed line in Figure 6.15(b)). But there are significant changes between the different stage enclosures. The most exposed stages, NH, WH, WHR, show reductions of approximately 2 dB, while the most enclosed stages NL and WL show reductions of 3–4 dB. From trumpet to double bass corresponding shift of  $G_l$  values is 1.9 dB higher without the orchestra on stage.

Values of  $C_{80}$  for the six different configurations show a variation of 7.2 dB. The narrow enclosures show the highest values (1.0, 2.3 and 1.9 dB for NL, NLS and WH respectively) while the wide enclosures show the lowest values (–1.2, –4.9 and –2.1 dB for WL, WH and WHS respectively). With the orchestra absent, the variation of  $C_{80}$  between the different stage enclosures is reduced to 5.7 dB. On an empty stage the narrow enclosures show values of  $C_{80}$  ranging from 1.7 to 6.5 dB, while the wide enclosures show a range of 0.5 to 1.9 dB. This shows that the changes with configurations are consistently larger with an orchestra on stage.

## 6.6.5 Discussion

For the narrow stage enclosures we see from resulting impulse responses across the stage (violin to double bass) that the levels of reflections arriving within 10–50 ms are significantly higher compared to the wide stage enclosures. On the contrary, late reflections arriving after 150 ms are comparable for all the six stage enclosures, except from NL and WL showing higher levels. These differences are also seen from the acoustic measures, where the narrow enclosures have higher values of  $C_{80}$  and the enclosures with a low reflective ceiling (NL

and WL) show higher values of  $G_i$ . This suggests that a narrow and high stage enclosure will provide the best temporal clarity without a build-up of reverberant sound within the stage enclosure itself.

Adding the reflector (WLS) on the wide and high enclosure introduces significantly more reflections within 10–40 ms, but the levels are not as high as for the narrow and high. The most significant effect of adding the reflector is that values of  $C_{80}$  are increased. These results agree well with findings in Chapter 3, where the players commented on improved clarity with introduction of overhead reflecting surfaces. These results would suggest that the narrow enclosures will give better compensation for low within-orchestra sound levels across the stage, and a lack of narrow side walls cannot be fully compensated for by an overhead reflector. For the narrow enclosures, the enclosure NH shows the smallest delay of the first compensating reflection across the stage. Low enclosures lead to higher levels of late/reverberant sound on stage, while splaying the side walls and ceiling, and vertically tilting the side walls help reducing levels of late reflections. The results indicate that such conditions help reducing sound levels generally on stage and allow the late/reverberant sound from the main auditorium being audible. By keeping the late/reverberant sound level low within the stage enclosure the acoustic response from the main auditorium will not be perceptually masked, enabling the players to have an impression of ‘projection’ as discussed in Chapter 5. These observations also suggest that a narrow and high enclosure provides the most beneficial conditions.

For resulting impulse responses from the back of the stage (trumpet to double bass), the narrow and low (NL and NLS) and the wide and low enclosure show the highest level of reflections within 25–75 ms (and beyond 75 ms as well). The narrow and high enclosure (NH) shows the lowest levels within 25–75 ms. This would suggest that low stage enclosures will lead to the highest levels of competing reflections.

The differences seen between resulting impulse response may be quantifiable in terms of time arrival of compensating and competing reflections or similar. The objective measure *EMDT* proposed by Dammerud & Barron (2007) (the early-to-mid decay time of forward integrated time response) may be more subjectively relevant if based on responses with an orchestra present on stage.

For results with orchestra absent, the variations of results are in general reduced. This suggests that differences in acoustic conditions between different enclosures will be less apparent if investigating without a full symphony orchestra present (similar to results in Section 6.5).  $G_i$  was in Chapter 3 found to be relevant for assessing the impression of acoustic support (‘bloom’) from the auditorium. Investigating  $G_i$  on stage and in the audience area appears relevant for assessing the level of the late acoustic response provided by the main auditorium and the stage enclosure, as well as to what degree the stage is acoustically coupled to the main auditorium (how exposed the stage is to the main auditorium acoustically). The results from this study suggest that having a stage with a high ceiling, both the side walls and ceiling splayed or an exposed stage contribute to avoid raising the late sound level on stage. For the hall models studied  $G_i$  was approximately 1 dB within the front half of the audience area. This is in the lower range compared to what was found to be a preferred range in

Chapter 3, indicating that the stage enclosure's effect on  $G_i$  on stage is somehow exaggerated for this study.

The results from this study agree well with expected acoustic conditions, based on knowing the effect of the orchestra, stage dimensions and amount of diffusion, as investigated in Chapters 4 and 5. These investigations showed that compensating reflections are needed and that such reflections should appear from the sides with small delay to maximise temporal clarity and minimise negative masking effects.

## 6.7 Conclusions

From comparisons with corresponding scale model investigations, a valid way to represent a full symphony orchestra on stage in computer models has been developed. It appears crucial for the validity that the density of surfaces on stage is optimal for the source-receiver distances studied. With other types of computer modelling software compared to the particular one used for this study, slightly different solutions may be necessary. Results with the orchestra included in the models show more significant differences between the different stage enclosures, compared to modelling with an empty stage.

A set of different locations of reflecting surfaces, surface properties and stage enclosures were studied with orchestra present. The overall goal was to study how low within-orchestra sound levels are compensated for by the reflecting surfaces introduced, as well as build-up of reverberant sound/late acoustic response on stage. This was studied at the frequency range 1–2 kHz. A reflection back to the orchestra contributing to compensate for low within-orchestra sound levels has been called a compensating reflection, while a reflection contributing to raise the sound levels unnecessarily has been called a competing reflection. Some of the main findings from these studies follows here.

Providing unobstructed reflections from surfaces close to the orchestra at the side appears most beneficial. Under such conditions, low within-orchestra sound levels are compensated for with minimum delay (relative to the direct sound), without introducing significant competing reflections or later arriving higher order reflections (late/reverberant sound). The alternative of placing a solid reflecting surface above the orchestra instead of at the sides shows comparable results in terms of the combined sound level of the compensating reflections and the within-orchestra sound level. But such a reflecting surface appears to create competing reflections at a higher level as well as a reverberant sound field on the stage itself. Making the overhead reflecting surface scattering and/or partially open contribute to reduce the late sound level on stage (reducing  $G_i$  and increasing  $C_{80}$ ). But by introducing scattering and/or openings, the level of the compensating reflections will be reduced. Regarding overall sound levels on stage, a high ceiling and splayed surfaces are found to contribute to lower the average value of  $G_i$  on stage. These results agree well with results from the orchestra collaboration as well as the analytical studies of the relevance of the location of reflecting surfaces close to the orchestra (Chapters 3 and 5).

The details of resulting impulse responses from the computer models (including the orchestra) have been found very instructive. Results with orchestra present show more significant differences between different stage enclosure designs, compared to results for an empty stage. The resulting impulse responses across the stage can be used to study both how low within-orchestra sound levels are compensated for, the presence of competing and reverberant sound provided by the stage enclosure. Some criteria to time arrivals, the levels of the early reflections or forward integrated levels or curves appear possible to develop.



## Chapter 7

# Acoustic measures for assessing acoustic conditions on stage

### 7.1 Introduction

Normally stage acoustic conditions are investigated by use of an omnidirectional loudspeaker and an omnidirectional microphone to obtain monophonic room impulse responses. The method for obtaining room impulse responses are described in ISO 3382:1997. Based on measured responses, acoustic measures can be calculated (like for instance  $ST_{\text{early}}$ ). For the most valid results, the acoustic conditions assessed should be as close as possible to relevant acoustic conditions. If not, the relevance of obtained acoustic measures is likely to be low when comparing to subjective impressions of the acoustic space assessed. For acoustic conditions within the audience area, the audience seats normally have acoustic properties close to those of a seated audience. This leads ideally to small differences in acoustic conditions within the audience area for an empty compared to a fully occupied hall. On stage, there will be a significant difference in acoustic conditions with a full symphony orchestra, compared to an empty stage, as demonstrated in Chapter 4. For this reason, [Halmrast \(2000\)](#) has proposed measuring the room impulse response on stage with a full symphony orchestra present. Such investigations will often be expensive – most studies of stage acoustic conditions by others have been carried out without an orchestra present.

In this chapter, the consequences of measuring acoustic conditions on stage without an orchestra (or equivalent group of people and/or objects) present are studied. Results from Chapter 4 indicate that the effect of a symphony orchestra on acoustic conditions on stage is highly significant at octave bands above 500 Hz, while not significant below 500 Hz. The effect of omitting the orchestra on stage is investigated in this chapter by scale model investigations of a generic concert hall stage. Values of a set of acoustic measures within the 500–2000 Hz, and impulse responses at 2 kHz are compared with and without a model orchestra on stage under eight different stage conditions. How the source-receiver distance used will affect the reliability and correspond with conditions experienced by the players are also studied.

To what degree objective measures correspond with subjective characteristics of stage acoustic conditions was studied in Chapter 3, where the objective acoustic measures  $T$  and  $G_i$  were included (as well as five architectural measures). In Chapter 8, such relations between objective measures and subjective characteristics are further studied. The results from these studies are combined to assess which acoustic measures (based on omnidirectional responses) appear physically valid, reliable and subjectively significant. The potential use of directional dependent room impulse response methods is also discussed.

## 7.2 Effects of an orchestra on stage measurements

For getting an impression of how the acoustic conditions on stage are affected by the presence of a symphony orchestra on stage, a series of impulse response measurements were carried out on stage in a generic concert hall scale model with a model orchestra present and absent. For more information about the scale modelling system used, see Chapter 4. The generic concert hall scale model was a shoe-box shaped concert hall with a stage enclosure having detachable panels along the walls and ceiling. The stage enclosure was 22 m wide, 17 m high and 10 m deep. The detachable panels enabled four different stage enclosures to be configured with the same overall shape, but with the degree of acoustic diffusion varying: non-scattering walls and ceiling within the stage enclosure, scattering side and back walls only, scattering ceiling only, and scattering side and back walls as well as ceiling. Additionally a riser system was designed for the stage. This resulted in eight different stage conditions. The main scope for the study was to investigate to which degree the change of acoustic responses were consistent with and without a full symphony orchestra present, for these eight different configurations.

Figure 7.1(a) shows the stage in the scale model for one of the eight stage configurations: with the orchestra on a flat floor and flat (non-scattering) walls. Figure 7.1(b) shows the configuration with orchestra present on risers and scattering walls. For each configuration, eight measurements were done with the orchestra absent: four measurements from source position A to receiver positions 1–4, and four measurements from source position B to the receiver positions 5–8. The source and receiver positions are indicated in Figure 7.1(b). Then the same set of measurements was repeated with the orchestra present. The source-receiver distances varied within 10–12 m for source position A (receivers 1–4), and within 6–12 m for source position B (receivers 5–8). The average source-receiver distance was 10 m.

### 7.2.1 Changes of impulse responses

For viewing the room impulse responses, the responses were plotted within 0–200 ms (relative to arrival of the direct sound) versus level (dB) normalised to the direct sound level without the orchestra present. The impulse responses are studied for the 2 kHz octave band since the effect of the orchestra on stage is found highly significant at this octave band (see Chapter 3), and much information on transient sounds is contained at such high frequencies.

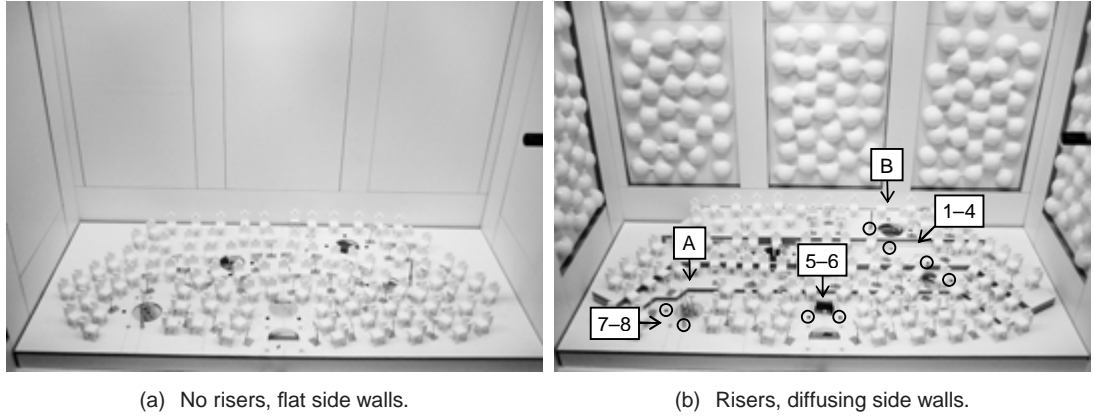


Figure 7.1: Scale model of a generic concert hall stage, scale 1:25, showing two of the stage configurations with orchestra present on stage.

Additionally, an integrated response was calculated, mimicking the temporal integration by the human auditory system as used by [Cremer \(1989\)](#). The integrated response is calculated as the convolution of the measured impulse response squared and an exponentially decaying function (representing the ear integration with a time constant  $\tau_e$ ). The expression for finding the resulting response is shown in Equation (7.1). For the 2 kHz octave band a time constant  $\tau_e$  of 10 ms was used.

$$i(t) = h(t)^2 * e^{-t/\tau_e} \quad \text{dB} \quad (7.1)$$

## 7.2.2 Results and discussion for measured impulse responses

Figure 7.2 shows the results for measured impulse responses from source position A to receiver position 4 (source-receiver distance of 12.2 m) with a non-diffusing and diffusing stage enclosure, without risers. The top responses (a) and (b) are without and with musicians for a non-scattering stage enclosure, while (c) and (d) are corresponding responses with walls and ceiling scattering. When comparing the responses without and with orchestra, we see that the sound level is considerably lowered within 0–50 ms (relative to the arrival of the direct sound) with the orchestra present. From the measured impulse responses we see that the direct sound level drops about 18 dB at 2 kHz. This agrees well with results from the scale model investigations of how the orchestra obstructs the direct sound level and immediate early reflections (within the orchestra itself) on the stage (Chapter 4). According to results from Chapter 4, the direct sound level measured across the stage with orchestra on stage at 12 m distance is typically 14–17 dB lower at 2 kHz compared to levels on an empty stage. Beyond 100 ms, the responses look similar without and with orchestra, but the integrated level is generally lowered by about 3 dB with the orchestra present.

Within 10–50 ms, the specular reflections appear to be significantly lowered with both a non-scattering and a scattering enclosure. These specular reflections come from the side and back walls, which are significantly obstructed/attenuated with the orchestra present. A lot of the diffuse reflections appear to be less obstructed with the orchestra present, leading to the

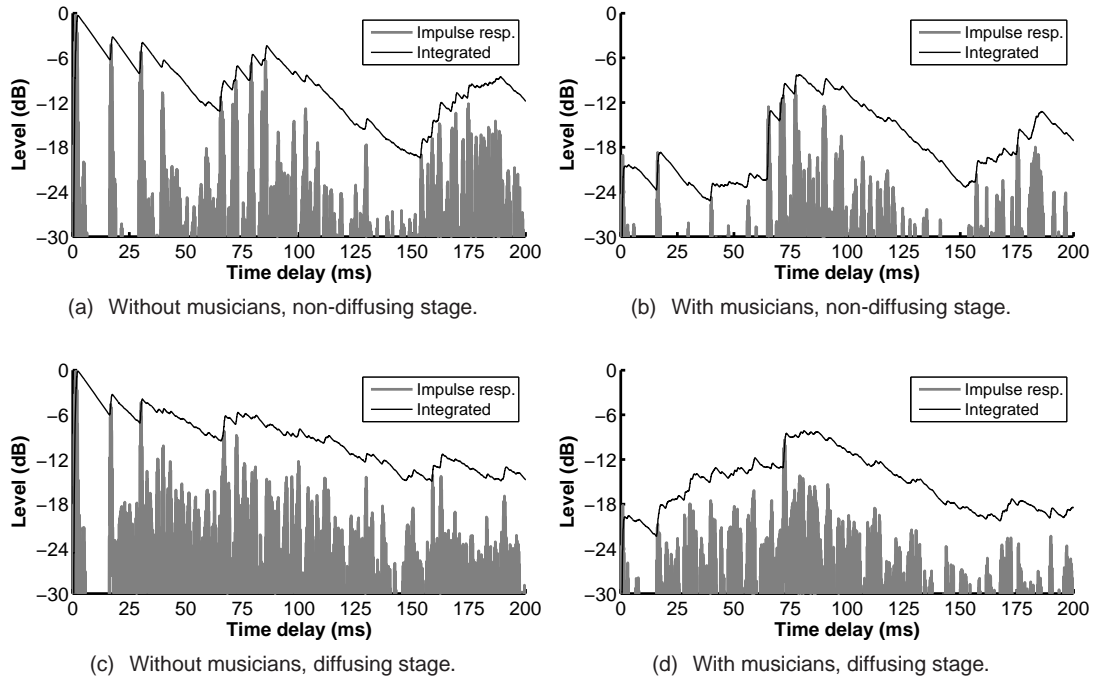


Figure 7.2: Impulse responses at 2 kHz in scale model with orchestra absent (top) and present (bottom). From source position A to receiver position 4.

diffuse reflections being dominant within 10–50 ms. In this stage enclosure the side walls are straight. If sections of the walls were angled vertically or for instance with balcony overhangs on stage, non-obstructed paths would exist for specular reflections from the sides or back of the stage. From this we can conclude that because of the architectural details (like for instance straight or tilted side walls) it will be difficult to predict responses with the orchestra present, based on measured responses on an empty stage – particularly within 0–50 ms.

### 7.2.3 Changes of acoustic measures

From the measured monophonic omnidirectional impulse responses the following stage acoustic measures were included:  $ST_{\text{early}}$  and  $ST_{\text{late}}$  as proposed by Gade (1989b).  $ST_{\text{total}}$  was not included since it was from 40 individual stage measurements (see Section 7.3) found to correlate highly with  $ST_{\text{early}}$  ( $r=0.96$ , significant at the 1 % level). The acoustic measures reverberation time ( $T_{30}$ ), early decay time (EDT) and temporal clarity ( $C_{80}$ ) were also included even though they were originally designed for assessing acoustic conditions within the audience area. These measures were calculated according to ISO 3382:1997. Based on calculated  $C_{80}$  and  $G$ , early and late Strength,  $G_e$  and  $G_l$ , were also derived according to Equations 7.2 and 7.3.  $G$  was found by comparing measured levels to a reference microphone at 1 m distance from the source (see Chapter 4 for more details). In addition,  $G_{7-50}$  was calculated based on  $G$  and calculated temporal energy ratios, comparable to  $G_e$  and  $G_l$ .  $G_e$  will be comparable to  $G_{0-50}$ , used by Skålevik (2007) for investigating the effect of an overhead reflector on stage, while  $G_{7-50}$  will correspond to the quantity  $LQ_{7-40}$  as proposed by van den Braak & van Luxemburg (2008).

$$G_e = G_{0-80} = 10 \cdot \log_{10} \left( \frac{10^{C_{80}/10} \cdot 10^{G/10}}{1 + 10^{C_{80}/10}} \right) \quad \text{dB} \quad (7.2)$$

$$G_l = G_{80-\infty} = 10 \cdot \log_{10} \left( \frac{10^{G/10}}{1 + 10^{C_{80}/10}} \right) \quad \text{dB} \quad (7.3)$$

The values of the listed acoustic measures were found as average (arithmetical) value within the three octave bands 500–2000 Hz. This frequency range was in Gade (1989b) found most relevant for assessing ensemble conditions on stage. Results from all the eight source positions were included in average values, except for the  $ST$  measures. For the  $ST$  measures, the response from the reference microphone at 1 m distance from the source was used. The acoustic measures were calculated using WinMLS 2004 and MATLAB R2006a.

## 7.2.4 Results and discussion for acoustic measures

In general the variations of the acoustic measures are significant between the different enclosure properties, but the differences are more significant with the orchestra present. This agrees well with the results from Chapter 6.

Figure 7.3 shows how values of the acoustic measures with orchestra absent correspond to values with orchestra present. The results are split up in results with and without risers on stage. For studying the relationship of values without and with orchestra, 1<sup>st</sup> order linear regression analysis was carried out on the results. The resulting regression lines included in Figure 7.3 indicate the average change of values when adding the orchestra on stage. For consistent reductions, the regression line should be close to parallel with the black diagonal dashed line. This will indicate a constant reduction independent of properties of the stage enclosure and riser system.

From Figure 7.3 we see that the introduction of the orchestra leads to a reduction of values for all the acoustic measures, except for values of  $ST_{\text{early}}$  becoming slightly higher for one of the configurations. The acoustic measures  $ST_{\text{early}}$ ,  $ST_{\text{late}}$ ,  $G_l$  and  $C_{80}$  are closest to having both regression lines parallel to the diagonal line. Reductions of  $G$  are most consistent, indicated by the high correlation between values without and with orchestra ( $r$  above 0.98 with and without risers). For  $G_e$ ,  $G_{7-50}$ ,  $T$  and  $EDT$  the regression lines are far from being parallel to the diagonal line. The highest reductions are found for the non-scattering enclosure. If ignoring the results with a non-scattering enclosure (the right-most points in Figure 7.3(g)) for  $T_{30}$ , the regression lines become close to parallel with risers present (indicated by the extra dashed line in Figure 7.3(g)). The effect of risers is most significant on  $G_e$  and least significant on  $G_l$ .

Table 7.1 shows the average reduction of the acoustic measures when adding the orchestra, based on results from the linear regression analysis. Only reductions being close to constant with the four different stage configurations are listed. For  $ST_{\text{early}}$  the reduction is less consistent with risers present, while the reduction of  $G_e$  is only close to being constant with risers. For

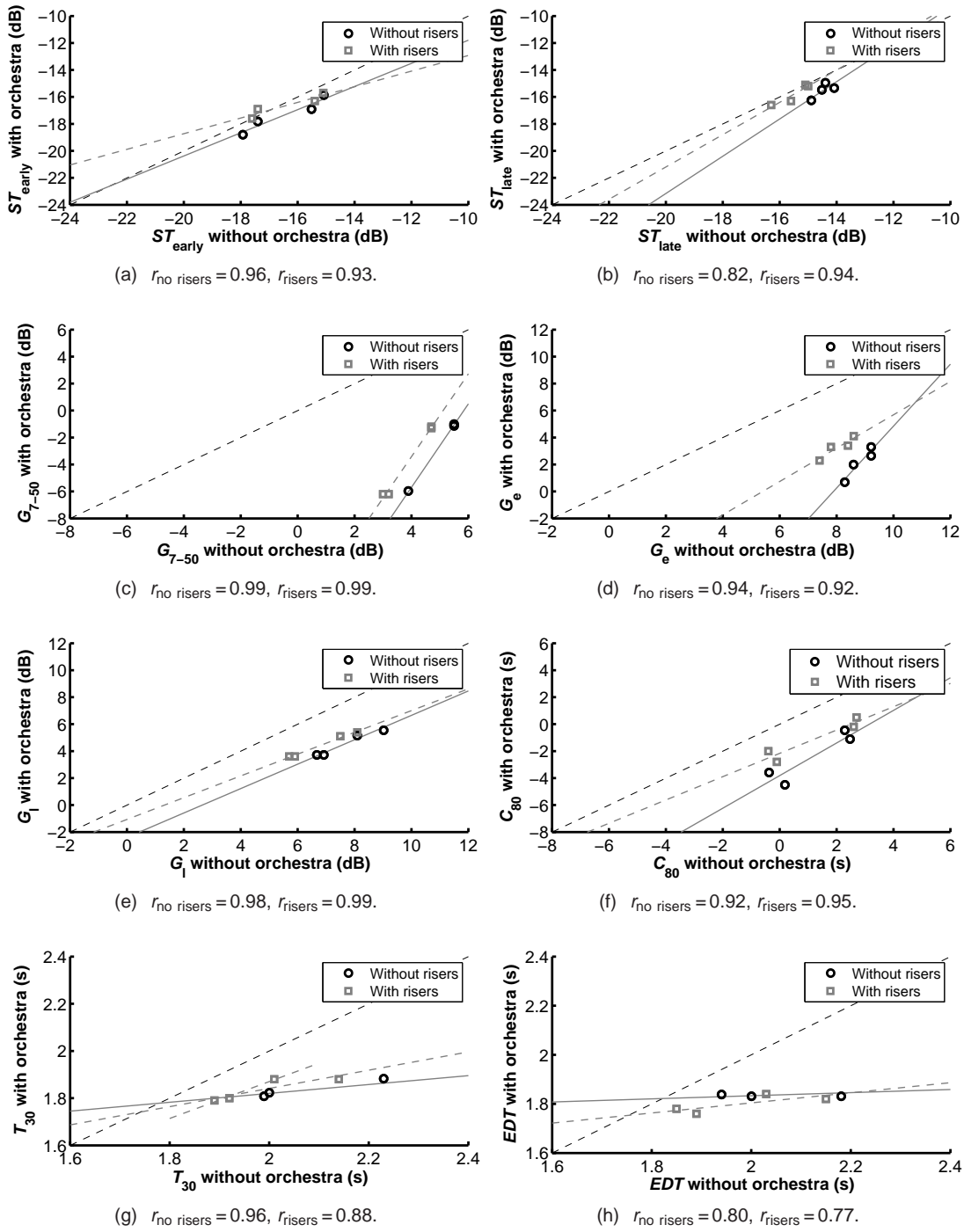


Figure 7.3: Relation of acoustic measures with and without an orchestra on stage. Linear regression curves added for the two data sets.

$T_{30}$  the non-scattering stage configuration is excluded for a close to constant reduction with risers present.

From these results we can conclude that the acoustic measures relating to the late acoustic response,  $G_I$  and  $ST_{\text{late}}$ , are reduced most consistently when the orchestra is introduced under different stage and enclosure conditions. The moderate width and large height of the actual stage enclosure suggest that the stage will be highly exposed to the main auditorium (acoustically coupled to the main auditorium to a high degree), leading to the late acoustic

Table 7.1: The average reduction of acoustical measures with and without risers on stage. Only sufficiently constant reductions are included. \*For  $T_{30}$  the non-scattering configuration must be excluded for sufficiently constant reductions.

Staging	$ST_{\text{early}}$	$ST_{\text{late}}$	$G_{7-50}$	$G_e$	$G_l$	$C_{80}$	$T_{30}$	$EDT$
Without risers	0.9	1.0	–	–	3.1	3.6	–	–
With risers	–	0.3	–	4.8	2.4	2.4	0.11*	–

response on stage being significantly controlled by the late acoustic response of the main auditorium. This suggests that changes to the stage enclosure will have less influence on  $G_l$  on stage for this particular hall compared to halls with other stage enclosure dimensions and shapes. Results from the computer model investigations (Chapter 6) showed that the reduction of  $G_l$  when introducing the orchestra varied within approximately 2 dB with different enclosure designs. For stages moderately or highly exposed  $G_l$  was consistently reduced approximately 2 dB in the computer models which is in good agreement with the results from Table 7.1. The reduction of  $G_l$  with the orchestra present is likely to be mainly controlled by the overall absorption and diffusion introduced by the orchestra. Measurements of the absorption of the scale model musician show reasonably good agreement with full-scale measurements (see Chapter 4 for more details).

The acoustic measures  $G_e$  and  $G_{7-50}$  are based on early energy levels and show less constant reductions, particularly if the direct sound is included (for  $G_e$ ). The presence of risers significantly change the reduction of the direct sound levels with orchestra present.  $ST_{\text{early}}$  is based on the total level within 20–100 ms of measured impulse response. By excluding the first 20 ms of the impulse response and integrating up to 100 ms (at 1 m distance), the reductions are close to being constant, but the presence of risers is still significant. The small reduction of  $ST_{\text{early}}$  when adding the orchestra with risers (0.9 dB) agrees well with results by O’Keefe (1995). The effect of risers on  $ST_{\text{early}}$  values could be associated with the reference level used for the  $ST$  measures. The reference level used for  $ST_{\text{early}}$  and  $ST_{\text{late}}$  is based on the total sound level within 0–10 ms of the measured impulse response, which is sensitive to presence of risers. This will contribute to a lowered reliability of the  $ST$  measures, as further discussed in Section 7.7.

The reductions of  $C_{80}$  are also close to being constant, but depends more heavily on the presence of risers compared to  $G_l$ .  $C_{80}$  is dependent on  $G_e$  which is found to not change consistently with the presence of risers and orchestra. The relatively constant reduction of  $C_{80}$  can be a result of the particular stage enclosure studied and not have general validity. The less consistent reduction of  $T_{30}$  appears to have been exaggerated in the scale model hall due to the non-scattering stage enclosure configuration having an extreme low level of diffusion. If ignoring this non-diffusing configurations, values of  $T_{30}$  are close to having a constant reduction with risers present.

The reductions of  $ST_{\text{late}}$  and  $G_l$  are both found to be close to constant, but the reductions of  $ST_{\text{late}}$  are generally lower. This appears to relate to the differences in time limits and source-receiver distances (100–1000 versus 80– $\infty$  ms and 1 versus 6–12 m). The correlation coefficients,  $r$ , between results with and without orchestra present are highest for  $G_l$ ;  $r$  varies within 0.98–0.99 for  $G_l$ , while within 0.82–0.94 for  $ST_{\text{late}}$ . The lower correlation coefficients



found for  $ST_{late}$  appears to relate to the reference level used for  $ST_{late}$ , like for  $ST_{early}$  discussed above. This leads to a preference for  $G_l$  instead of  $ST_{late}$  for assessing the level of the late acoustic response on stage. To summarise, the following measures appear to be sufficiently physically valid and reliable for assessing acoustic conditions without an orchestra present:  $G_l$  and potentially also  $C_{80}$ . Given the stage has risers  $G_e$  may also be valid, as well as  $T_{30}$  for stage enclosure having some amount of diffusion.

### 7.2.5 The effect of chairs on stage

Measuring with chairs on stage is an alternative to measuring on an fully empty stage (as was the condition in the scale model investigations). For the study of eight performance spaces, six of the stages were measured both fully empty and with chairs. These measurements are described in further detail in Section 7.3. When comparing results with and without chairs, only minor differences were seen: the reduction of  $T_{30}$  values were within 0.01–0.07 s. Values of  $G_l$  and  $ST_{late}$  were reduced less than 0.5 dB.  $ST_{early}$  was measured 0.9 dB lower with chairs at one of the stages, while being within 0.5 dB for the three other halls. The results for reduction of  $ST_{early}$  agree well with findings by O'Keefe (1995). The differences found without and with chairs are considerably smaller than the differences seen without and with a full orchestra present, suggesting that the use of chairs cannot serve as an acceptable substitute for a full orchestra. But the use of chairs contributes to the conditions being closer to what the players' experience, as further studied in Section 7.4.

## 7.3 Acoustic measures collected from eight stages

Acoustic conditions on stage and in the audience area in eight existing performance spaces were investigated for this project, consisting of two proscenium stage theatres and six purpose-built concert halls or multipurpose venues. These investigations were carried out with an unoccupied hall and stage (with and without orchestra chairs). The subjective impressions of these eight performance spaces were also investigated; see Chapter 8 for more details. Figure 8.1 shows photographs taken in these eight performance spaces.

Measurements of acoustic room impulse responses were carried out on stage and in the audience area in these eight venues. A dodecahedron loudspeaker (diameter 0.33 m) was used, along with H//H S500D power amplifier and computer software with an audio interface (WinMLS 2004 with Duran Audio D-Audio, swept-sine technique). See Section 7.4 for more details on the loudspeaker used. On stage an omnidirectional microphone (BSWA 1/2 inch) was used. For the audience area a variable directivity pattern microphone (AKG C414 EB) was used to measure with both an omnidirectional and figure-of-eight directivity pattern. Calculations of the acoustical measures based on the measured impulse responses were done in WinMLS 2004 and MATLAB R2006a.

Figure 7.4 shows the source positions used on stage with coordinates for the positions seen relative to the centre line ( $x$ ) and stage front ( $y$ ). At each position impulse responses were



measured with the microphone 1 m from the source and with the microphone at the four other source positions. This resulted in 25 measurements on the stage: 5 measurements with the microphone 1 m from the source and 20 measurements across the stage with a source-receiver distance varying from 2.8 to 9.0 m. The distribution of source-receiver distances was as follows: five at 1, three within 2.8–3, seven within 4–5, six within 6–7, and four within 8–9 m distance. Measurements with the microphone 1 m from the source were done with the microphone at the stage right side of the source (facing the audience) and the loudspeaker had the same rotation relative to the microphone for all measurements at 1 m distance (for achieving the highest reliability of measured  $ST$ ). For the other measurements across the stage, the source rotation was kept fixed (in the position set for the measurement 1 m from the source). Both the loudspeaker and the microphone were set 1.0 m above the stage floor. The measurements on stage were carried out with chairs present, the number of chairs varied within 47–80. On six of the stages (denoted as BC, BP, CD, EU, PG and WP in Chapter 8) measurements were also carried out on a fully empty stage.

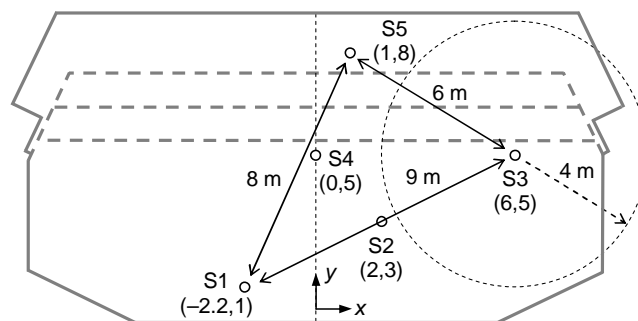


Figure 7.4: Source and receiver positions used on stage.

For measuring  $ST$  there are certain requirements to the source and receiver positions; see Section 7.7 for more details. Some of the measurement positions on the different stages violated this requirement to minimum distance to reflecting surfaces, like position S3 in Figure 7.4. When calculating average (arithmetic) value of  $ST_{\text{early}}$  based on the five source positions, results from invalid positions were omitted from the average. This led to  $ST_{\text{early}}$  being averaged within 3–4 source positions at the eight different stages (S3 excluded for all the stages). In Gade (1989c), three source positions on stage was suggested for obtaining average (arithmetic) stage value for the  $ST$  measures. The source positions on stage used for  $ST$  were at comparable locations referring the positions used by Gade (1989c).

For measuring  $G$  (Strength) in the audience area, a continuous noise method was used with the same loudspeaker and amplifier, a pink noise generator (CEL Type 213a), bandpass filter (Kemo Dual variable filter Type VBF/14J) and a real time sound level analyser (CEL-593) used in octave bands. This system was previously calibrated in an anechoic chamber. To measure  $G$  on stage, the measurement system was calibrated in-situ with the WinMLS system, averaging over 29 different source rotations (according to ISO 3382:1997). Having the loudspeaker 2 m above the stage floor and the microphone 2 m away from the loudspeaker at 2.4 m above the stage floor, resulted in a time window of 8.6 ms where only the direct sound was present. When comparing results for the two measurement systems at the same positions within the audience area, a good agreement was found in the frequency range 250–2000 Hz (less than 1 dB differences). For the octave band 125 Hz,  $G$  obtained with the WinMLS system

showed higher values compared to the noise method. This is likely to be caused by the truncation of the impulse response at 8.6 ms. A correction value was applied to the results of  $G$  on stage at 125 Hz to compensate for this.

For a list of all acoustic measures calculated from measured impulse response, see Section 8.3.1. Frequency average values of acoustic measures were derived for the three octave bands 500–2000 Hz, like in Section 7.2. However, the most recent definition of the  $ST$  measures (Gade, 1992) suggest a frequency average within the four octave bands 250–2000 Hz. This four octave average is used for the  $ST$  measures in this study.

The acoustic conditions in the audience area (unoccupied) were also measured to investigate relations between conditions on stage compared to the audience area. The source was set 3 m from the stage front at the centre of the stage, 1.2 m above the stage floor with the stage fitted with chairs. A total of 7–17 measurements were taken within the audience area depending on the complexity of the audience area (like balcony overhangs or curved walls). The following measures have been calculated from the impulse responses measured in the audience area:  $T_{30}$ ,  $EDT$ ,  $C_{80}$ ,  $G_l$  and Lateral Fraction  $LF$ . Spatial averages were taken within the full set of measurements (global average). For  $T_{30}$ ,  $EDT$ ,  $C_{80}$  and  $G_l$ , spatial average values were also calculated for stalls positions only with source-receiver distances within 10–20 m (excluding measurement position in balcony seats and below balconies), a total of 2–10 measurements for the different venues. Average values for  $T_{30}$ ,  $EDT$ ,  $C_{80}$  and  $G_l$  were found within 500–2000 Hz, as for the stage measures, while  $LF$  was found within the four octave bands 125–1000 Hz.

## 7.4 Spatial average value of acoustic measures assessed without orchestra

Common practise for the  $ST$  measures is to represent individual stages by average values of the acoustic measures. This poses the question of how many stage measurement positions are necessary to accurately represent a stage and what source-receiver distances to use. This section investigates the validity of using such single average values to represent the conditions on stage. For measurements within the audience area, source-receiver distances less than 10 m are rare. Possible source-receiver distances for assessing acoustic responses on stage span typically from 1 to 20 m. With short source-receiver distance the direct sound and floor reflection component become more dominant in measured response. The combined level of direct sound and floor reflection is highly dependent on source-receiver distance, as demonstrated in Chapter 4, and source directivity. The acoustic measures including the direct sound like  $EDT$  and  $C_{80}$  will be most prone to such variations. This section studies what source-receiver distance should be used to obtain stage average values. Variations of both the very early part of the impulse response,  $L_{0-7}$ , and a set of acoustic measures are included in this study.

### 7.4.1 Variations of the very early part of the impulse response

Figure 7.5 shows the dodecahedron loudspeaker used in the investigations of the eight venues, with measured frequency response (FFT) of the direct sound at 2 m distance. According to the frequency response with four different source rotations relative to the measurement microphone, the loudspeaker cannot be treated as fully omnidirectional at frequencies above 500 Hz. The octave band levels at 1 and 2 kHz vary within 1 and 2 dB respectively, in the direct field. These measured responses of the direct sound from the loudspeaker show that measured responses will significantly depend on the rotation of the source relative to the measuring microphone – particularly for short source-receiver distances.

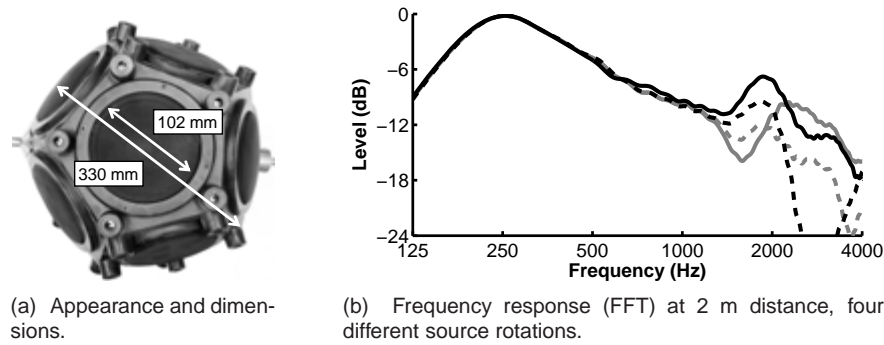


Figure 7.5: The dodecahedron loudspeaker used for investigations of acoustic conditions in venues.

The combined level of direct sound and floor reflection on stage can be estimated from  $L_{0-7}$ , the sound level within the first 7 ms of the impulse response. The theoretical omnidirectional direct sound level at corresponding source-receiver distance was used as reference level for  $L_{0-7}$ . Figure 7.6 shows the average value and standard deviation ( $\sigma$ ) for  $L_{0-7}$  measured at different source-receiver distances, with and without chairs on stage. The analysis is based on the 25 measurements carried out on the eight stages studied and the results are categorised as source-receiver distance of 1, 3, 5, 6, 8 and 9 m. Standard deviations are given as  $+\sigma$  without chairs and  $-\sigma$  with chairs. The value of  $L_{0-7}$  was found within the three octave bands 500–2000 Hz. The theoretical value of  $L_{0-7}$  on a fully empty stage,  $L_{df}$ , was calculated using an ideal omnidirectional source. The theoretical values are included in Figure 7.6 for source and receiver at either 1.0 m or 1.2 m height above the floor.

The results show that measured values of  $L_{0-7}$  agree moderately well with would we would expect theoretically. The deviations seen are likely to be related to the particular source used with its directional characteristics. Average value of  $L_{0-7}$  is lowest at source-receiver distance around 9 m with chairs on stage. Raising the transducers to 1.2 m height appears theoretically to contribute to higher values of  $L_{0-7}$  within 5–8 m distance. The low standard deviation found at 1 m distance is most likely caused by the rotation of the sound source being kept constant relative to the measuring microphone (as described in Section 7.3), but the absolute level measured are significantly dependent on source directivity.

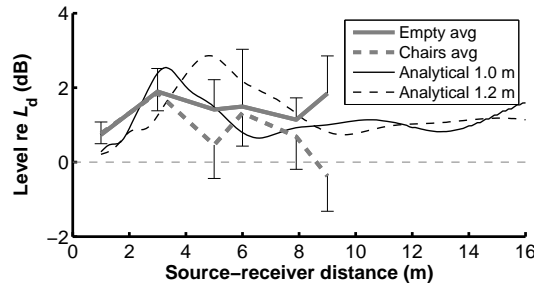


Figure 7.6:  $L_{0-7}$  at 500–2000 Hz. Standard deviation indicated as  $+\sigma$  for empty stage,  $-\sigma$  for chairs on stage. The theoretical level,  $L_{df}$ , for source and receiver heights of 1.0 and 1.2 m are as included as thin lines.

### 7.4.2 Variations of acoustic measures

Figure 7.7 shows the standard deviation of the acoustic measures studied assessed with chairs on stage within different ranges of source-receiver distances – within 1, 3–4, 5, 6–7 and 8–9 m. The analysis is based on the 25 measurements carried out on the eight stages studied. The results from the two theatres are separated from the results for the six other venues. From Figure 7.7 we see that the standard deviation is high for source-receiver distances within 3–5 m. This is likely to be caused by variations of source rotation relative to the measuring microphone and interference between the direct sound and the floor reflection (being sensitive to small variations of source-receiver distance at these distances). Again the standard deviation is low at 1 m distance, and low for source-receiver distances above 6 m, if excluding the two theatres.

### 7.4.3 Discussion and conclusions

The above results suggest that measuring at source-receiver distances above 6 m with chairs provide the lowest level of  $L_{0-7}$  and lowest standard deviation of the acoustic measures, for transducer heights of 1 m. Achieving low values of standard deviation at 1 m is very dependent on high accuracy of source-receiver distance, source rotation and directivity, and should therefore be avoided. This is further discussed in Section 7.7. Below are listed the possible advantages of measuring above 6 m distance with chairs:

- The combined level of direct sound and floor reflection will be low, relative to responses at shorter distances. This corresponds best with the conditions the players experience and lowers the influence of source rotation, source directivity and source-receiver distance.
- The combined level of direct sound and floor reflection is at short source-receiver distances very sensitive to small variations of the source-receiver distance. This contributes to higher standard deviation and unreliable reference level of measured values at short distances.
- On concert hall stages, musicians are likely to have most difficulty hearing distant colleagues and nearby musicians are probably producing reasonably consistent masking noise on different stages.

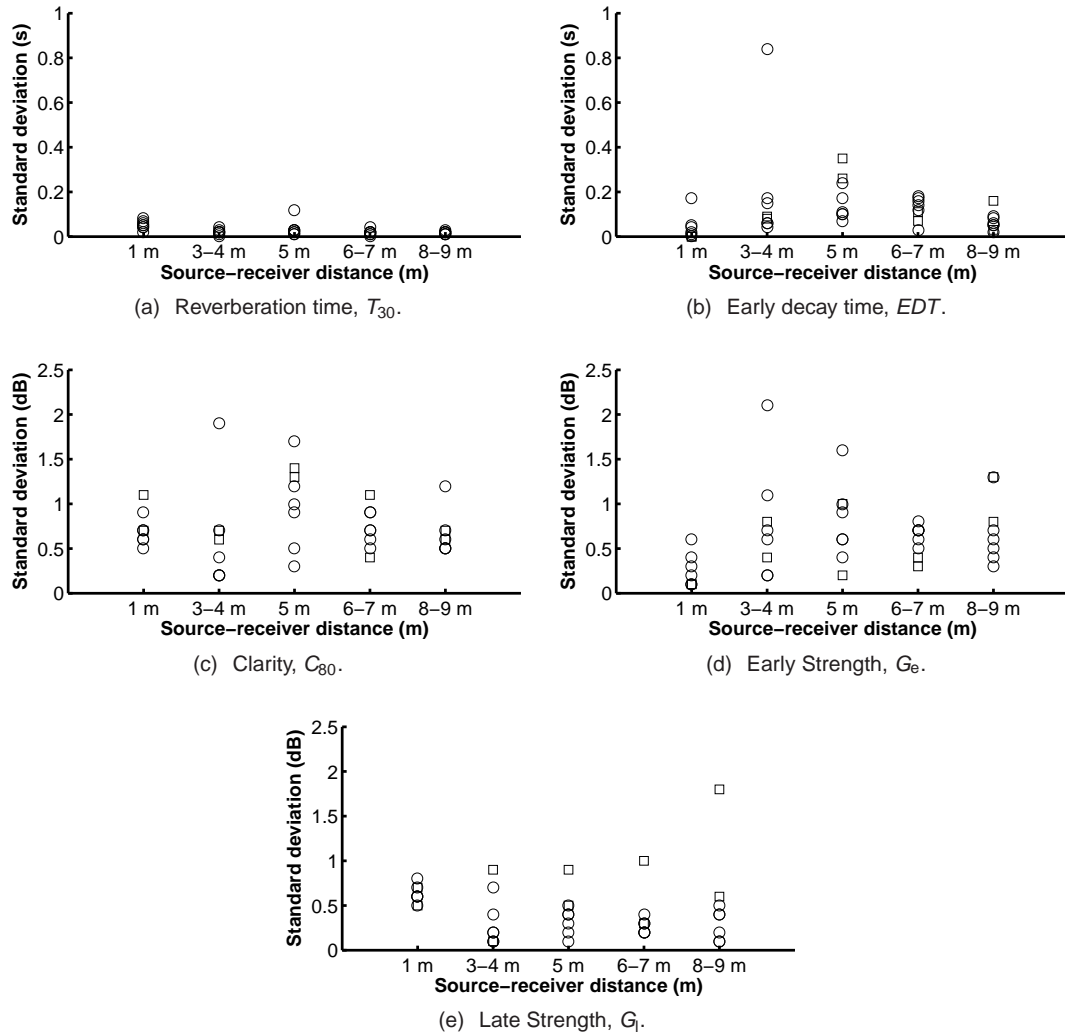


Figure 7.7: Standard deviation of acoustic measures assessed on eight different stages with chairs.  $\square$  indicate results for the theatres BP and WP,  $\circ$  indicate results for the six other halls.

From this we can conclude that measuring with source-receiver distance above 6 m is beneficial both for reliability and also for measuring at distances where the acoustic response appear most crucial for the players. If transducers heights are 1.2 m instead of 1 m, the results suggest that the source-receiver distance should be above 8 m instead of 6 m.

## 7.5 Results for objective acoustic measures

### 7.5.1 Stage measurements

Table 7.2 shows results for acoustic measures on the eight stages with chairs on stage. The stage average values were obtained from average (arithmetic) value of the responses measured with source-receiver distance within 6–9 m (totally ten responses).

Table 7.2: Average values of acoustic measures on the eight stages, with source-receiver distances within 6–9 m.

Hall	$T_{30}$	$EDT$	$C_{80}$	$G_l$	$ST_{early}$	$ST_{late}$
BA	1.93	1.43	5.1	4.3	−12.8	−15.6
BC	1.98	2.19	3.3	3.9	−16.5	−16.6
PG	1.16	1.06	5.6	2.0	−14.8	−18.2
PL	2.08	1.77	3.0	5.8	−13.9	−14.4
BP	1.36	1.19	7.9	−0.9	−17.1	−19.6
WP	0.80	0.87	8.4	−1.0	−16.8	−19.4
CD	1.89	1.82	4.4	2.7	−17.5	−17.4
EU	1.63	1.20	5.1	5.2	−11.5	−15.0

Student's t test analysis was carried out to study if the differences between average values found for the different stages appear to be significant (at the 5 % level). The results show that differences of  $C_{80}$ ,  $G_e$  and  $ST_{early}$  cannot be regarded as significant for several of the halls. We would expect enclosures with a comparable architectural design to also have comparable values of the acoustic measures. For  $G_l$  as well as  $T$ , insignificant differences are mainly found for similar enclosures, like BP and WP as well as BA and CD. See Chapter 8 for images of the enclosures. For  $C_{80}$ ,  $G_e$ ,  $ST_{early}$  and  $ST_{late}$  insignificant differences are found between stage enclosures that architecturally differ significantly. For instance, values of  $ST_{early}$  are not found to be statistically significant between CD and BC as well as between CD and PG. This suggests that acoustic responses including early reflections vary significantly between different locations on the same stage, making it difficult to find reliable average values. On the contrary, assessing the late acoustic response with  $G_l$  appears to result in statistically reliable values, where for instance the presence of risers have a less effect on measured values compared to  $ST_{late}$ . Not only  $ST_{early}$ , but also  $G_{7-50}$  are found to have higher standard deviation of measured values within the same stage, compared to  $G_l$ . The standard deviation of  $G_{7-50}$  is typically 3 times higher compared to  $G_l$ .

## 7.5.2 Correlation between the acoustic measures assessed on stage

Overall, most of the objective measures are highly correlated when looking at stage average values (only including positions with source-receiver distance above 6 m). This would be expected in acoustic spaces being moderately diffuse.  $G_l$  is the measure mostly correlated with the other measures.  $T_{30}$ ,  $C_{80}$ ,  $G_e$  and  $ST_{early}$  all correlate significantly with  $G_l$  ( $r=0.81$ ,  $r=-0.89$ ,  $r=0.77$  and  $r=0.70$  respectively). Some of the other measures are equally highly correlated:  $G_e$  and  $ST_{early}$  ( $r=0.97$ ) as well as  $G_l$  and  $ST_{late}$  ( $r=0.98$ ). Measured  $T_{30}$  correlates highly with  $EDT$  and  $C_{80}$  ( $r=0.86$  and  $-0.87$  respectively). All these listed correlations are significant at the 1 or 5 % level.

When studying the relation between measured values at individual positions (200 measurements totally) the correlation coefficients are generally reduced, and the values of  $EDT$ ,  $C_{80}$  and  $G_e$  are highly correlated with the source-receiver distance.  $G_l$  is significantly less correlated with  $C_{80}$  and  $G_e$ , as well as  $G_e$  significantly less correlated with  $ST_{early}$ . But  $ST_{early}$  as well as  $G_{7-50}$  are still highly correlated with  $G_l$  based on individual measurements ( $r > 0.7$

for both), which appears to relate to the unattenuated direct sound (and floor reflection) being excluded for these measures. These results suggest that the early reflections level in fact is significantly correlated with the late reflections level on stage. The results also suggest that the source-receiver distances used when obtaining acoustic measures including the direct sound (like  $EDT$ ,  $C_{80}$  and  $G_e$ ) must correspond when comparing results between different stages (which was done when assessing the eight stages within this project).

### 7.5.3 Audience area measurements

Table 7.3 shows results for the measurements carried out in the audience area with the spatial average calculated within the whole audience area (G – global average) and within the stalls area only (S – stalls, source-receiver distance within 10–20 m, excluding measurement position in balcony seats and below balconies). For the global average value the standard deviation  $\sigma$  is within 0.01–0.04 s for  $T_{30}$ , 0.08–0.25 s for  $EDT$ , 0.6–1.8 dB for  $C_{80}$ , 0.9–2.2 dB for  $G_l$  and 0.04–0.09 for  $LF$ . The differences between the two spatial averages are least significant for  $T_{30}$ . This indicates that  $G_l$  within the audience area estimated from measured  $T$  and hall volume  $V$  (according to Equation 3.1) will not very sensitive to the measurement positions used for measuring  $T$ . Studying levels of  $G_l$  within stalls area only, instead of within the complete audience area, can be seen as more relevant for assessing the level of acoustic response provided by the main auditorium for the musicians on stage. If finding spatial average values of  $G_l$  within the stalls area only,  $\sigma$  is within 0.6–1.7 dB. This is a significant reduction of the deviation. How to obtain reliable results from the perspective of the audience is not discussed here – this has been discussed by for instance Barron (2005).

Table 7.3: Results for acoustic measures assessed in the audience area. G represents global spatial average value, while S represents spatial average within the stalls area only.

Hall	$T_{30}$		$EDT$		$C_{80}$		$G_l$		$LF$ G
	G	S	G	S	G	S	G	S	
BA	1.95	1.94	1.85	1.85	0.1	0.0	2.4	3.3	0.23
BC	1.99	2.01	1.86	2.02	1.1	0.5	0.8	2.4	0.15
PG	1.22	1.21	1.17	1.25	2.7	2.4	–2.1	–1.4	0.19
PL	2.15	2.13	2.13	2.13	–1.8	–1.6	3.6	4.2	0.20
BP	1.40	1.41	1.27	1.32	2.9	3.5	–1.4	–1.4	0.20
WP	0.87	0.88	0.79	0.84	6.6	6.5	–3.8	–4.2	0.16
CD	1.91	1.90	1.91	1.69	0.0	0.7	–0.8	1.0	0.17
EU	1.68	1.68	1.69	1.78	0.2	–0.1	1.8	2.6	0.19



## 7.6 Relationships between stage and audience average values

Jordan (1982) studied the ratio of measured values on stage compared to in the audience area (the 'Inversion Index'). A clarity measure (presumably  $C_{80}$ ) as well as  $EDT$  were included (among others). He proposed that these ratios should be above 1 for good acoustic conditions. In this section, the results from Tables 7.2 and 7.3 are used to study such relations. For the audience area measurement the spatial average within the stalls area only has been used, since that reduces the variation between halls caused by balconies in the auditorium. Figure 7.8 shows results for measured stage average values of  $T_{30}$ ,  $EDT$ ,  $C_{80}$  and  $G_I$  versus respective average audience values. From Figure 7.8 we see that values of  $T_{30}$  are very consistently reduced by approximately 0.03 s on stage ( $r=0.99$ , significant at the 1 % level). For  $C_{80}$  and  $G_I$ , average values are consistently increased on stage, while for  $EDT$  the values are less consistently shifted.

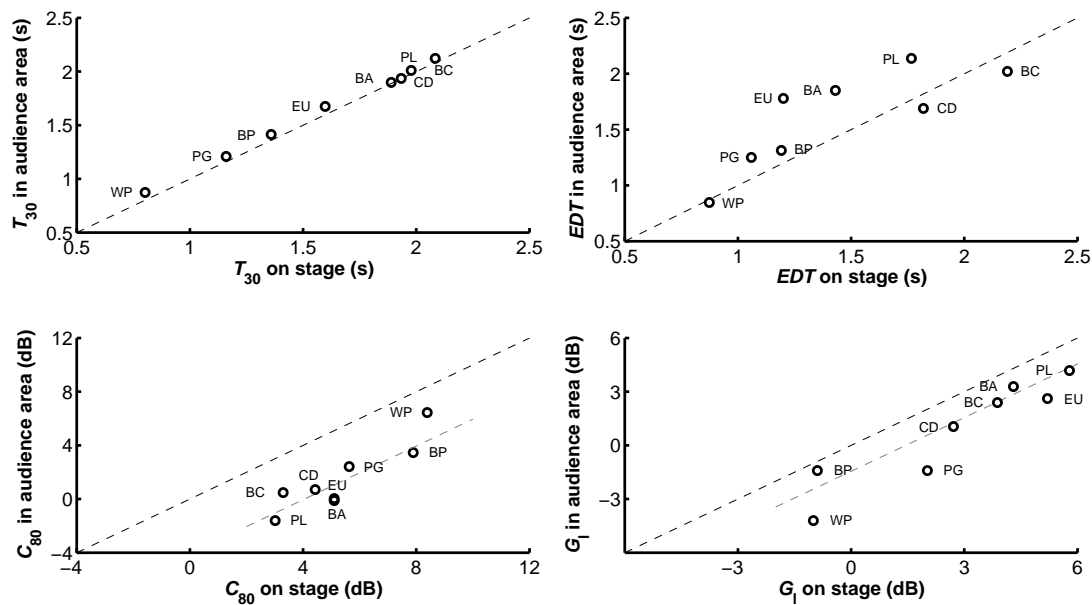


Figure 7.8:  $T_{30}$ ,  $EDT$ ,  $C_{80}$  and  $G_I$  measured on stage versus in the audience area.

If we study the results for  $C_{80}$  and  $G_I$  in detail, we see that the measured values are significantly increased on stage for most of the halls. If we study only the purpose-built concert halls (BA, BC, CD and PL) only, the average values of  $C_{80}$  and  $G_I$  are increased by 4 and 1.5 dB respectively on stage (indicated by dashed lines in Figure 7.8). The increase of  $C_{80}$  is likely to be associated with a higher number of reflecting surfaces close to the source and receiver on stage. The reduction of the average source-receiver distance from approximately 15 to 8 m on stage will result in  $G_I$  being raised by 0.6 dB according to Equation 3.1. The remaining 0.4–1.1 dB increase of  $G_I$  on these four stages could be associated with the stage enclosure projecting late reflections towards the stage and/or late arriving reflections within the stage enclosure itself.

For the four remaining halls (BP, EU, PG and WP) the increase of values on stage are below and above the average increase for the purpose-built halls. It is worth speculating why the four remaining halls show different increases. Both the theatres (BP and WP) have a very absorbing stage enclosure. On the stage of BP part of the stage is outside the absorbing enclosure and the stage is very deep (15.3 m). These conditions are likely to lead to some early reflections at the stage front while not much of the late/reverberant response from the main auditorium reaching the back half of the stage. This may explain the moderate increase of  $C_{80}$  and low increase of  $G_i$  on this stage. In WP the complete stage is inside the absorbing stage enclosure and the stage is shallow (10.9 m). WP also has ceiling sections close to the stage angled vertically. These conditions are likely to result in a very low level of early reflections, while the late reflections/reverberant response from the main auditorium is projected down towards the stage. This may explain the low increase of  $C_{80}$  and high increase of  $G_i$  on this stage. The large increase of  $G_i$  on stage in PG could be associated with an enclosed reflective stage enclosure.

## 7.7 Reliability of the Support measures

Gade (1989b) and Gade (1992) proposed a set of acoustical measures called  $ST$ , which were found to correlate well with perceived aspects of stage acoustic conditions among symphony orchestra musicians. The Support ( $ST$ ) measures sum the level of sound reflections returning back to the stage, by use of omnidirectional loudspeaker and microphone. The source is set on stage with the microphone at 1 m distance from the (centre of the) source to simulate a musician with instrument. Both loudspeaker and microphone should be at 1 m height. The sum of reflections is taken within different time intervals relative to the emission of sound. The time intervals for  $ST_{early}$ ,  $ST_{late}$  and  $ST_{total}$  are 20–100, 100–1000 and 20–1000 ms respectively. The mathematical definitions of the  $ST$  measures are shown in Section 2.3. Gade has recommended measuring  $ST$  with chairs on stage.

The reference for this early sound level is the combined level of the direct sound and the floor reflection, summed within the time interval 0–10 ms (from the same measured impulse response), as shown in Equation (2.1). To keep this reference consistent, Gade recommended having no objects on stage that would reflect back sound arriving within 0–10 ms. This implies that all chairs or other objects (except the microphone) closer than 2 m from the loudspeaker should be removed while carrying out the measurements. Additionally for  $ST_{early}$ , the source and receiver should be at least 4 m from any reflecting surfaces (except from the floor) to avoid any of early reflections arriving before 20 ms. The use of 20 ms as the lower time limit appears to be caused by the measurement method being used at the time the measures were proposed. Based on Gade (1982), the measurement method involved sine bursts of 20 ms duration emitted from the sound source. By use of such an excitation signal, reflections arriving before 20 ms would fuse with the direct sound and floor reflection response, making the measured energy reference (0–10 ms) inconsistent.

An alternative to  $ST_{early}$  is the measure  $G_{20-100}$  ( $G$  within 20–120 ms) at 1 m.  $G_{20-100}$  more effectively uses the source sound power as a reference, or more precisely  $G$  values are based

on the direct sound level at 10 m as reference averaged for 29 source rotations (according to ISO 3382:1997) to minimise the effect of source directivity. The different source-receiver distance used for the reference level (10 instead of 1 m) contributes to values of  $G$  being 20 dB higher compared to  $ST_{\text{early}}$ .  $G_{20-100}$  ignores the contribution from the floor reflection (and interference effects between the direct sound and floor reflection), which roughly contributes another 1 dB difference between  $G_{20-100}$  and  $ST_{\text{early}}$  (totally roughly 21 dB difference). How a single measure of  $ST_{\text{early}}$  relates to  $G_{20-100}$  is expressed in Equation (7.4), where  $\epsilon_1$  represents the effect of the floor reflection inclusion in the reference,  $\epsilon_2$  represents the variations caused by the source directivity and  $\epsilon_3$  represents variations due to offsets from 1 m transducer heights and source-receiver distance.

$$ST_{\text{early}} = G_{20-100} - 20 + \epsilon_1 + \epsilon_2 + \epsilon_3 \quad \text{dB} \quad (7.4)$$

From this we can conclude that the reference level and source-receiver distance used for  $ST$  introduces technical complications and contribute to a reduced the reliability. Even if taking great care with keeping the source-rotation and source-receiver distance fixed, the reference level will be sensitive the directivity of the particular loudspeaker used and presence of risers. Based on experiences within this study, values of  $ST$  (averaged 250–2000 Hz) can easily change 1 dB if the receiver is positioned within 0.1 m off the 1 m distance from the centre point of the source, or if the sound source is rotated. According to [Gade \(1992\)](#), significant changes of stage enclosure lead to only minor changes of  $ST_{\text{early}}$  – typically within 1 dB. This leads to a poor reliability when comparing different stage enclosure designs, in particular if looking at stage average values. Values of  $ST_{\text{early}}$  are found to vary significantly between different source positions on a single stage; see Section 7.5.1. The lower time limit of 20 ms for evaluating the early energy level in  $ST_{\text{early}}$  can also cause complications and misleading results. If measuring responses outside the centre area of the stage or with different stage configurations, some of the reflections from the stage enclosure can for some of the measurements appear before 20 ms, making it difficult to isolate the effect by the stage enclosure and the integration time limits as illustrated by [Jeon & Barron \(2005\)](#) and [van den Braak \*et al.\* \(2005\)](#).

## 7.8 Monophonic omnidirectional measures for assessing acoustic conditions without orchestra present

The results from this study suggest that only a few acoustic measures based on monophonic omnidirectional responses show a consistent reduction of value when a full symphony orchestra is introduced. The acoustic measure  $G_i$  (as well as  $ST_{\text{late}}$ , but less reliable) and to a certain degree also  $T$ ,  $C_{80}$  and  $ST_{\text{early}}$  show the most consistent reductions. The reductions of  $G_e$  and  $G_{7-50}$  appear too dependent on both presence of risers and properties of the stage enclosure. In Chapters 3 and 8 values of a set of objective measures (both acoustic and architectural) were compared to the subjective impressions of existing stages in concert halls purpose-built for symphonic music. The stages studied were visited regularly by the orchestras involved. A large set of acoustic measures were totally included, but only  $G_i$ ,  $T$  and

$C_{80}$  (or measures very similar to those) were found to significantly correlate with subjective characteristics.  $G_I$  showed the most significant correlations which agrees well with the findings in this chapter. These three measures correlated most significantly with impressions of reverberance/acoustic response and sound levels on stage. Studying values of  $C_{80}$  at separate octave bands appeared in Chapter 8 to be relevant for assessing presence of early reflections and perceived reverberation on stage. This implies that the acoustic measures which are most valid in objective physical terms relating to the conditions experienced by the players (Section 7.2), also correlate best with subjective impressions of overall acoustic response and sound levels. The exception appears to be  $ST_{\text{early}}$ , showing reasonably consistent reductions with the orchestra introduced, but no significant correlations to perceived conditions. These results were based on studying both stage average values and results at individual positions and differences between individual positions. The results from Section 7.2.3 indicate that values of  $T$  appear to be most validly assessed physically with risers on stage. All the stages included in the subjective studies mentioned above have risers on stage, leading to sufficiently valid assessment of  $T$  on an empty stage.

Why acoustic measures related to early reflections do not correlate significantly with subjective characteristics could be related to the following factors:

- Assessing levels of early reflections with sufficient reliability and validity compared to conditions with orchestra present appears difficult. The suffering reliability refers mainly to the level of early reflection vary significantly at different locations on stage, and the suffering validity refers mainly to the orchestra significantly attenuating early reflections.
- For  $ST_{\text{early}}$  the direction of early reflections is ignored, and the reference level used contributes to reduced physical reliability. The direction of early reflections appears highly relevant for perceived ensemble conditions (as investigated in Chapters 3, 5 and 8).

With regard to the ratio of values of acoustic measures on stage compared to in the audience area, Jordan (1982) proposed that good stage conditions are indicated by values of  $EDT$  and clarity being higher on stage. From the study of eight performance spaces there are no signs of the four most preferred halls (BA, CD, PL and EU) having ratios above 1 for  $EDT$ . On the other hand such a requirement may be relevant for  $C_{80}$  and  $G_I$ . Moderately raised values of  $C_{80}$  and  $G_I$  on stage may provide necessary early reflections back to the orchestra and project the late/reverberant response from the main auditorium towards the players. The impression of hearing the acoustic response from the main auditorium was in Chapter 3 found to be important for the players, and is further discussed in Section 5.9. The raised level of  $G_I$  on stage can also be caused build-up of reverberant sound within the stage enclosure itself. With omnidirectional room impulse capturing methods it will not be possible to detect where the late reflections on stage originate from.

This project has included acoustic measures based on the use of an omnidirectional source and receiver, assessed in an unoccupied hall and empty stage with chairs. Based on the above considerations and the findings from the other investigations part of this research project, the

apparent relevance of such acoustic measures for assessing acoustic conditions for symphony orchestra on concert halls stages is as follows:

- The level of late acoustic response provided by the main auditorium which appears relevant for perceived 'bloom' (acoustic support) and 'projection' (acoustic communication with the audience) among the players. If the hall has a lack of acoustic response it will be difficult to compensate for this by having a very reflective stage enclosure, since this apparently contributes to an excessive loudness and lack of clarity of sound on stage. An excessive loudness can be compensated for to a certain degree by the musicians playing softer. But it will often limit the dynamic range since not all instruments will be able to play softly enough, and the wanted character of the sound is difficult to achieve if playing very softly. The most popular halls within this project have  $1 \leq G_l \leq 3$  dB (within 500–2000 Hz).  $G_l$  within the audience area was estimated from global average value of  $T$  (unoccupied) and hall volume  $V$  (using a source-receiver distance of 15 m) or measured within the stalls area (unoccupied, with source-receiver distance within 10–20 m and excluding measurement positions in balcony seats and below balconies). What optimal range may apply for other ensembles, like chamber groups, has not been investigated. The validity of  $G_l$  within the audience area will depend on the type of audience seats used. The optimal range found is based on moderately upholstered seats.
- To what degree the stage is acoustically exposed to the main auditorium that appears relevant for the experience of 'projection' (acoustic communication with the audience) among the players. The most popular stages within this project have  $3 \leq G_l \leq 5$  dB (within 500–2000 Hz) on empty stage with chairs – approximately 2 dB above the level within the stalls section. A lack of late acoustic response on stage can be more validly detected, since the orchestra will contribute to reduce levels further. The audibility of the late acoustic response may be assessed with  $C_{80}$  measured on stage.
- Overall levels of early and late reflections relevant for perceived loudness and detection of early reflection levels that potentially can provide compensation for low within-orchestra levels. Extreme levels (too low or too high) of early and/or late acoustic response can to a certain degree be detected by measuring  $G_e/G_{7-50}$ ,  $G_l$  and  $C_{80}$  on stage. Excessively low values of  $G_e$ ,  $G_l$  above 500 Hz on empty stage can be a valid indication of problematic conditions, since levels will be further reduced with the orchestra present.
- Measured values at the octave bands 63 and 125 Hz on an empty stage should be sufficiently valid compared to conditions with orchestra present.
- Conditions with orchestra present will be most cost-efficiently studied in computer or scale models. Details of measured impulse responses and values of for instance  $G_e$  and  $G_l$  on stage can be used to calibrate the models if studying existing stages. Measures based on measured  $G$  has within this project been found highly reliable and not very sensitive to small variations in source-receiver distance or transducer heights when using a source-receiver distance of minimum 6 m (preferably above 8 m if having the transducers 1.2 m above the stage floor), as opposed to  $ST_{early}$ . Using source-receiver distances above

8 m will also focus on paths within the orchestra where the acoustic response from the stage enclosure appears most critical.

The results from Chapter 4 suggest that both average values within 500–2000 Hz and at single octave bands from 125 to 4000 Hz are relevant. Results at individual position or stage average values may be used, but studying results at individual positions instead of stage average values appears to make the acoustic measures less correlated. Values of  $G_l$  measured at different locations on stage with a source-receiver distance above 6 m show low standard deviation. This suggests that the results of  $G_l$  on stage are not very sensitive to how  $G_l$  is obtained (like actual measurement positions used and looking at individual instead of stage average values). If values of  $G_l$  are not available, values of  $T$  may be used as a substitute. The proposed relevant measures appear to only be relevant for revealing the most problematic acoustic conditions on stage. The measures do not discriminate well between halls receiving overall acoustic impression within 4–10 (out of 10), as discussed in Chapters 3 and 8.

## 7.9 Directionally dependent assessment of stage acoustic response

In Chapters 3 and 5 the architectural measures proposed in this project were found relevant for assessing perceived acoustic conditions. The success of these measures appears to be related to direction of reflecting surfaces being taken into account, and that these measures provide a sufficiently valid indication of acoustic conditions with the orchestra present. The direction of reflections are relevant since the sound levels within the orchestra itself vary significantly sideways compared to front-to-back on stage (see Section 5.2). The level and time distribution of the reflections provided by surfaces defining  $W_{rs}$  and  $H_{rb}$  will be affected by the finer details architecturally of these surfaces. For instance side walls tilted vertically will lead to higher level of side reflections, since such reflections will be less obstructed by the orchestra. These details are not represented in the architectural measures. This suggests that the actual levels of early reflections are not validly assessed by these measures. Based on this, the success with the architectural measures appears to first of all relate to the direction of early reflections being assessed. For existing stages, the use of directionally dependent capture of room acoustic responses may prove relevant for studying the level and ratios of reflections from the sides, above and from the back of the stage. With such methods the direction of late/reverberant acoustic response can also be assessed, which appears relevant for the sense of ‘projection’ on stage.

The acoustic measure Lateral Fraction,  $LF$ , was originally proposed for assessing the impression of sound source broadening (Barron & Marshall, 1981). This measure compares the sound energy from a figure-of-eight microphone within 5–80 ms of the impulse response compared to the sound energy from an omnidirectional microphone within 0–80 ms, both at the same receiver position. By orienting the figure-of-eight in the stage width direction, the level of early reflections from the sides compared to level of early reflections from all directions can be assessed. If relating to the architectural measures,  $LF$  would in a simplified manner



correspond to  $\frac{1/W_{rs}}{1/W_{rs}+1/H_{rb}+1/D}$ . By rotating the figure-of-eight vertically,  $LF$  would in a simplified manner correspond to  $\frac{1/H_{rb}}{1/W_{rs}+1/H_{rb}+1/D}$ . To achieve the highest discrimination between side and overhead reflections using  $LF$ , the source and receivers should be placed at the middle of the stage with the direct sound path along the cross-sectional direction. The upper time limit of 80 ms will include reflecting surfaces at a maximum distance of approximately 15 m from the receiver with a 4 m source-receiver distance. With source and receiver at the middle of the stage, this means that side walls wider than 30 m from each other will not contribute to a higher value of  $LF$ , while a ceiling higher than 16 m will not contribute to a lower value of  $LF$ . This measure was not included on the real stages investigated in this project, so modelling would be the most accessible option for investigating the potential use of a directional dependent measure at an initial stage. See Appendix E for details on computer models developed for studying values of  $LF$  on two stages.

The  $LF$  measure will have a limited angular discrimination based on the use of one figure-of-eight and one omnidirectional microphone. An alternative method for providing more detailed information with regard to direction of reflections is B-format impulse response measurements. B-format is the 1<sup>st</sup> order Ambisonics format with sound information encoded into four channels: one omnidirectional microphone and three figure-of-eight microphones facing forward, to the left and up (Gerzon, 1985). By decoding the responses from these four channels, the particular direction of reflections within a specific time interval can be found. Merimaa & Pulkki (2005) and Merimaa (2007) have proposed methods and techniques for analysing the time-dependent direction of arrival, intensity vector and diffuseness of measured multichannel responses. Gover *et al.* (2004) used a spherical array of 32 microphones to determine the directional properties of reverberant sound. Such methods could be relevant for determining the direction of dominating early and late reflections on stage.

The results from Chapter 3 suggest that mid-ranging halls are most difficult to discriminate between due to a lack of physical validity and the finer details of the acoustic response and the enclosure not being represented by the objective measures studied. This problem is likely to also exist for directional dependent measures assessed without an orchestra, since the level of both early and late reflections on stage appear to be significantly affected by the presence of a full symphony orchestra on stage. Therefore, measurements carried out on an empty stage appear most relevant for calibrating scale or computer models (where the orchestra can be included) and directional dependent assessment of the acoustic response on stage may prove beneficial for this purpose.

## 7.10 Conclusions

The results from this study suggest that investigating acoustic conditions without orchestra present have limited validity within 500–2000 Hz when comparing to conditions with orchestra present. This was based on measuring monophonic omnidirectional room impulse responses in a scale model of a generic stage. The low validity found is largely related to the orchestra obstructing reflections from the stage enclosure. Additionally, the variation of the acoustic conditions is more marginal without the orchestra present. This makes it more difficult to



discriminate between different enclosure designs assessed without an orchestra present. Measured responses at low frequencies, at the octave bands 63 and 125 Hz may though be both valid and relevant, since the orchestra does not obstruct sound significantly at these frequencies (as found in Chapter 4).

Based on monophonic omnidirectional responses without an orchestra present, the acoustic measure  $G_l$  in particular as well as  $T$  and  $C_{80}$  are found to be most valid and reliable without the orchestra present. The specific concert hall design used for the scale model investigation is likely to have overestimated the validity of the late acoustic response assessed on empty stage. Results from the computer model investigations (Chapter 6) suggest that the stage enclosure design affects the reductions of  $G_l$  when adding the orchestra to a significant degree and that an exposed stage results in the most consistent reductions of  $G_l$ . This limited validity compared to an orchestra present appears to significantly limit the subjective relevance of acoustic measures assessed without the orchestra present. The three acoustic measures  $G_l$ ,  $T$  and  $C_{80}$  are found to have some subjective relevance: to what degree the main auditorium is suitable for symphonic music, the sense of acoustic communication with the audience area and general sound levels on stage.  $G_e$  and/or  $G_{7-50}$  can be used to assess the presence of potentially useful early reflections provided by the stage enclosure. When comparing with subjective characteristics, both average values within 500–2000 Hz of these acoustic measures and at individual octave bands within 125–4000 Hz obtained on empty stage with chairs appear relevant. By use of omnidirectional responses it will be difficult to isolate the contribution from the stage enclosure from the contribution from the main auditorium on measured stage values, though the differences between stage and audience area average values can be instructive. For more enclosed stages there appears to be a mutual relation between the enclosure projecting early sound out of the stage area towards the main auditorium (without projecting too large a portion of it towards the absorbing audience area) and the late acoustic response from the main auditorium being projected back towards the musicians. This appears to be more relevant for overhead compared to side reflecting surfaces, since overhead reflecting surfaces are found less suitable for providing early reflections for the orchestra compensating for low direct sound levels within the orchestra.

Values of the acoustic measures related to the level of early reflections are not found to not be reduced consistently when adding an orchestra. In addition, measured values are found to vary significantly at different positions on the same stage. Such variations make it difficult to establish an average value based on a few number of measurements, and deviations of source and receiver positions from a defined set of measurement positions will have a significant effect. These results suggest that the results at individual position must be studied, instead of stage average values, if assessing the level of early reflections on stage. Using a source-receiver distance above 6 m reduces the influence of direct sound level variations. Assessing the level of early reflections was found most valid when excluding the first 20 ms of the impulse response. This first part is excluded when calculating values of  $ST_{\text{early}}$  contributing to higher physical validity, but such a time limit leads to only valid positions within the centre area of the stage. If measuring for instance measuring close to a side wall, the side wall reflection will be ignored which is likely to be subjectively highly relevant. The direction of reflections being ignored and low physical reliability found for  $ST_{\text{early}}$  appear to be the main factors leading to poor relevance to perceived ensemble conditions for this measure.

Though the acoustic measures  $G_i$ ,  $C_{80}$  and  $T$  have proven to be sufficiently subjectively relevant when assessed on an empty stage with chairs, the main benefit of measurements on empty stages appear to relate to calibrating scale or computer models where the orchestra can cost-effectively be included. The calibration may be based on for instance measured  $G_e$  and  $G_i$  as well as details of the impulse response. The developed models will then serve as the basis for decisions related to stage enclosure design. Even though directionally dependent measures may prove relevant assessed on an empty stage, it may only complicate the measurement procedures without adding much more relevant information compared to what the musicians experience. When assessing early reflections on stage, studying results along specific paths within the orchestra appears more relevant compared to stage average values.

## Chapter 8

# Impressions of eight performance spaces visited regularly

### 8.1 Introduction

This chapter covers the impressions of the acoustic conditions among musicians of one symphony orchestra in the eight different performances spaces they regularly performing in. Chapter 3 covers a similar study with seven different orchestras participating. Some of the results from the study including seven different orchestras indicated that judgements of stage conditions in halls visited on a regular basis are most valid. The orchestra participating was the Bournemouth Symphony Orchestra (England), and the halls studied in the south-west England and Wales were:

The Anvil, Basingstoke (BA)  
Colston Hall, Bristol (BC)  
Guildhall, Portsmouth (PG)  
The Lighthouse, Poole (PL)  
Pavilion, Bournemouth (BP)  
Pavilion, Weymouth (WP)  
St David's Hall, Cardiff (CD)  
University Great Hall, Exeter (EU)

Figure 8.1 shows images taken of the stage enclosure mainly, for the eight halls included.

The spaces where the Bournemouth Symphony Orchestra performs regularly range from purpose-built concert halls to smaller theatres. The subjective impressions by the players have been collected by questionnaires distributed to each player within the orchestra. The players responded based on their memory of several years of visits to these halls. Two meetings were also arranged with some of the players to discuss their impressions of the eight stages. The physical acoustic conditions have been derived from monophonic omnidirectional impulse responses measured on the stage and in the audience area. The impulse responses on stage



(a) The Anvil, Basingstoke.



(b) Colston Hall, Bristol.



(c) Guildhall, Portsmouth.



(d) The Lighthouse, Poole.



(e) Pavilion, Bournemouth.



(f) Pavilion, Weymouth.



(g) St. David's Hall, Cardiff.



(h) University Great Hall, Exeter.

Figure 8.1: Images of the halls regularly visited by th Bournemouth Symphony Orchestra.

were measured with chairs on the stage, without the orchestra present. The details of these objective results are given in Chapter 7. The subjective results have been compared with the measured objective results.

Ten subjective characteristics from the questionnaire were initially included in the analysis. The subjective characteristics were split up in average values for the different instrument groups and for the orchestra as a whole. The four different instrument groups were string, woodwind, brass and percussion players. For the objective acoustic measures, 21 measures were initially included and stage average values obtained. Among these were well established acoustic measures, acoustic measures proposed for evaluating stage conditions (Gade (1989b), Gade (1992), Griesinger (1995)) and other alternative measures. Seven architectural measures were also considered.

To investigate the relationship between the subjective characteristics, correlation and factor analysis were performed. The relationships between the objective and subjective characteristics were studied by correlation analysis where all the subjective and objective measures were included. Following an initial correlation analysis, it was clear that there was a certain redundancy in the measures selected. For this reason three of the subjective and thirteen of the objective acoustic measures were abandoned, leaving seven subjective, five objective acoustic measures and seven objective architectural measures.

## 8.2 Method for subjective investigations

Questionnaires were distributed to the musicians in the Bournemouth Symphony Orchestra (England) with a two page long questionnaire for each of the eight halls. The questionnaire was run anonymously. Before the questionnaire was distributed, it was piloted by some representatives of the orchestra. See Appendix B for a sample of the questionnaire distributed.

For each hall, the players were asked in the questionnaire to describe their impressions of acoustic aspects along bipolar semantic differential scales (Likert rating) ranging 1–5 and to make comments on these questions. The seven rating questions included in the finals analysis were:

- Physical comfort (*Co*): “Is the stage comfortable for you to play on?”  
1 = Uncomfortable – 5 = Comfortable
- Hearing self (*HS*): “How easily can you distinguish your own voice from surrounding instruments?”  
1 = Insufficiently – 5 = Sufficiently
- Hearing others (*HO*): “Do you struggle to hear some instruments or groups in this hall?”  
1 = Severe problem – 5 = Not a problem
- Clarity (*CI*): “How clearly can you hear the instruments you need to hear?”  
1 = Struggle to hear details – 5 = Easy to hear details

- Hall reverberance (*Rev*): “How do you find the acoustic response from the hall (resonance of the room)?”  
1 = Dead, no response – 5 = Live, reverberant
- Other instruments not too loud (*LNP*): “Do some instruments or groups become too loud for you in this hall?”  
1 = Severe problem – 5 = Not a problem
- Overall impression (*OAI*): “Overall impression for you as a performer of the acoustical conditions of this hall”  
1 = Very poor – 5 = Very good

To avoid the ‘halo effect’, the questions covering *CI*, *Rev* and *LNP* had a reversed scale in the questionnaire – the scale direction has here restored so that all measures have the most positive impression represented as a score of 5. More aspects of acoustical and musical conditions were part of the questionnaire, but they were in initial studies found to correlate highly with the aspects mentioned above. These aspects were relating to perceived timbre, reverberation character, ease of achieving pianissimo and fortissimo effect, and awareness of late discrete reflections.

For all preference rating questions, average (arithmetic) values were obtained for the four different instrument groups, string, woodwind, brass and percussion players, and for the orchestra as a whole. The average value representing all the players are taken as the average value of individual responses, since there was not found significant differences in responses between the instrument groups (see Section 8.5.2 for more details). The statistical analyses were carried out using SPSS version 15 and MATLAB R2006a.

## 8.3 Methods for objective investigations

### 8.3.1 Acoustic measures

The details on how the room acoustic impulse responses were obtained on stage and in the audience area are given in Chapter 7. In Chapter 7, the validity of such measurements carried out on a stage without the orchestra present was discussed, as well as the source-receiver distance to use to achieve the most reliable responses. The results from these investigations suggest that only  $G_l$  may be sufficiently valid. Values of  $G_l$  also show the most significant differences between the eight venues studied. Despite these results, a large number of different acoustic measures were initially included when comparing objective and subjective results, searching for significant relations.

The following acoustic measures were calculated according to ISO 3382:1997 from the monophonic omnidirectional impulse responses measured on stage: Reverberation time  $T_{30}$ , Early Decay Time  $EDT$ , Clarity  $C_{50}$  and  $C_{80}$ , Centre Time  $T_s$ , Strength  $G$ , Support  $ST_{early}$ ,  $ST_{late}$ ,  $ST_{total}$  and  $ST_{early} - ST_{late}$  (according to Gade (1992)), Early Ensemble Level  $EEL$  (according to Gade (1989b)) and Running Reverberation  $RR160$  (according to Griesinger



(1995)) were also calculated (these measures are not part of ISO 3382:1997). The two acoustic measures proposed at an early stage of this project, *EB* and *EMDT*, were also included (according to Barron & Dammerud (2006) and Dammerud & Barron (2007)). The Strength measure *G* within time intervals,  $G_{7-50}$ ,  $G_{7-80}$ ,  $G_{50-150}$ ,  $G_{150-400}$ ,  $G_{7-\infty}$ ,  $G_e$  ( $G_{0-80}$ ), and  $G_l$  ( $G_{80-\infty}$ ), were found based on *G*,  $C_{50}$ ,  $C_{80}$  and the ratio of sound energy within 0–7 ms relative to 7–50 ms. All time intervals are relative to the arrival of the direct sound.

Correlation analysis of the objective measures showed that most are highly and significantly correlated with each other. This has allowed us to reduce the number of objective measures down to a set of five acoustic measures on stage:  $T_{30}$ ,  $C_{80}$ ,  $G_l$ ,  $ST_{\text{early}}$  and  $ST_{\text{late}}$ . These measures were also found physically most valid when being assessed without an orchestra present, as studied in Chapter 7. Correlation analysis with the full set of subjective and objective measures was initially carried out, but the acoustic measures left out did not show any significant correlation which could not be seen from the five measures selected.

With regard to obtaining the stage average value, three different spatial average values were calculated: average value including measured responses with source-receiver distance within 4–9, 6–9 and 8–9 m. For these three different set of measurements, the analysis (including all the acoustic measures listed above) showed very comparable results when relating stage average values to subjective results. The results from Chapter 7 suggest that the source-receiver distance should be within 6–9 m for most reliable results (using transducer heights of 1 m), with a sufficient number of measurements as basis for spatial average value (ten in this case). The range 6–9 m was therefore used for the results presented in this chapter.

### 8.3.2 Architectural measures

In Chapter 3 a set of objective measures based on architectural drawings of the stage enclosure was proposed:  $W_{rs}$ ,  $H_{rb}$ ,  $D$ ,  $H_{rb}/W_{rs}$  and  $D/W_{rs}$ . These measures represent the distance to reflecting surfaces at the sides and above the stage, stage depth as well as two ratios based on these measures. These five measures were in Chapter 3 found to correlate significantly with the musicians' overall acoustic impression of twelve different stages. Gade (1989a) found that the stage volume correlated significantly with the level of acoustic support. Depending on the architectural design of the hall in general and the stage enclosure in particular it will often be difficult to define the volume associated with the stage. The stage volume,  $V_s$ , was here estimated as  $W_{rs} \cdot H_{rb} \cdot D$ . This quantity is only considered in Section 8.9 since this measure showed poor correlation with subjective data. The stage area  $A$  was also included among the architectural measures. This measure showed poor correlation with the subjective data and has therefore been omitted from the main correlation results.

Table 8.1 shows the architectural measures obtained for the eight halls of this study based on visual inspection of the stages and architectural drawings being available. Information relating to presence of risers, the stage enclosure design type (enclosed stage or stage exposed to the overall hall) and plan form of the venues are also included Table 8.1. In all cases where risers were present on stage, the risers covered the rear part of the stage only (for the woodwind, brass and percussion sections only).



Table 8.1: Architectural data for the eight halls studied. Presence or absence of risers, stage enclosure design and overall venue type are also indicated.

Hall	$W_{rs}$	$H_{rb}$	$D$	$\frac{H_{rb}}{W_{rs}}$	$\frac{D}{W_{rs}}$	$A$	$V_s$	Risers	Exposed	Plan
BA	17.6	19.6	12.6	1.11	0.72	179	4103	Yes	Yes	Arena type
BP	25.4	16.8	15.3	0.66	0.60	187	6528	No	No	Theatre
BC	18.4	10.5	10.0	0.57	0.54	120	1932	Yes	No	Shoe-box
CD	19.5	18.5	11.0	0.95	0.56	179	3968	Yes	Yes	Arena type
EU	16.1	6.6	10.7	0.41	0.66	153	1137	Yes	No	Shoe-box
PL	27.5	9.0	9.1	0.33	0.33	184	2252	Yes	No	Shoe-box
PG	20.8	11.4	10.5	0.55	0.50	195	2490	Yes	No	Shoe-box
WP	26.0	18.0	10.3	0.69	0.40	157	4680	No	No	Theatre

## 8.4 Questionnaire results

There was a response rate of 34 % (24 out of 70) to the questionnaires. 16 string players (3 1<sup>st</sup> violin, 3 2<sup>nd</sup> violin, 6 viola, 3 cello and 1 double bass player), three woodwind players (1 'woodwind', 1 clarinet & bass clarinet and 1 bassoon player), 4 brass players (1 trumpet, 1 French horn, 1 trombone and 1 tuba player) and 1 percussion player responded. This shows a reasonable spread and representation of players within the four instrument groups.

Table 8.2 and Figure 8.2 show the results for orchestra average values of the subjective characteristics for the eight halls. The halls are sorted according to orchestra average overall acoustic impression (OAI) with the most preferred hall on top.

Table 8.2: Orchestra average values of the subjective characteristics studied. Sorted according to overall acoustic impression OAI with the most preferred hall on top.

Hall	Co	HS	HO	CI	Rev	LNP	OAI
BA	4.2	4.1	4.5	4.2	4.1	3.9	4.6
CD	4.6	3.9	4.4	3.8	3.8	4.0	4.2
BC	2.2	4.1	3.9	3.9	3.9	3.4	4.0
EU	2.8	4.1	4.0	3.9	3.9	3.2	3.8
PG	2.7	3.5	3.5	3.2	2.6	3.1	3.1
PL	3.0	3.0	2.4	2.5	2.8	2.4	2.6
BP	2.8	3.3	1.8	1.8	1.3	4.0	1.2
WP	2.0	2.6	1.9	1.7	1.0	3.6	1.0

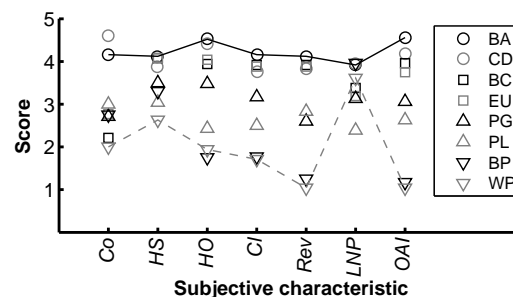


Figure 8.2: Orchestra average values of the subjective characteristics studied. Sorted according to overall acoustic impression OAI with the most preferred hall on top, with solid line through values for the most preferred and dashed line through values for the least preferred hall.

### 8.4.1 Comments from the players and meeting with players

It was difficult to extract individual comments from the players related to each of the venues, but Table 8.3 shows some of the comments made by the players regarding comfort on stage, the sound timbre in the hall, character of the reverberant sound and overall acoustic impression. The venues are sorted according to overall impression (*OAI*, orchestra average) with the most preferred hall on top. The comments are slightly edited (unless within quotation marks) to better represent the general experience reported by the players. The instrument of the commenting player is indicated if relevant. Comments on non-acoustic conditions relating to thermal comfort are not included – the general trend was that the least preferred halls receive more comments regarding poor thermal comfort.

The main findings from the meeting with some of the players of the orchestra were: PL is very loud with a symphony orchestra on stage and it is difficult to hear different instruments on the stage. The sound on stage is described as undefined with loud sound above the orchestra. With smaller ensembles PL is much better to play in. The back wall behind the percussion and brass and a shallow stage is often a problem since this contributes to raise the sound level of these instruments. Horns on the other hand often enjoy having a reflecting wall behind them, since that enables them to hear the sound/timbre they project towards the audience better. The players spoke positively about riser systems having quite large level differences for percussion and brass relative to woodwind and strings, unless the riser platforms were too narrow. Narrow risers often lead to the percussion and brass players being forced to sit close up front to other players. Behind the proscenium arch on the theatre stage, the players find there is a lack of reverberant sound.

Table 8.3: Extract of comments in the questionnaires on the eight halls sorted according *OAI* (orchestra average) with most preferred hall on top.

	Comfort	Timbre	Reverb char.	Overall acoustic impression
BA	Sometimes squashed, chairs not good, otherwise good.			Rewarding, good balance between instruments, still not enough room on stage.
CD	Some visibility problems for string (as usual).			A good hall, overhang from the choir seating found to distort sound for horns.
BC	Not enough space on stage, risers too narrow.	Some dead spots experienced for woodw.		Sound quality is good, overall good balance but poor staging (trumpet too loud for woodw.).
EU	Not enough space on stage.			"Enjoy it here unless in back desks being deafened." (cello) A good hall sound.
PG	Not enough space on stage.	Metallic sound.	Reverb almost non-existing.	"Feels totally isolated towards the back" (2 <sup>nd</sup> violin) Poor staging, lack of depth.
PL	Not enough space on stage, difficult to see (strings).	Muffled, harsh sound, difficult to distinguish.	Can't hear other side (1 <sup>st</sup> violin).	Too boomy, ensemble difficult, not enough. reverb, lack of clarity, too much reflections.
BP	Noise problems, chairs not good, no risers.	Dry, scratchy, abrasive.	No reverb.	"Not a venue for rewarding music making." (viola) Sound goes up, never comes down.
WP	Noise and space problems, chairs too low.	Flat, tinny, dull sound.	No reverb.	"Should not be used for orchestral concerts." Typical theatre.

## 8.5 Relationships between subjective characteristics

Studying the relationships between the subjective characteristics can provide useful information with regard to mechanisms of ensemble hearing. For instance, to what degree the ability to hear one's own instrument is linked with the ability to hear the others. This study only covers eight different halls judged by 24 players. With such small number of samples, the relations found from this study are likely to not be generally valid. The significance of differences between judgements of each of the halls and between the instrument groups are considered. This is followed by an discussion of the importance of reverberant sound from the main auditorium. Results from factor analysis, shown in Table 8.4, indicate that most of the subjective characteristics from this study are moderately or highly correlated, in particular measures related to ensemble conditions (*HS*, *HO*, *CI*) and overall acoustic impression (*OAI*). The responses from the players were based on memory over a time span of several months, which could have led to a more one-dimensional response. Based on this, only relationships between *OAI* and the other subjective characteristics are here considered.

Table 8.4: Correlation coefficients,  $r$ , from factor analysis of the subjective dimensions for six halls (excluding the two proscenium theatres), extracting two factors. Total number of samples  $N = 136$ .

Var.	Factor 1	Factor 2
<i>Co</i>	0.48	0.72
<i>HS</i>	0.69	0.15
<i>HO</i>	0.86	0.09
<i>CI</i>	0.83	0.11
<i>Rev</i>	0.69	0.44
<i>LNP</i>	0.63	0.45
<i>OAI</i>	0.87	0.05

### 8.5.1 Subjective characteristics related to overall acoustic impression

Given the limitations for this study mentioned above, studying relations between *OAI* and the other subjective characteristics may still be relevant as an indication of which subjective characteristics contributes the most to *OAI*. Table 8.5 shows the results for the correlation coefficients,  $r$ , between *OAI* and *Co*, *HS*, *HO*, *CI*, *Rev* and *LNP* among all the players. The results from BP and WP are here excluded to make more valid comparisons, as explained in Section 8.6.2. The number of responses ( $N$ ) for these six venues varied between 136 and 143. The results show that *HO*, *CI* and *Rev* are most correlated with *OAI* ( $r = 0.69$ ,  $0.68$  and  $0.61$  respectively). This agrees well with the findings from Chapter 3, where most players independent of instrument they played agreed that good acoustic conditions were recognised as being able to hear all other players clearly. These results also agree reasonably well with results by others. Gade (1981) found the most important aspects among 32 symphony orchestra musicians to be 'Reverberance', 'Support', 'Timbre', 'Dynamics', 'Hearing others', 'Hearing self', sorted according to frequency mentioned by the players (most frequently mentioned aspect listed first). Genta et al. (2007b) found perceived 'Ensemble' and 'Clarity' to be of most concern for musicians within two symphony orchestras.

Table 8.5: Correlation coefficients,  $r$ , between *OAI* and the other subjective characteristics. All correlations are significant at the 1 % level. Number of samples  $N=136-143$ .

Var.	<i>Co</i>	<i>HS</i>	<i>HO</i>	<i>CI</i>	<i>Rev</i>	<i>LNP</i>
<i>OAI</i>	0.33	0.53	0.69	0.68	0.61	0.49

The two measures *Co* and *LNP* can be seen as mainly controlled by physical stage conditions (like chairs, space available, air quality and risers). The correlations relating to *Co* and *LNP* are only moderate ( $r$  of 0.33 and 0.49 respectively). Such moderate correlations may be expected in any case, since there appears to be a tendency that halls purpose-built for symphony orchestras have favourable physical and acoustic conditions. Orchestra average values of *LNP* are moderate for most of the halls, which indicate that other instruments are a bit too loud on most stages. This situation does not appear to affect their judgement of *OAI* significantly. The comments from the players support such a conclusion: they comment on poor stage conditions, but judge the overall acoustic conditions as good for some of the halls (like BA). For some special/extreme cases the physical staging conditions appear to affect judgements of *OAI*, like *OAI* of BC particularly among the wind players as described in Section 8.5.2.

If including the two theatres BP and WP, the correlation between *OAI* and *Rev* is higher ( $r=0.85$ ). This agrees well with findings reported in Section 8.6.2. In principle, if only halls with an optimum level of reverberant sound were included when studying relations between objective and perceived conditions, the importance of reverberant sound may be hidden (the correlation between *OAI* and *Rev* is likely to be low). The results from the correlation analysis above and from Section 8.6.2 suggest that a suitable level of acoustic response is a primary requirement for good stage acoustic conditions.

## 8.5.2 Differences of subjective characteristics between the eight venues and instrument groups

To establish the subjective differences between the eight venues, Student's  $t$  tests have been conducted on orchestra average values of the seven subjective characteristics. The subjective measure showing the least significant differences is first considered, followed by increased significant differences. The results indicate that judgements of others not too loud *LNP* do not differ significantly (at the 5 % level) between most of the halls – only PL differ significantly from the other halls. The insignificant differences found for *LNP* could indicate that the sound level on stage is highly controlled by the orchestra arrangement (not so much the stage enclosure or the rest of the hall), but some exceptions like PL can exist. PL is reported as excessively loud, which could be caused by the particular combination of stage depth, ceiling height and riser system in PL; see Section 8.8 for more details. For *HS*, *HO*, *CI* and *Rev* the results indicate that differences in judgements between the four most preferred halls (BA, CD, BC, EU) and between the two least preferred halls (BP and WP) are not significant. For physical comfort (*Co*) most of the differences between the six least preferred halls are found insignificant. These halls have all a significantly lower score on *Co* compared to the two most popular halls BA and CD, as seen in Figure 8.2. Results of overall acoustic impression (*OAI*) show the most significant differences between the eight halls. This suggests that *OAI* is the subjective

measure which best discriminate between the eight halls. Figure 8.3 shows the results for *OAI* (orchestra average) for the eight halls, along with standard deviation indicated. Judgements of *OAI* for the four most preferred halls all differ significantly from judgements of each of the four least preferred halls. Insignificant differences of *OAI* are seen between CD, BC and EU, between PG and PL and between BP and WP.

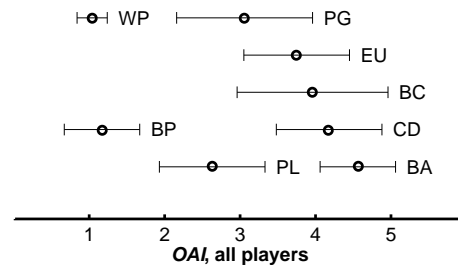


Figure 8.3: *OAI* (orchestra average) for the eight halls, including standard deviation ( $\pm\sigma$ ).

Variations of *OAI* between the four different instrument groups were also studied. Results from Student's *t* test analysis show that average values of *OAI* within strings, woodwind, brass or percussion do not differ significantly (at the 5 % level) from the orchestra average value – except for the one percussionist differing significantly for EU. With only one player representing the percussion group, this finding cannot be seen as significant for percussionists in general. This suggests that the overall acoustic impression is much a common experience among the players because it largely involves being able to hear all the others. The variation of *OAI* within each venue appears to be linked to personal differences as much as the type of instrument they play. The standard deviations within the different instrument groups are comparable to the standard deviation for the whole orchestra. For BC though, the average within woodwind and brass differ significantly from the average within string players. This can explain the high standard deviation of *OAI* for this hall. Based on the comments from the players several string players enjoy this hall, but many wind players comment on the shallow stage and the riser system contributing to very high sound levels on stage and problems with hearing the other players.

For the other subjective characteristics, also here only a few significant differences are found (also at the 5 % level). If ignoring responses from the single percussionist, *LNP* shows the most significant differences between the instrument groups (for BA, CD and PG). This agrees well with findings in Chapter 3: the string players find loud instrument less of a problem (higher values of *LNP*) compared to the woodwind and brass players. The other measures show significant differences in some cases, but it is difficult to find any general trends in the detected differences.

## 8.6 Results for objective acoustic measures

The details on the results of acoustic measures on stage and in the audience area for the eight venues studies are given in Chapter 7. This section only considers these results

relating to what may be regarded or known in general as noticeable perceived differences and recommended ranges.

The acoustic measures vary significantly more than published just noticeable differences (*JND*) for listeners among the audience. According to ISO 3382:1997, the *JND* for  $T_{30}$  is 5 % and 1 dB for  $C_{80}$  and  $G$  for listeners among the audience. The *JNDs* for musicians may be different compared to audience listeners, but the difference limen known can serve as an indication of how values of the acoustic measures can explain differences found in the subjective material. The results from Chapter 7 indicate that differences in values of  $T_{30}$  and  $G_I$  are found statistically significant, while several halls show insignificant differences of  $C_{80}$  values. Some halls have very comparable values of  $C_{80}$ , like BA, CD, EU and PG. The variation of  $T_{30}$  measured on stage is 160 % for the eight halls, while the variation of  $C_{80}$  and  $G_I$  is 8.4 and 7.0 dB respectively (average values within the three octave bands 500–2000 Hz). The high variation is much due to the two theatres (BP and WP). If excluding these two venues, the variations are 79 %, 1.6 and 3.2 dB respectively for  $T_{30}$ ,  $C_{80}$  and  $G_I$ . If relating to the known *JNDs*, the acoustic measures studied appear to only partly have values that appear to be clearly judged as different conditions.

For a concert hall in general, recommended ranges are  $T_{30}$  within 1.8 to 2.2 s,  $C_{80}$  within  $-2$  to  $+2$  dB and  $C_{80}$  and  $LF$  within 0.10 to 0.35 at mid frequencies, according to Barron (1993). All the three most preferred halls (BA, CD, BC) as well as the less preferred hall PL have average measured values for these three measures within the recommended ranges. This suggests that these four halls are the halls which are in general most suitable for symphonic music, but the architectural design of the stage enclosures vary considerably between these halls (as seen from Table 8.1). The stage enclosure may therefore be the significant factor leading to differences in judgements of these four venues, whereas for the other four venues the architectural design of the main auditorium in general may not lead to acoustic conditions suitable for symphonic music. See Section 8.6.2 for a discussion of the relevance of measured  $T_{30}$  and  $G_I$  with regard to isolating the effect of the stage enclosure.

### 8.6.1 Relationships between the acoustic and architectural measures

The correlation coefficients,  $r$ , between the acoustic and architectural measures have been found to be low. Between the architectural measures mutually, values of  $r$  are low except for some of the ratio measures. Between  $H_{tb}/W_{rs}$  and  $H_{tb}$   $r$  is 0.88 (significant at the 1 % level) and between  $D/W_{rs}$  and  $W_{rs}$   $r$  is  $-0.78$  (significant at the 5 % level). These correlations indicate that the stage enclosures tend to be either narrow and high or wide and low, and either shallow and wide or deep and narrow. This agrees well with the results from Chapter 3.

### 8.6.2 The importance of hall reverberation

The two proscenium stage venues BP and WP show the lowest (least favourable) score on most subjective characteristics. These two venues have drapes surrounding the orchestra on

stage and have no risers on stage. The measured reverberation time is short ( $T_{30}$  of 0.80 and 1.36 s) and particularly the level of the reverberant sound is lower than the six other halls ( $G_i$  of  $-1.0$  and  $-0.9$  dB respectively). See Section 7.5 for more details on the results of acoustic measures. The reverberant characteristics are typical values found within drama theatres.

In Chapter 3, eight different orchestras were through a questionnaire asked how they would describe good acoustic stage conditions and to rate halls they played in regularly. The results indicate that an optimum level of acoustic response from the main auditorium is important for good acoustic conditions. Hearing reverberant sound from the main auditorium was reported by the players with several positive aspects, among them: a sense of communication with and reaching through to the audience ('projection'), useful information with regard to level balancing and articulation, and it allows the wind players to breathe between phrases. A lack of audible reverberant sound, particularly from the audience area, appears to be a large problem for the players participating in the mentioned study and this study. When the players comment on their impression of BP and WP, a lack of reverberant sound is mentioned very frequently.

The results with regard to the importance of reverberant sound, particularly from the audience area, indicate that the level of reverberant sound also affect perceived ensemble hearing. The implication of this is that stage enclosures can only be compared if the levels of acoustic response in the main auditorium for the venues studied are comparable. If not, it will not be possible to sufficiently isolate the effect of stage enclosure and the main auditorium. In addition there might be a 'Halo effect' associated with (in this case) a lack of reverberant sound. If one of the aspects of perceived acoustic conditions are found totally flawed, it can affect their judgement of other aspects. For this study, these results suggest that the two venues BP and WP should only be included in the analysis when we discuss the effect of reverberation. For other aspects of acoustic conditions, in particular conditions relating to ensemble hearing (represented by *HS*, *HO* and *CI*), we should only include halls with comparable levels of reverberant sound. Based on the findings in Chapter 3 and measured  $G_i$  in the audience area (see Section 7.5.3), only the four halls BA, BC, CD and EU may have a main auditorium suitable for symphonic music, but studying only four halls may be regarded as a too small number for valid results.

Another condition not directly linked with the stage enclosure is the presence or absence of a riser system on stage. Significant variation of or the absence of a riser system can also lead to invalid comparisons of stage enclosures. The six remaining halls of this study all appear to have a reasonable level of acoustic response, based on both comments from the players and objective results, and they all have risers installed on stage.



## 8.7 Relationships between subjective and objective measures

Figure 8.4 shows results for average  $T_{30}$ ,  $C_{80}$ ,  $G_e$ ,  $G_{7-50}$ ,  $G_l$  and  $ST_{early}$  versus frequency for the octave bands 125–4000 Hz.  $G_e$  and  $G_{7-50}$  have been included since  $G_e$  relates to  $C_{80}$  and  $G_{7-50}$  excludes the direct sound. The shaded areas in Figure 8.4 define the range for the four most preferred halls. The four least preferred halls show values below or above the shaded areas, except for  $ST_{early}$  where the four most preferred halls define almost the entire range of results. For  $G_e$  and  $G_{7-50}$  the two theatres BP and WP show marginally lower values for some of the octave bands. For  $T_{30}$ ,  $C_{80}$  and  $G_l$  the two theatres are clearly distinguished, as well as PL with the high values of  $T_{30}$  and  $G_l$  (particularly at the 125 Hz octave band) and low values of  $C_{80}$ .

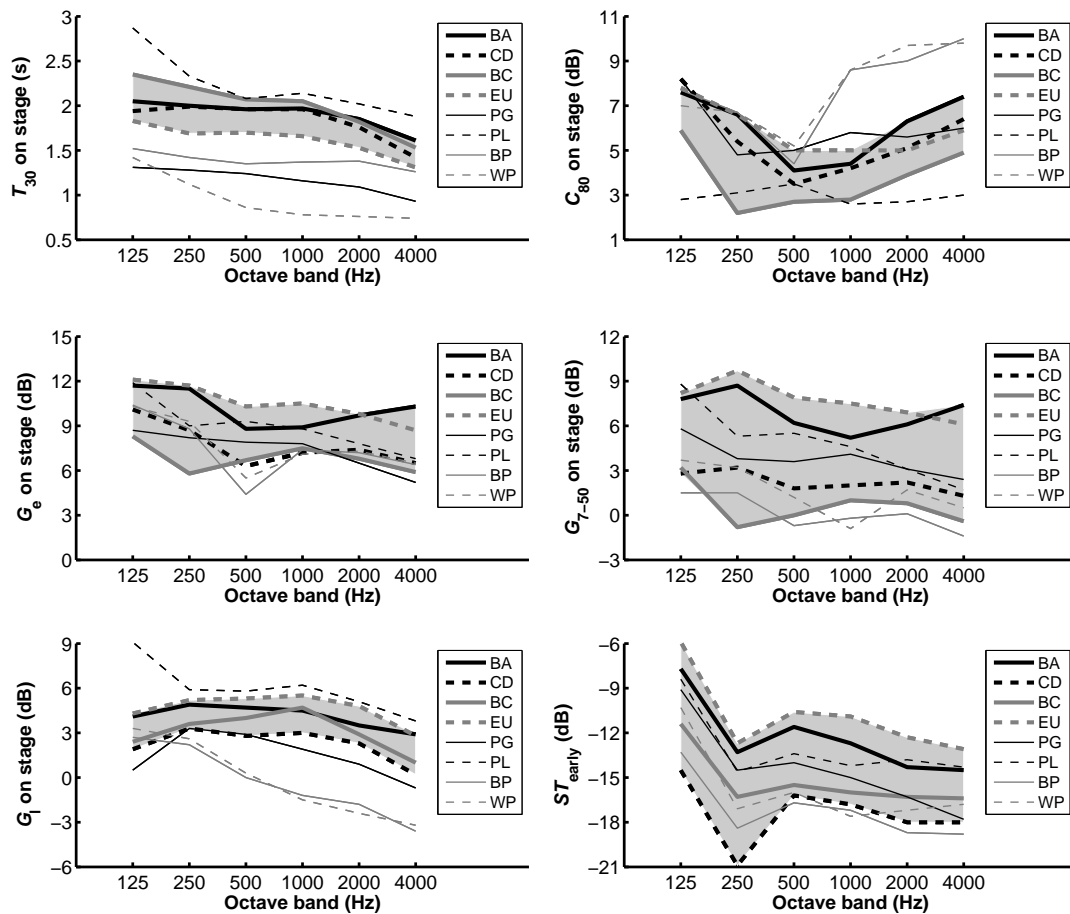


Figure 8.4:  $T_{30}$ ,  $C_{80}$ ,  $G_e$ ,  $G_{7-50}$ ,  $G_l$  and  $ST_{early}$  measured on stage versus frequency, for the octave bands 125–4000 Hz. Sorted according to  $OAI$  (orchestra average) with the most preferred hall on top. Shaded area spans values for the four most preferred halls.

As suggested in Chapter 7, studying stage average values may lead to a significant lack of information regarding the variation of levels of early reflections at different positions on stage, and lead to  $G_e$  and  $G_{7-50}$  being more correlated with  $G_l$ . Based on these findings, values of  $G_e$ ,  $G_{7-50}$  were also studied at different source-receiver distances and paths, and values of  $ST_{early}$  were studied at individual source positions and differences between for instance front

and back position on stage (S4 minus S1). These results also showed a large spread for the four most popular halls and no clear trends similar to the results in Figure 8.4.

### 8.7.1 Results of correlation analysis

The correlation coefficients,  $r$ , between the orchestra average values of the seven subjective characteristics and the ten objective measures were investigated. With responses from all the eight halls included, only the subjective characteristics *Rev* and *OAI* were studied (for reasons described in Section 8.6.2). With the two theatres BP and WP excluded, the relations between all the seven subjective and the ten objective measures were studied. Table 8.6 shows the results with all eight halls included. The results show that  $G_l$  has the highest and most significant correlation with *Rev* ( $r=0.82$ ). With regard to *OAI*, the three acoustic measures  $T_{30}$ ,  $C_{80}$  and  $G_l$  show high values of  $r$ , in particular  $G_l$ . For the architectural measures,  $W_{rs}$  show the highest correlation with the subjective characteristics.

Table 8.6: Correlation coefficients,  $r$ , between subjective (orchestra average) and objective stage measures including all eight halls. Bold numbers indicate significance at the 1 %, underlined at the 5 % level. Total number of samples  $N=8$ .

Var.	$T_{30}$	$C_{80}$	$G_l$	$ST_{early}$	$ST_{late}$	$W_{rs}$	$H_{fb}$	$D$	$\frac{H_{fb}}{W_{rs}}$	$\frac{D}{W_{rs}}$
<i>Rev</i>	<u>0.78</u>	<u>-0.79</u>	<b>0.82</b>	0.48	<u>0.75</u>	<u>-0.81</u>	-0.25	-0.30	0.22	0.49
<i>OAI</i>	<u>0.71</u>	<u>-0.73</u>	<u>0.75</u>	0.43	0.65	<u>-0.83</u>	-0.13	-0.25	0.34	0.52

Since this study is not needed to demonstrate that orchestras find performing on a theatre stage difficult, the remaining analysis will concentrate on the remaining six halls. It is however worth noting that the major recorded subjective difference between the theatre spaces and the other halls concerned hall reverberance. The theatre spaces used no risers for the orchestra and the orchestra was surrounded by sound absorbing theatre drapes. The presence of a proscenium opening also restricts communication between the main auditorium and the stage area. Such a lack of communication with the main auditorium appears to be indicated by measured  $G_l$  on stage being comparable to  $G_l$  measured in the audience area. Such conditions are found for BP, see Section 7.6 for more details. Standard advice for auditoria with proscenium openings when they are to be used for orchestral music is that a stage enclosure should be used.

The correlation matrix between subjective and objective stage parameters for the remaining six halls is given in Table 8.7. This shows no significant correlations with the measured acoustic measures, while on the contrary the architectural measures generally show high values of  $r$ . With regard to *OAI*, all the architectural measures show  $r$  above 0.67.

### 8.7.2 The relevance of acoustic measures

The eight halls studied vary from theatres to purpose-built concert halls. From the acoustic measures,  $T_{30}$ ,  $C_{80}$  and  $G_l$ , assessed on stage it appears to be possible to distinguish between the most preferred halls, which are halls purpose-built for symphonic music, and the other

Table 8.7: Correlation coefficients,  $r$ , between subjective (orchestra average) and objective stage measures, excluding BP & WP. Bold numbers indicate significance at the 1 %, underlined at the 5 % level. Total number of samples  $N=6$ .

Var.	$T_{30}$	$C_{80}$	$G_I$	$ST_{early}$	$ST_{late}$	$W_{rs}$	$H_{rb}$	$D$	$\frac{H_{rb}}{W_{rs}}$	$\frac{D}{W_{rs}}$
Co	0.26	0.23	-0.20	-0.16	-0.09	-0.09	<u>0.86</u>	0.62	0.81	0.33
HS	0.04	0.36	-0.15	0.04	-0.15	<b>-0.96</b>	0.32	0.68	0.54	<u>0.91</u>
HO	-0.03	0.50	-0.39	-0.09	-0.34	<u>-0.89</u>	0.61	<u>0.83</u>	0.77	<u>0.90</u>
CI	0.06	0.39	-0.19	0.03	-0.17	<b>-0.94</b>	0.43	0.76	0.64	<b>0.93</b>
Rev	0.47	0.03	0.16	0.04	0.18	-0.74	0.39	0.60	0.57	0.78
LNP	0.03	0.44	-0.50	-0.28	-0.44	-0.73	0.80	<u>0.84</u>	<u>0.90</u>	0.78
OAI	0.25	0.28	-0.19	-0.09	-0.14	-0.79	0.67	<u>0.82</u>	<u>0.82</u>	<u>0.86</u>

halls. The four most preferred halls are clearly distinguished from the other halls with these three measures. The results suggest an optimum range of  $T_{30}$ ,  $C_{80}$  and  $G_I$  for the performers. Within the four most preferred halls it is difficult to see any clear differences between these halls in terms of measured  $T_{30}$ ,  $C_{80}$  and  $G_I$ . These results and the correlation analysis results suggest that the acoustic measures averaged within 500–2000 Hz are mainly relevant for assessing effects associated with reverberation like perceived reverberance and sound levels, but not relevant for perceived ensemble conditions (like ability to hearing other players). That  $RR_{160}$  has not been found relevant regarding perceived reverberance can be associated with poor physical validity of the first 160 ms of the impulse response measured without musicians. The relevance of the acoustic measures is further discussed in Section 8.9.

Values of  $G_e$ ,  $G_{7-50}$ ,  $G_I$ ,  $C_{80}$  at individual octave bands may be relevant for perceived sound levels on stage, temporal clarity and presence of early reflections. The highly absorbing stage enclosure in the theatres BP and WP can be detected by use of  $G_e$  and  $G_{7-50}$ , in particular  $G_{7-50}$  since the time interval of 7–50 ms will include mostly the response from the stage enclosure as well as exclude the direct sound and floor reflection. With the orchestra present levels of  $G_{7-50}$  will be further reduced, so a measured lack of early reflections will hold true also with the orchestra present. In PL measured  $G_I$  is high while measured  $C_{80}$  is low at 125 Hz. This corresponds well with the comments from the players regarding high sound levels on stage and a lack of clarity. Results by Zha & Fuchs (2002) and Adelman-Larsen *et al.* (2010) suggest that reverberant sound at low frequencies (63–125 Hz) is important for perceived ensemble conditions and clarity of sound among musicians, but with only one hall showing extremely high values of  $G_I$  and low values of  $C_{80}$  it is difficult to conclude regarding the relevance of perceived temporal clarity for these measures. Results from Chapter 4 show that acoustic conditions at low frequencies (for the 63 and 125 Hz octave band) are not significantly affected by the presence of the orchestra on stage. This suggests that measurements of acoustic conditions at low frequencies on an empty stage will be reasonable valid compared to the conditions with an orchestra present. The moderately raised values of  $C_{80}$  for the 2 and 4 kHz octave bands found for the four most preferred stage may be beneficial for retaining temporal clarity when the orchestra enters the stage, and is an indication of the level of early reflections on stage (as long as  $G_I$  is not excessively low or high). In Section 7.2, values of  $C_{80}$  within 500–2000 Hz were reduced by the introduction of the orchestra, and values of  $C_{80}$  within 500–2000 Hz for the six most preferred stages correlate moderately ( $r=0.50$ ) with the impression of hearing others (HO). The very high values of  $C_{80}$  for the theatres (BP and WP)

may indicate a lack of late acoustic response entering the stage from the main auditorium (or within the stage enclosure itself).

Results for  $ST_{\text{early}}$  show no clear discrimination between the four most and least preferred halls. The time window of early reflections in the definition of  $ST_{\text{early}}$  (20–100 ms) will mainly include early reflections from the stage enclosure in purpose-built concert halls. In smaller halls like the theatres BP and WP, reflections from the main auditorium are also included within 20–100 ms. This leads to values of  $ST_{\text{early}}$  in the theatres that are comparable to one of the purpose-built concert halls (CD), even if the stage enclosure consist of drapes (which is normal for theatres). The generally raised levels at 125 Hz and reduced levels at 250 Hz of  $ST_{\text{early}}$  appear to be caused by the method of obtaining the reference level for  $ST_{\text{early}}$ . For  $ST_{\text{early}}$  the reference level is defined as the combined level of the direct sound and floor reflection (energy in impulse response within 0–10 ms). The interference effect between the direct sound and the floor reflection is frequency dependent (as showed in Section 4.2), causing the reference level for  $ST_{\text{early}}$  to also vary with frequency.

### 8.7.3 The relevance of architectural measures

The relevance of the architectural measures (based on stage enclosure dimensions) were only studied without the two theatres, BP and WP. The results from the correlation and regression analysis show correlation coefficients of moderately high values, between all five architectural measures and most of the subjective characteristics. For assessing perceived ensemble conditions, the architectural measures combined with visual inspection of the architectural detail stage enclosure (see more details below) therefore appear much more relevant compared to the acoustic measures studied. The architectural measures are simplified representations of the real acoustic conditions provided by the stage enclosure, but appear useful as ‘rules of thumb’ to assess stage enclosures. The high correlation between  $H_{\text{rb}}/W_{\text{rs}}$  and  $OAI$  may be caused by several aspects of stage acoustic conditions being assessed by  $H_{\text{rb}}/W_{\text{rs}}$ , as suggested in Chapter 5. The results suggest that low values of  $H_{\text{rb}}/W_{\text{rs}}$  (typically below 0.4), especially in combination with a non-exposed stage enclosure, will lead to poor acoustic conditions for symphony orchestras. This agrees well with comments made by the players, for instance related to PL (a purpose-built concert hall with a wide and low stage enclosure with a shallow stage). The relevance of the architectural measures is further discussed in Section 8.9.

That  $H_{\text{rb}}$  correlates better with  $LNP$  than  $G_l$  or  $G$  could be related to the following: results from the computer model study in Chapter 6 showed that reflections from above are less obstructed by the orchestra compared to reflections from the sides. On the contrary simulated values of  $G$  for an empty stage showed very similar values with side reflecting surfaces compared to overhead surfaces. Also [Berntson & Andersson \(2007\)](#) found measured values of  $G$  on an empty stage to not correspond well with experienced loudness on stage.

## 8.8 Architectural details relating to acoustic impressions

The architectural measures only represent the architectural design of the stage enclosure in a very simplified manner. It is there relevant to study the architectural details of stage enclosure in a qualitative way as well. If we study the two most popular stages (BA and CD), these stages have side walls close to the orchestra. These side walls are about 2.5 m high with tilted top sections. The stage depth is relatively generous, the stage is acoustically highly exposed to the rest of the hall volume and the dominating horizontal surface above the stage is more than 15 m above the stage floor. If we study the least popular purpose-built concert hall (PL), we see that this stage has a low and flat ceiling, as well as a shallow and very wide stage. The stage side walls on this stage consist of staggered bricks creating a curved sound scattering surface.

Based on the findings from Chapters 5 and 6 the preference for the above mentioned three stages may be explained as follows: BA and CD provide beneficial compensating reflections with minimum delay, while keeping the level of competing sound low (except for the reflective back wall on these stages, particularly on BA). This contributes to a good balance between the different sections, enabling the players to hear all the other players clearly. The tilted side walls and high ceiling may also allow the players to hear the acoustic response from the main auditorium. In PL all these factors are negatively reversed, and the players complain about a loud stage with poor balance and clarity of sound, not being able to hear the acoustic response from the main auditorium.

In EU the stage is small and the stage enclosure low compared to the seven other halls. The angled ceiling appears beneficial to reduce the level of reflections from percussion and brass as well as project the acoustic response from the main auditorium down towards the orchestra.

## 8.9 Combined study including results from comparable studies

With a limited number of halls studied, there is a high risk of finding invalid correlations. For a more valid investigation of the relevance of the objective measures, analysis were carried out including results from this study, results from Chapter 3 and Cederlöf (2006). Cederlöf (2006) carried out a comparable study investigating five different orchestra's impressions of the stage acoustic of their home venues. All the five venues were built to suite a symphony orchestra. Results from the first orchestra study (Chapter 3) suggest that studies including home orchestras could be less valid, due to adaptation to the acoustic conditions – it is not known to what degree these orchestras are regularly visiting other venues as well which may affect the validity of their judgements of their home venues. But no other studies have been found that has investigated only impressions of halls visited on a regular basis. Her study did not compare subjective and architectural measures (only subjective and acoustic measures), but the five proposed architectural measures were obtained from Cederlöf (2006) and from home pages for these halls on the Internet. Table 8.8 shows the results for Cederlöf's study,

where  $G_l$  is estimated from measured  $T_{30}$  and hall volume based on Equation 3.1. These three studies combined results in a total of 22 halls including the two theatres BP and WP. The different scales of  $OAI$  were converted to represent a common scale ranging 1–5 for all the halls in the following manner:  $OAI_{1-5} = \frac{4}{9} OAI_{1-10} + \frac{5}{9}$  for the results from Chapter 3, and  $OAI_{1-5} = \frac{4}{10} OAI_{0-10} + 1$  for the results by Cederlöf (2006).

Table 8.8: Acoustic and architectural measures for the halls studied by Cederlöf (2006), sorted according to overall impression  $OAI$  among all players.  $OAI$  ranging 0–10.

Hall	$OAI$	$T_{30}$	$G_l$	$ST_{early}$	$W_{rs}$	$H_{rb}$	$D$	$\frac{H_{rb}}{W_{rs}}$	$\frac{D}{W_{rs}}$	$A$	Risers
VCH	9.3	1.80	3.8	−11.0	14.8	15.8	12.4	1.07	0.84	190	✓
GCH	5.5	1.70	2.7	−14.0	19.1	12.0	12.4	0.63	0.65	210	✓
NLG	4.5	2.03	2.3	−16.0	21.5	7.7	15.5	0.36	0.72	255	✓
MCH	4.1	2.03	3.3	−12.7	21.0	9.5	15.0	0.50	0.71	286	✓
SB	4.1	1.93	2.8	−13.7	30.0	14.0	15.0	0.47	0.50	224	✓

Table 8.9 shows the result for correlations coefficients,  $r$ , with the theatres BP and WP excluded. The results for the correlation coefficients agree well with the results in Chapter 3 and Section 8.7.1.

Table 8.9: Correlation coefficients,  $r$ , between objective and subjective characteristics for the three different studies. Bold numbers indicate significance at the 1 % level, underlined significance at the 5 % level.

Var.	$T$	$G_l$	$ST_{early}$	$W_{rs}$	$H_{rb}$	$D$	$\frac{H_{rb}}{W_{rs}}$	$\frac{D}{W_{rs}}$	$V_s$
$OAI$	−0.10	−0.04	0.16	<u>−0.56</u>	<u>0.56</u>	−0.09	<b>0.77</b>	0.35	0.11

Figure 8.5 shows the acoustic measures plotted versus  $OAI$  (orchestra average), while Figure 8.6 shows similar plots for the architectural measures. The standard deviation of  $OAI$  is included where visually suitable. For  $T$  and  $G_l$ , the two theatres BP and WP is here included. Values of  $T$  and  $G_l$  represent average value within the audience area for all the halls.  $G_l$  was estimated based on measured  $T$  and  $V$  or measured within stalls area (for studying the most comparable values). The results from the three different studies, as well as the two theatres BP and WP are given different symbolic representation in Figures 8.5 and 8.6. The figures include linear and parabolic (2<sup>nd</sup> order polynomial) regression curves with corresponding correlation coefficients  $|r|$  (the absolute value of  $r$ ). The parabolic regression curves are useful for revealing potential optimum ranges, not easily discovered from correlation analysis (which is based on linear regression analysis).

The results for both acoustic and architectural measures agree well with the results from Chapter 3, where the acoustic measures  $G_l$  and  $T$  only were found relevant for assessing level of acoustic response, which appear to be reasonably suitable for all the 20 halls (excluding BP and WP). For the most preferred halls, no clear relations between  $OAI$  and  $G_l$  and  $T$  are seen. As mentioned in Chapter 3 it is likely that a multidimensional space from a set of different objective measures will be most relevant to study. The acoustic measures appear most relevant for assessing perceived ‘projection’ and ‘bloom’ while the architectural measures appear relevant for assessing the ability to hear other players clearly. For a discussion of  $ST_{early}$ , see below. For stage volume,  $V_s$ , no clear relations are seen relating to  $OAI$ .



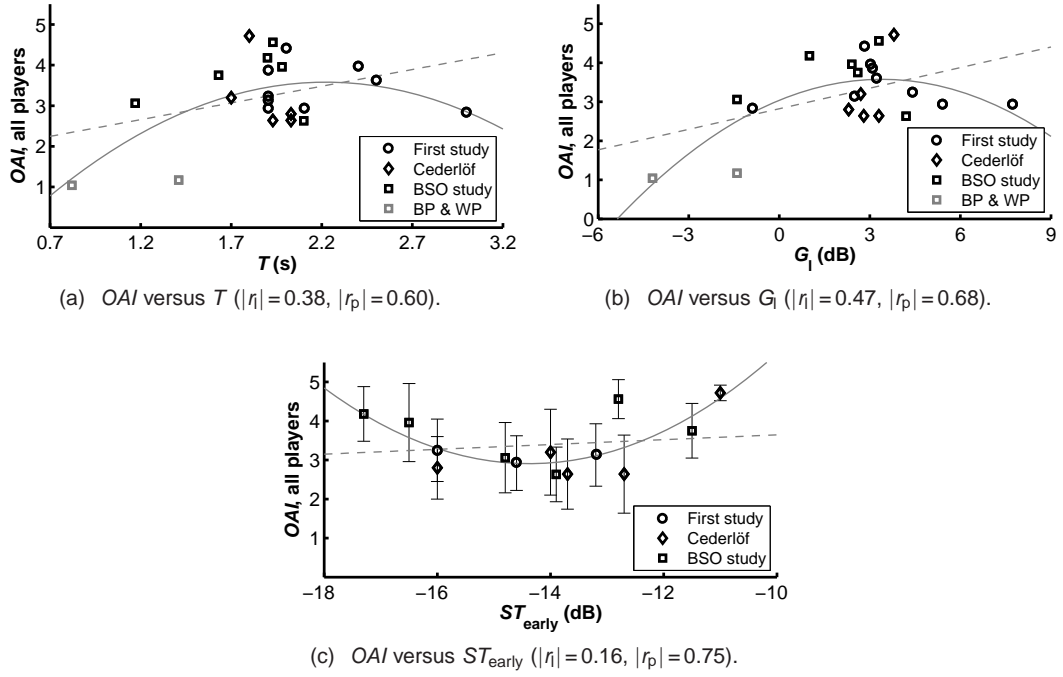


Figure 8.5:  $OAI$ , all players versus acoustic measures for the three studies combined. Standard deviation of  $OAI$  marked as  $\pm\sigma$ . The curves represent linear (dashed) and parabolic (solid) regression curves, with the correlation coefficients  $|r_l|$  (linear regression) and  $|r_p|$  (parabolic regression) indicated. The theatres BP and WP are here included for  $T$  and  $G_l$  while excluded for  $ST_{early}$ .

Halls with  $0.35 < H_{rb}/W_{rs} < 0.6$  have a large spread of  $OAI$ . Halls with  $H_{rb}/W_{rs} \leq 0.35$  show consistently low values of  $OAI$ , and halls with  $H_{rb}/W_{rs} \geq 0.6$  show consistently high values of  $OAI$ . This agrees well with the results found in Chapter 3. The finer details of the stage enclosure design, not only overall dimension, appear most critical for intermediate values of  $H_{rb}/W_{rs}$  and  $H_{rb}$ . The finer details can affect the presence of compensating and competing early reflections and to what degree the stage is exposed to the acoustic response from the main auditorium. By use of  $W_{rs}$  and  $H_{rb}$  focus has been on compensating reflections from the sides compared to competing reflections from above. To what degree compensating reflections can be provided above the string players instead of at the sides have not been studied in detail, much due to  $H_{rs}$  being highly correlated with  $H_{rb}$  for the halls studied. The more significant subjective relevance of  $H_{rb}/W_{rs}$  compared to  $W_{rs}$  and  $H_{rb}$  could be associated with  $H_{rb}/W_{rs}$  assessing the balance between compensating and competing early reflections; see Section 5.11 for a discussion of the subjective relevance of the architectural measures. None of the most preferred halls are of popular halls from the 19<sup>th</sup> century (like Musikverein in Vienna or Symphony Hall in Boston), but they all have a stage which is reasonably exposed to the rest of the auditorium.

For  $D$  a parabolic relationship is found relating to  $OAI$ , as opposed to a linear relationship in Chapter 3. This is caused by the deep stages included in Cederlöf's study having low values of  $OAI$ . The indication of an optimal range of  $D$  is supported by the subjective results from Chapter 3, which indicate that (particularly) French horn players prefer having a reflecting surface behind them at moderate distance. Percussionists may also appreciate a reflecting surface close to them, for enhancing low frequencies, as discussed in Chapter 5. The players



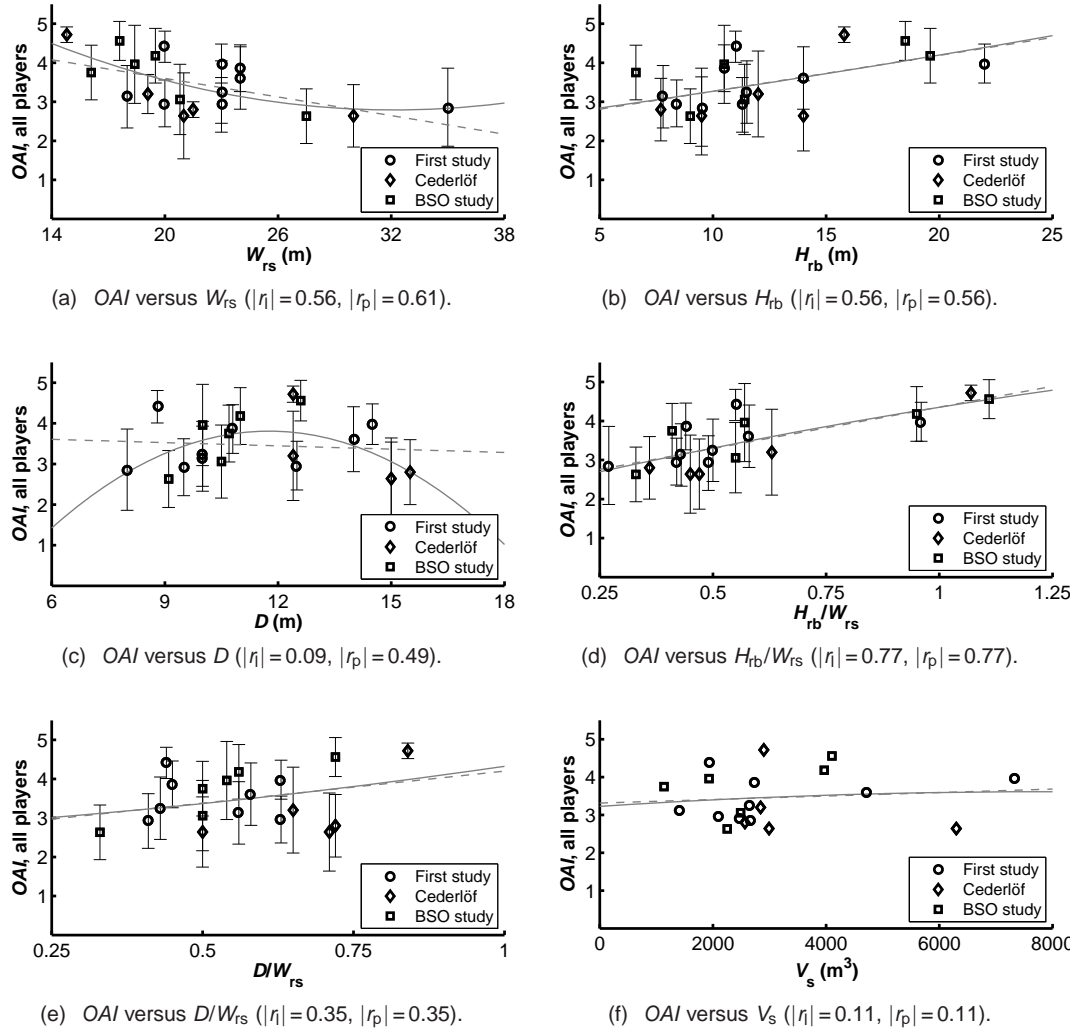


Figure 8.6:  $OAI$ , all players versus architectural measures for the three studies combined. Standard deviation of  $OAI$  marked as  $\pm\sigma$ . The curves represent linear (dashed) and parabolic (solid) regression curves, with the correlation coefficients  $|r_l|$  (linear regression) and  $|r_p|$  (parabolic regression) indicated. The theatres BP and WP are here excluded.

appear to appreciate sitting close to each other in general, since large distances introduce more delay and attenuation of the mutual sound. But very shallow/small stage are not practical to play at since the players need some free space around them to play comfortably.

The relevance of the architectural measures for perceived acoustic conditions was in Chapter 5 studied analytically with references to perceptual effects like masking of sound and the cocktail-party effect. In Chapter 6, computer modelling was carried out to study more complete impulse responses with orchestra present on stage, with regard to compensating and competing reflections provided by the stage enclosure. Together, these studies support the conclusion that a narrow and high stage enclosure acoustically highly exposed to the main auditorium will provide the most beneficial listening conditions for orchestral musicians. For stage enclosures initially being wide, reflecting surfaces above the orchestra only providing compensating reflections down towards the string players may have a positive effect, though the studies above suggest that overhead reflecting surfaces will be less beneficial for the string players compared to side reflections.

For the two Norwegian symphony orchestras who participated in the survey described in Chapter 3, the players were also asked about their impressions of their home venues. The stage enclosures for their home venues have recently been changed in attempts to improve the acoustic conditions for the players. The players' reported experiences relating to changes in acoustic conditions caused by the modifications of the stage enclosures agree well with the studies of existing stages and the computer modelling investigations; see Appendix G for more details.

With regard to Gade's proposed stage measures (Support,  $ST$ ), the results indicate that his proposed  $ST_{late}$  correlates highly with  $G_l$  ( $r=0.97$ , significant at the 1 % level).  $G_l$  has been found relevant for evaluating the level of acoustic response on stage and within the audience area. The calibration method used for obtaining values of the  $ST$  measures appears less reliable compared to the calibration method for obtaining  $G$  (ISO 3382:1997), leading to a preference for  $G_l$ ; see Section 7.7 for more details. On the other hand, the results from both subjective studies as well as the combined study show no significant correlations between  $ST_{early}$  and subjective characteristics when only including halls that appear to have a moderately suitable level of acoustic response in the main auditorium.  $ST_{total}$  was within this study found to correlate significantly with  $ST_{early}$  ( $r=0.96$ , significant at the 1 % level). Results from recent studies by others (Cederlöf (2006), Genta *et al.* (2007a), Berntson & Andersson (2007) and van Luxemburg *et al.* (2009)) also indicate that values of  $ST_{early}$  are not significantly correlated with subjective characteristics. The lack of subjective relevance of  $ST_{early}$  is likely related to the direction of the early reflections not being assessed and the physical reliability of the measure. The relationship between  $OAI$  and  $ST_{early}$  shown in Figure 8.5(c) shows no sign of an optimum range for  $ST_{early}$ . The halls with  $H_{rb}$  below 11 m tend to have values of  $ST_{early}$  around  $-13$  to  $-12$  dB, and low values of  $OAI$ . This can explain the minimum point of the parabolic regression curve in Figure 8.5(c). The shape of the regression curves are also likely to be affected by a limited number of halls included as well as problems associated with obtaining a stage average value, as described in Section 7.5.1. But studying the results of  $ST_{early}$  at individual positions on stage does not, from this study, appear to increase the subjective relevance.

No information is given on hall volumes for the halls studied by Gade, but the information provided in Gade (1989c) indicates that both subjective studies carried out by Gade included halls with low values of  $T$  which scored very low on perceived ensemble conditions (like the two halls BP and WP in this study which were excluded when considering stage enclosures). This may provide some explanation to why  $ST_{early}$  was found to correlate significantly with perceived ensemble conditions by Gade. From this study  $ST_{early}$  was found subjectively more relevant when including the two theatres (which were found to be too dead acoustically), since  $ST_{early}$  will assess the level of the acoustic response. In Section 7.5.2  $ST_{early}$  was found to correlate significantly with  $G_l$ . Therefore, if including halls with a lacking or excessive level of acoustic response from the main auditorium, combined with not including stage enclosures with very low values of  $H_{rb}/W_{rs}$ ,  $ST_{early}$  is likely to correlate positively with for instance  $OAI$ . Additionally, some of the halls in Gade's study were judged by home orchestras or by one orchestra judging halls they had only visited once (on a tour). Results from the first subjective study of this project (Chapter 3) suggest that judgements of home venues or halls only visited occasionally should

be excluded. Based on these findings, both of Gade's two studies may be criticised for not providing a valid selection of halls and orchestras for comparing different stage enclosures.

## 8.10 Conclusions

Finding clear relations between perceived conditions and physical properties is difficult due to low controllability of the physical conditions and most symphony orchestras only play regularly in a limited set of halls. This study has investigated the impressions of eight different halls experienced by one orchestra regularly playing in these halls. This is likely to overcome some of the uncertainty factors involved, since the players have built their impression over a long period of time.

The results from this study suggest that an optimum level of late/reverberant acoustic response on stage is critical. For optimal conditions, it also appears important that the late/reverberant acoustic response from the audience area should be the dominating late/reverberant response on stage. Ensuring that the level of acoustic response provided by the main auditorium is suitable for symphonic music is likely to lead to more valid comparisons of different stage enclosure designs. These findings agree well with the findings in Chapter 3. The acoustic measures based on monophonic omnidirectional impulse response that appear most relevant to subjective characteristics are listed in Chapter 7.

When studying only venues that apparently have a suitable level of acoustic response from the main auditorium (for a symphony orchestra), the acoustic measures studied show no significant relations to the perceived conditions when being assessed without the orchestra present. The architectural measures assessing distance between reflecting surfaces show the best correlation with subjective characteristics, in particular  $H_{rb}/W_{rs}$ . This finding supports the developed concept within this project of compensating and competing early reflections provided by the stage enclosure and the importance of the stage being sufficiently exposed to the main auditorium. When doing similar analysis including all available results with regard to overall acoustic impression and objective measures, the architectural measures are confirmed as most relevant for assessing stage enclosures. On the contrary, the objective measure  $ST_{early}$  proposed for assessing ensemble conditions shows no significant relations to overall acoustic impression. The possible explanations for the insignificant relations found between  $ST_{early}$  appear to relate to both physical validity and reliability (as discussed in Chapter 7), the relevance of directions of early reflections for perceived ensemble conditions (as discussed in Chapter 5) and the elimination of halls having a main auditorium with an unsuitable level of acoustic response.

Differences of average values of quantitative measures between several venues, both objective and subjective, were found statistically insignificant. This demonstrates the limitations of quantitative studies and the need for including qualitative information when comparing acoustic conditions at different venues, like architectural details and dialogue with players regarding perceived conditions.

## Chapter 9

# Overall discussion and conclusions

There were three major goals for this study: to establish the musicians' impressions of acoustic conditions, to investigate characteristics of occupied stage enclosures and to determine the acoustic characteristics of the main auditorium which are beneficial for performers on stage. The scope of the study has been wide, searching for the most important relations between objective and subjective conditions. In this chapter the conclusions from individual chapters above are brought together for a concluding discussion.

The most significant results from this project may be summarised as follows:

- Complex aural perceptions are involved for musicians on concert hall stages. Being able to hear all the other players clearly, well balanced with the sound from one's own instrument and acoustic response from the main auditorium was found to be the most important aspects of acoustic conditions among the players.
- The attenuation of sound within the orchestra itself has been investigated and quantified. The sound level within the orchestra has been denoted the 'within-orchestra sound level'. String players are found to experience the lowest within-orchestra sound levels for the most typical orchestra arrangement.
- Early reflections provided by a stage enclosure have been categorised as either 'compensating' or 'competing' for studying how low within-orchestra levels between certain instrument groups are being improved or made worse by the stage enclosure. The direction and delay of early reflections provided by the stage enclosure appears highly relevant. Early reflections from the sides with minimum delay are found to provide compensating reflections back to the string players most efficiently, compared to early reflections from above.
- Acoustic measures based on monophonic omnidirectional room acoustic responses on empty stages are found to correlate poorly with impressions of hearing others clearly and one's own instrument. Such measures are found most significant regarding assessment

of perceived reverberance and acoustic communication with the audience and for detecting a general lack of or excessive early and late acoustic response. The acoustic measures found subjectively most relevant are also found to be the most physically valid measures when comparing with results with an orchestra present.

- Differences in acoustical responses and measures between different stage enclosure designs are found more significant if assessed with an orchestra present compared to empty stage.
- If having narrow side walls close to the string players, beneficial conditions can apparently be reached by having the stage highly exposed to the main auditorium without overhead reflecting surfaces at heights below 13 m (relative to the stage floor). If the stage enclosure is wide, results suggest it will be difficult to fully compensate for this by use of overhead reflecting surfaces – also based on considering the conditions for the conductor.
- A method for including a symphony orchestra in computer simulation models has been developed. Results from computer modelling of different generic stage enclosure designs with orchestra present showed significant differences in simulated impulse responses across the stage.

This discussion and conclusions chapter focuses on the three major goals of this study, overall outcomes and ends by considering how future investigations of the acoustics of concert hall stages might be pursued.

## **9.1 The musicians' impressions of acoustic conditions**

Two subjective studies were carried out which involved dialogues with a few players and questionnaires distributed to eight orchestras in total where the players responded anonymously. This has provided very useful information with regard to how the musicians within professional orchestras relate to and experience acoustic conditions on stage, in purpose-built concert halls as well as other venues not primary designed for orchestral performance. There are significant differences between responses made by individual players, and the responses are not strongly linked to the instrument they play for most acoustic aspects. For issues relating to loudness of other instruments and physical staging conditions (like space available and riser systems), the instrument they play appears significant. For judgements of other acoustic aspects, the variation of judgements appears to relate to personal preferences and training as much as the instrument they play. When asked about overall acoustic impression, significant differences were found between the most and least preferred purpose-built concert halls. To obtain valid and relevant judgements from the players the following conditions need to be fulfilled:

- When asking about conditions relating to ensemble, the halls judged should all have an acoustic response suitable for a symphony orchestra. If including halls the players find too 'dead' or 'live', sufficiently valid comparisons cannot be made of different stage enclosure designs.

- The players should play regularly in the halls they are requested to judge, but home venues should be excluded. If halls visited only occasionally or home venues are included, the validity of their judgements could suffer due to limited experience or adaptation to certain acoustic conditions.

Previous studies of stage acoustic conditions, by [Gade \(1989c\)](#) for instance, have not been carried out according to the conditions above. This means that the results from these studies may not be entirely valid for large orchestras on stage. This may help explain why some results from this project contradict the results of others.

In this project, meetings were successfully arranged with a few number of musicians who find it interesting discussing how acoustic conditions affect a symphony orchestra. On the other hand, the response rate on questionnaires distributed to the participating orchestras was generally low. Most players agree that acoustic conditions are essential to them, but apart from giving their overall acoustic impression, most players struggle to describe in detail how the acoustic conditions or the design of the stage enclosure affect them. The players appear to be able to tell when acoustic conditions differ, but struggle to define *what* they experience as different and what could be the cause(s). It therefore appears easier for the players to relate to changes of acoustic conditions, compared to describing their impressions of different existing venues. This may relate to both their focus as performers and the mismatch of background between musicians and acousticians, as discussed in the Introduction. It may also relate to political aspects, like being uncomfortable with criticising the design of certain existing venues – maybe in particular their home venue. In this respect, excluding judgements of home venues could be positive for the validity of results (as indicated above) and the participation of players. When designing questionnaires for quantitative studies, as well as qualitative, it appears essential to take into account these perspectives.

The results from the collaborations with individual musicians and orchestras have provided information regarding how the players will describe/define good acoustic conditions, what acoustics aspects are more frequently a problem for them and their impressions of existing halls.

## 9.2 Acoustic conditions imposed by the arrangement of a symphony orchestra

A significant portion of this research has focused on the acoustic conditions of a symphony orchestra on stage and how the instrument groups appear to synchronise relative to each other. Both scale and computer model investigations have studied acoustic conditions with a full symphony orchestra present on stage. This issue was raised by [Halmrast \(2000\)](#), but no other investigations have been found in the literature where a full symphony orchestra (or a similar group of people and objects) was included when investigating specific stages. This can explain why the results from this study show results that deviate significantly from results by others, like for instance [Gade \(1989c\)](#).

Early in this study it became obvious that the presence of an orchestra on stage has a major influence on objective stage acoustic conditions. This needed to be quantified before making any study of the effects of stage enclosures. The conclusions from these studies with reference to general knowledge about perceptual effects support the conclusions from the subjective investigations of this research – also with regard to their preference relating to existing stages.

The results from the studies of the acoustic conditions of a symphony orchestra show that sound between players far apart on stage is at higher frequencies significantly attenuated by other players and objects (music stands and instruments), particularly for players sitting on flat floor. Such low sound levels compared to the sound level from other instrument groups, make acoustic communication between these players problematic. On most stages this effect is most significant for the string players. The acoustic communication problems between string players appears to be made even worse as a results of how the different instrument groups synchronise relative to each other. The sound between string players will be at risk of being temporally masked by the sound from other loud instruments within the orchestra (typically percussion and brass).

### **9.3 Requirements of auditoria for suitable stage conditions for symphony orchestras**

The results above indicate that it is important that the main auditorium has an optimum level of late/reverberant acoustic response for a symphony orchestra. For halls where the main auditorium has a very low or high level of acoustic response, the overall acoustic impressions among the players are consistently low. If there is a lack of reverberant sound from the main auditorium, it will be difficult to compensate for this by making the stage enclosure reverberant. The results from this project and by others suggest that reverberant stage enclosure will represent a risk of excessive sound levels, lack of temporal clarity and lack of audibility of the acoustic response originating from the main auditorium.

The objective measure  $G_l$  has been found to best correlate with overall acoustic impression and perceived reverberation. That the level of reverberant response is more relevant than reverberation time agrees well with findings by [Kahle & Jullien \(1994\)](#) and [Griesinger \(1995\)](#). When comparing stage enclosures, the result for  $G_l$  in the audience area (estimated from measured  $T$  and hall volume  $V$  or calculated from measured  $G$  and  $C_{80}$ ) can be used to assess a venue's suitability for a symphony orchestra and to ensure that only halls that appear to have a suitable level of acoustic response are included if comparing different stage enclosure designs. See Section 7.8 for more details.



## **9.4 Stage enclosure designs suitable for symphony orchestras**

When studying impressions of the acoustic conditions of specific stages, it has been found important to ensure that the level of acoustic response from the main auditorium is within an optimum range for all the stages included. Findings also suggest that the most valid judgements are made by players playing regularly in a set of halls, and judgements of home venues should be excluded due to adaptation. When including only this given set of halls and judgements, the results show poor subjective relevance for the acoustic measures studied. The architectural measures proposed by this research take the location of and distance between reflecting surfaces surrounding the orchestra into account and appear to give an indication of acoustic conditions with a full orchestra present. These measures correlate significantly with judgements of overall acoustic impression and perceived ensemble conditions for 20 purpose-built concert halls, where the stage enclosure designs differed significantly. The architectural measures offer a useful rule-of-thumb, but are not a replacement for any of the existing acoustic measures. A range of different aspects relate to perceived conditions. The results from this project suggest that a combination of objective measures, acoustic as well as architectural, together can provide some overall guidance when assessing stage enclosures.

Results from the orchestra collaborations suggest that the perceptual effects of level and temporal masking, as well as the cocktail-party effect, could be relevant for the players' impression of hearing all other players clearly. Detailed investigations of how these effects are affected by overall dimensions of the stage enclosure have not been found in the literature. Results from this study indicate that a stage enclosure generally described as narrow, high and moderately deep will lead to the least detrimental masking effects, minimise perceived delay of sound across the stage, aid the cocktail-party effect and enable the players to hear the acoustic response from the main auditorium.

The results associated with the architectural measures support the concept developed within the project regarding compensating and competing early reflections provided by a stage enclosure. The results from both subjective and objective studies consistently indicate that a stage enclosure being generally described as narrow and high, moderately deep and exposed to the main auditorium leads to the most beneficial acoustic conditions for the players. Such an enclosure appears to lead to the most beneficial conditions for the conductor and audience as well. For cases where for instance the enclosure is very wide or significantly enclosed from the main auditorium (like for a proscenium stage), carefully designed overhead reflecting surfaces (reducing the height on stage) may improve conditions even though it may not fully compensate for too remote reflecting surfaces at the sides of the string players – for instance introducing compensating reflections with a minimum delay at a sufficient level appears more difficult with overhead reflecting surfaces. Critical aspects of overhead reflecting surfaces (not studied in detail within this project) appear to be the balance of compensating and competing reflections as well as projection of the late acoustic response from the main auditorium towards the players particularly for enclosed stages.

Barron & Dammerud (2006) investigated findings by others regarding stage dimensions and preferred delay of reflections returning to the players. There was little evidence in the literature for the benefits of narrow and high stage enclosures. Results from some of the previous studies have suggested that narrow and high stage enclosures are beneficial, but results have been contradicting and several studies included only a small number of halls or orchestras. On the other hand, low overhead reflecting surfaces have previously been found by others to have negative effects. The results from this study with regard to compensating reflections in general and for the string players in particular agree well with the laboratory findings by Naylor (1988) and Gade (1989b). More recent studies by Cederlöf (2006), Andersson (2007) and Giovannini (2008) also show results with regard to dimensions or dimension-ratios of the stage enclosure which agree well with the results from this research.

## 9.5 Relevance of measured omnidirectional acoustic responses for assessing the stage enclosure

By use scale and computer models omnidirectional monophonic acoustic responses on stage with and without an orchestra present have been studied within this project. The overall conclusion is that the finer details of the acoustic response is highly affected by the presence of an orchestra on stage and that conditions on an empty stage is a poor indication of the acoustic conditions that the players experience. Such a conclusion agree well with the finding within this project that acoustic measures based on monophonic omnidirectional responses on empty stage are found to correlate poorly with impressions of hearing others clearly and one's own instrument. These results also agree well with more recent results by Cederlöf (2006), Genta *et al.* (2007a), Berntson & Andersson (2007) and van Luxemburg *et al.* (2009). The details on existing acoustic measures that appear relevant for assessing stage acoustic conditions are given in Section 7.8.

Acoustic measures based on impulse responses obtained in scale or computer model with orchestra present are likely to prove subjectively more relevant (compared to measures based on results from an empty stage with chairs). But such values of acoustic measures have not been compared to subjective characteristics for this project.

## 9.6 Overall outcomes

This research project has provided results regarding what type and level of reflected sound the musicians need to communicate efficiently and have acceptable working conditions. Some of the existing stages today have enclosures providing more early reflections than appear necessary, leading to excessive sound levels with risk of hearing loss among the players. A lack of reflected sound has within this project been found to be equally frustrating for the players. Beneficial conditions for the players regarding reflected sound rely not solely on the design of the stage enclosure, but also on a well designed main auditorium.

Well designed stage enclosures can make the venue more versatile, also with regard to repertoire. For instance better communication across the stage among string players can make it easier to use the German orchestra configuration (Appendix A), or select repertoire where for instance the structure and durations in the music are less predictable (more improvised music compared to classic or romantic repertoire). If the players are able to communicate easily between each other and enjoy making music, chances are high that they will make exciting music for the audience as well. A narrow and high, exposed stage is preferred by the orchestra and also appears to be beneficial for the conductor and audience as well (mentioned by Meyer (2008) and Griesinger (2006)). With a narrow stage enclosure the double basses will be next to a hard reflecting surface which helps raising sound levels at the lowest frequencies from the double basses contributing to a fuller sound.

When making sound recordings of symphony orchestras, reflecting surfaces close to the microphones are often problematic. Normally the microphones hang above the orchestra, so the finding regarding the benefits of a high enclosure within this project also appears to benefit conditions for sound recordings.

## 9.7 Future work

The results from this research have led to objective measures that successfully discriminate between the least and most preferred stages. This result is beneficial for being able to assess the risk of 'disastrous' conditions for the players and gives some indication of what objective characteristics are likely to lead to very favourable conditions. For moderately popular halls the proposed objective measures fail to discriminate between them. The major explanations for this limited discrimination appear to relate to the acoustic measures being obtained from measurement on stage without an orchestra present and that no directionally dependent acoustic measures were included or developed for this study. Quantitative studies, like acoustic measures will also have limited amount of information compared to qualitative studies. This appears also to be true for the subjective studies. From the results of this project, including the orchestra on stage appears more important compared to inclusion of directionally dependent measures. The most cost-effective way to include the orchestra on stage is by use of scale or computer modelling. The proposed method within this project for including the orchestra in a computer model should be further verified by measuring responses within a real orchestra on a real stage. In computer models the direction of arriving reflections can easily be studied. Some criteria to time arrivals and levels of early reflections for sufficient level balance and clarity of sound appear possible to develop. Acoustic measures based on omnidirectional responses may also prove more valid when being based on responses with an orchestra present.

Based on the observations above, scale and computer models appear to be the best option for studying objective acoustic conditions on stage. Quantitative studies, both objective and subjective, should be supplied with qualitative studies. Stage acoustic conditions for a symphony orchestra are a result of complex relations between a large set of variables. Such complex relations should be assessed without reducing the amount of information too

much. All acoustic measures are a very simplified representation of the detailed acoustic response. Existing acoustic measures cannot fully replace the study of the finer details of the acoustic response on stage, and for instance the experienced cocktail-party effect among the musicians (apparently relevant for perceived clarity of sound on stage) is not easily quantified. The potential success of developing new techniques for assessing acoustic conditions on empty stage (for instance by including directional discrimination) appears to be limited by both early and late reflections found to be significantly affected by the presence of the orchestra. Quantitative subjective studies may be improved by further developing the questions being asked to musicians through questionnaires, but a significant portion of the input from the musicians within this project has come through dialogue and open questions in the questionnaires (where the musicians could explain their experiences in their own language, and the interpretation of some of the received responses were discussed with some of the participating musicians after the questionnaires were returned).

Even with the orchestra present it appears difficult to predict perceived conditions based on measured acoustic responses within the orchestra, since perceived conditions are based on complex mechanisms. This suggests that the most valid studies of stage acoustic will involve a full symphony orchestra playing under realistic acoustic conditions, where the players identify the differences between highly controllable varying acoustic conditions. Only halls having a suitable level of acoustic response within the main auditorium (stalls area) should be included in such studies. The fixed design of most existing concert halls make such studies difficult, but for instance [Berntson & Andersson \(2007\)](#) and [Halmrast \(2000\)](#) provide examples where such investigations were possible based on one orchestra's own initiative to look at how the acoustic conditions could be improved for their home venue. Simulating acoustic conditions in an anechoic laboratory may be an alternative, but it appears essential that a full symphony orchestra is participating (to include relevant within-orchestra sound levels and masking effects) and that the generated acoustic conditions (by use of a set of loudspeakers) are realistic. How the players have adapted to specific conditions through their career is likely to affect the validity of their judgements. The results from this research indicate that the players participating should play in a set of different halls regularly (to not have a too biased view). Judging different acoustic conditions over a short period of time with a small range of musical program can make it difficult for the players to establish a well-balanced view of new conditions.

Good communication between acousticians and musicians about the quality of acoustic conditions appears beneficial to further raise an understanding of the musicians' point of view and how the different factors involved are interrelated. In general the communication between two parts will be more effective if both parts have some common references and respect the view of the other part. It is hoped that this thesis can contribute to an increased mutual understanding, particularly the acousticians better understanding the situation for the musicians better, on a qualitative level. It is, as mentioned in Chapter 1, challenging for the musicians to focus on how the acoustic conditions affect their performance and explain to the acousticians the characteristics of their preferred acoustic conditions. But luckily some of the players are found to be interested in these matters and willing to participate in dialogues with acousticians. Future projects investing stage acoustic conditions may benefit significantly from having such musicians involved in the project to improve the communication, scope and approaches for the investigations.

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## Appendix A

# The symphony orchestra

A symphony orchestra normally consists of 90 players (the size of the orchestra depends on repertoire) and consists of four major instrument sections: strings (typically 16 1<sup>st</sup> violins, 14 2<sup>nd</sup> violins, 12 violas, 10 cellos and 8 double basses), woodwinds (typically 2 flutes, 1 piccolo flute, 2 oboes, 1 cor anglais, 2 clarinets, 2 bassoons, 1 double bassoon), brass (typically 4 horns, 3 trumpets, 3 trombones, 1 tuba) and percussion (typically 1 timpani and 3 other percussion instruments), according to [Bennett \(1990\)](#). Figure A.1 shows the arrangement of a typical symphony orchestra. The depth of the orchestra normally varies within 8–14 m, and the width is rarely less than 16 m.

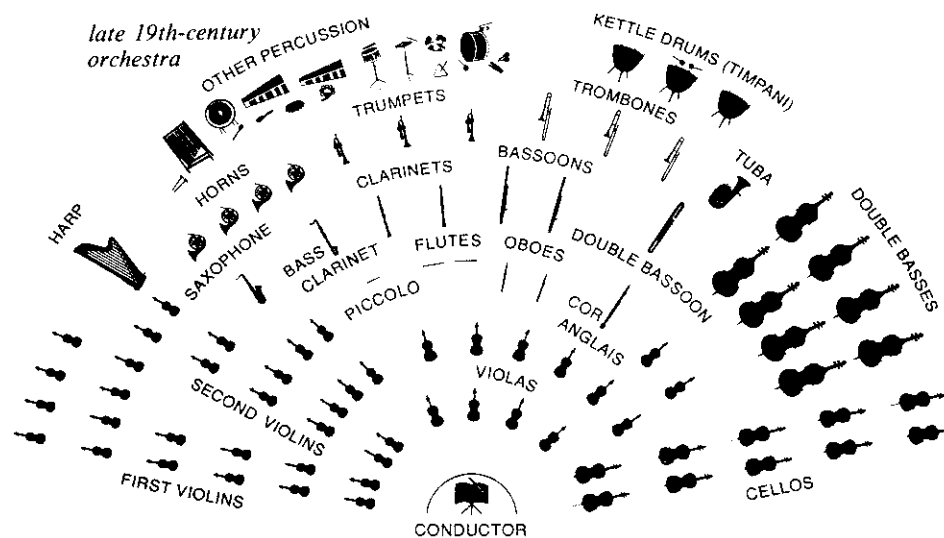


Figure A.1: The symphony orchestra, typical arrangement. From [Bennett \(1990\)](#).

## A.1 Orchestra arrangements

The arrangement of the string players can vary. Figure A.2 shows examples of different arrangements used, from [Meyer \(1987\)](#). The leftmost arrangement shown in Figure A.2



is known as the American. The central arrangement is associated with the conductor Furtwängler, while the rightmost is known as the German (or European) arrangement. The German arrangement results in a 'stereo effect' of the violins, with the first and second violins on opposite sides (Meyer, 1993). Several symphonic works have been written with this arrangement in mind, creating a 'dialogue' between the two violin sections for the audience. The American arrangement is said to be motivated by the monophonic recording technique used during the '50s, and it normally requires a shorter rehearsal time for the orchestra, according to Orestad (2005). With the American arrangement a synchronised onset of tone is easier achieved between the two violin groups since they are sitting together using this arrangement, and the stereo effect lost its value on mono recordings. During the 21<sup>st</sup> century the German arrangement has become more popular again due to its stereo effect and an interest for performing a piece with the orchestra arrangement it was originally written for. According to Orestad (2005), violin players have commented that it is easier to listen outside the violin group with the German arrangement. But at the beginning of rehearsals many violin players experience more difficulties with the two violin groups sitting on opposite sides of the stage.

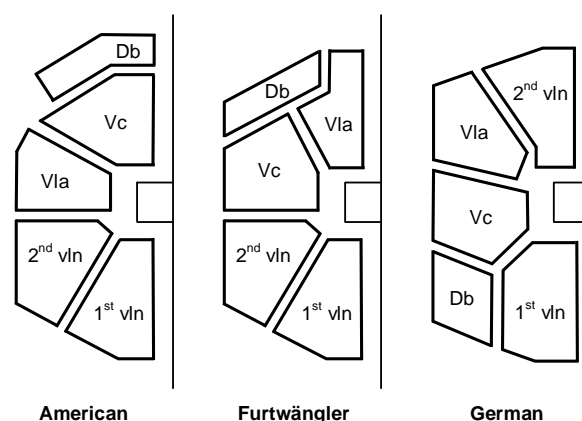


Figure A.2: Different arrangements of the string sections. 1<sup>st</sup> vln = 1<sup>st</sup> violin, 2<sup>nd</sup> vln = 2<sup>nd</sup> violin, Vla = viola, Vc = violoncello/cello, Db = double bass. From Meyer (1987).

## A.2 Directional characteristics of orchestra instruments

Most musical instruments within a symphony orchestra are directional at higher frequencies. In general, the directivity of instruments increases with increasing frequency. At lower frequencies almost all instruments are omnidirectional (they emit sound equally in all directions), but above 500 Hz most instruments start to radiate more sound energy in certain directions. Figure A.3 shows measured polar patterns for the radiation of sound from a violin and trumpet, according to Olson (1967). Meyer (2004) has also published an extensive collection of his own measured directivities of musical instruments.

The strings are among the weakest sounding instruments in the orchestra (Meyer, 2004). The brass instruments are directed towards the audience but also towards the woodwinds and strings. This leads to the direct sound levels varying significantly within the orchestra. The



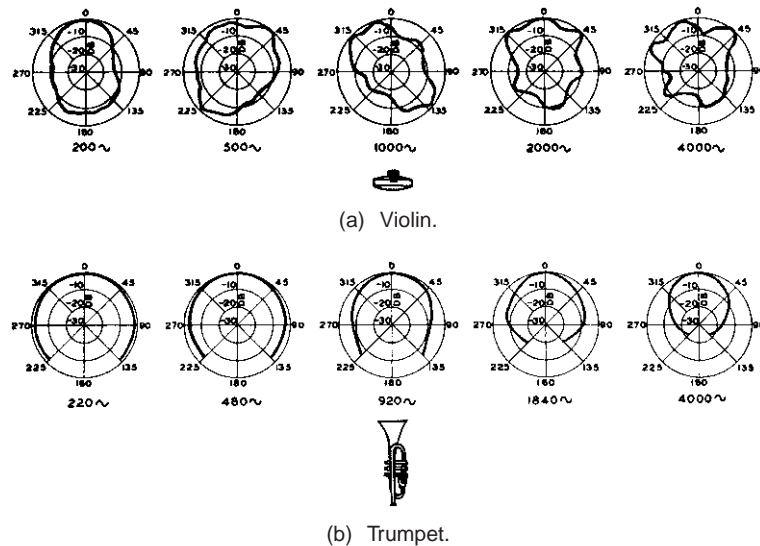


Figure A.3: Directivity of violin and trumpet, after [Olson \(1967\)](#).

directivity (spatial radiation pattern) of string instruments varies considerably with frequency, as shown in Figure A.3(a). The complicated directivity pattern is much influenced by the resonances of the instruments' body made of wood, and the resonance patterns vary significantly for each note played ([Hutchins \*et al.\*, 1971](#)). The brass, especially the trumpets and trombones, are among the loudest instruments and become highly directional at higher frequencies. Figure A.3(b) shows measured directivity patterns for a trumpet. The directivities of brass instruments show a more regular pattern, and are the most consistent between each note played, compared to string and woodwind instruments. This is due to the sound being radiated from the same physical point independent of note played on brass instruments (as investigated by [Otondo & Rindel \(2004\)](#), [Meyer \(2004\)](#) and [Vos \*et al.\* \(2003\)](#)).

### A.3 Stage floor area per musician

With regard to stage floor area per musician the recommendation according to [Barron \(1993\)](#) is:

- 1.25 m<sup>2</sup> for upper string and wind instruments
- 1.5 m<sup>2</sup> for cello and larger wind instruments
- 1.8 m<sup>2</sup> for double bass
- 10 m<sup>2</sup> for timpani, and up to 20 m<sup>2</sup> more for other percussion instruments

For a full 100-member orchestra (with a normal percussion section) this means a net covered area of about 150 m<sup>2</sup>. The smallest stage area observed, based on [Beranek \(2004\)](#) and [Barron \(1993\)](#), is 111 m<sup>2</sup> (Colston Hall, Bristol, UK), while the largest stage area observed is 397 m<sup>2</sup> (Sala São Paulo, Brazil).

## A.4 Stage risers

Risers (raised platforms) are common for the players at the back of the stage (woodwind, brass and percussion) for raising the direct sound levels and improving sightlines, both for the performers and the audience. Some stages have risers forming a semi-circular pattern, where woodwind, brass and percussion, as well as back desks of strings are on risers. Figure A.4 shows the layout for these two types of riser systems.

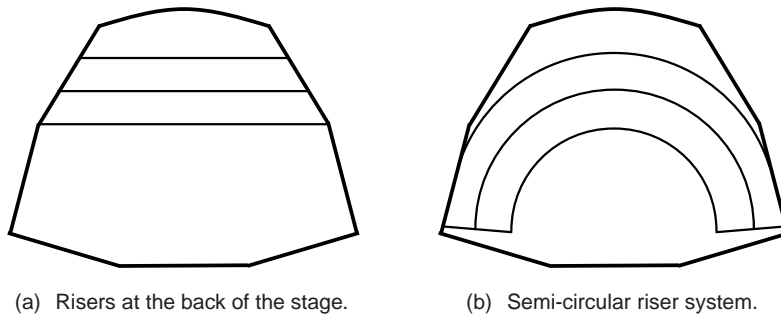


Figure A.4: The most common stage riser types.

## Appendix B

# Questionnaires

Pages 195–196 show a sample of one of the questionnaires covering impressions of stage acoustic conditions in general. Pages 197–198 show a sample of one of the questionnaires covering impressions of stage acoustic conditions for specific stages.



## University of Bath – Acoustic questionnaire

We are in the middle of a three year research project looking at acoustics for performers in concert halls. An important part of this project involves finding out from musicians what their own views are. Your orchestra very kindly offered to collaborate with us on this.

This questionnaire considers some general issues relating to your personal experiences. We would be most grateful to receive your response, please feel free to write further comments in the margins etc. Please make a cross in the appropriate boxes. The questionnaire is being run anonymously.

Which instrument do you play (including section for violins)? \_\_\_\_\_

If you are a string player, are you a tutti player or at the front? ☐ Tutti player ☐ Front desks

How long have you played in a professional symphony orchestra? \_\_\_\_\_ years

To what degree does the acoustics for you as a performer vary between the halls in which you play?

A little		Somewhat		A lot
<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4	<input type="checkbox"/> 5

What non-acoustic issues are significant to you that differentiate between the halls you play in (such as visibility of other players, lighting, thermal comfort etc.)?

----------------------

Which hall anywhere do you remember for providing you with the **most** sympathetic acoustic environment in which you have ever played (one only, please include town)?

Can you explain why you preferred this hall? \_\_\_\_\_

----------------------

1) How important is the floor area and space available to you on stage?

Seldom an issue		Moderately important		Very important
<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4	<input type="checkbox"/> 5

2) What is your preference regarding stage area for whatever reasons?

Compact		Medium		Large
<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4	<input type="checkbox"/> 5

3) What is your preferred riser configuration for providing best conditions for the orch. as a whole?

No risers	Woodw., brass, perc. only on risers	Curved risers	Other
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

If 'Other', please specify / Additional comments: \_\_\_\_\_

4) How often do loud instruments near you complicate your ability to play your own instrument?

Frequently		Sometimes		Very rarely
<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4	<input type="checkbox"/> 5

If so, which instruments are normally too loud? \_\_\_\_\_

5) How important is it for you being able to spatially separate the sound from different instruments?

Very important		Moderately important		Seldom an issue
<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4	<input type="checkbox"/> 5

6) How often do you have problems with focusing on particular instruments?

Frequently		Sometimes		Rarely
<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4	<input type="checkbox"/> 5

If so, please describe how you perceive this and how it affects you: \_\_\_\_\_

7) Are you aware of surfaces close to the stage which contribute positively or negatively to the acoustics for you?

Not aware		Moderately aware		Very aware
<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4	<input type="checkbox"/> 5

If so, please describe how you perceive this and how it affects you: \_\_\_\_\_

8) How important is it to hear the sound coming from the audience area?

Seldom an issue		Moderately important		Very important
<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4	<input type="checkbox"/> 5

In terms of hearing others, which instruments/groups are most important for you to hear to achieve good ensemble?

Do you agree or disagree with the following statements: "Acoustics for performers depends on the correct balance between hearing yourself and hearing other players" and "Good acoustics depends on clarity of sound from others"

Please comment on these two questions: 1) What type of useful information would you say there is in the reverberant sound coming back to you from the hall? 2) Does the direction of the reverb sound matter?

The following are seven halls in which you play regularly:

- |   |  |
|---|--|
| <input type="checkbox"/> Symphony Hall (Birmingham) | <input type="checkbox"/> Leeds Town Hall       |
| <input type="checkbox"/> Hanley Victoria Hall       | <input type="checkbox"/> Bedworth Civic Hall   |
| <input type="checkbox"/> Wolverhampton Civic Hall   | <input type="checkbox"/> Malvern Forum Theatre |
| <input type="checkbox"/> Cheltenham Town Hall       |  |

Please give each of these halls a score between 1 and 10 for their acoustics for the performer, 10 = very good. Two or more halls can have the same score.

Comment on the reasons for your choice of the best and worst halls:

Thank you very much for your patience in completing this. We are happy to share the results with those that are interested.

Mike Barron and Jens Jørgen Dammerud

## Basingstoke – The Anvil

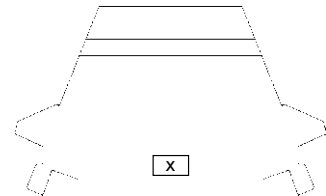
Roughly how many times you have played in this hall? \_\_\_\_\_

Which instrument do you play (including section for violins)? \_\_\_\_\_

If you play violin, viola or 'cello, are you a tutti player or at the front?

☐ tutti player ☐ front desk

Please indicate with a cross where you usually sit on this stage:  
(similar to the x at the conductor's position)



Physical comfort: is the stage comfortable for you to play on?

Comfortable ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Uncomfortable

If not fully comfortable, what problem do you have? \_\_\_\_\_

1) Ensemble – How easy is it to play in time with other players in this hall?

Difficult ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Easy

2) Ensemble – How easy is it to balance your sound with other players?

Difficult ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Easy

3) Ensemble – How easy is it to achieve correct intonation with other players?

Difficult ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Easy

4) Ensemble – How easily can you distinguish your own voice from surrounding instruments?

Sufficiently ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Insufficiently

5) Dynamics – How easy is it to achieve a fortissimo effect?

Easy ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Difficult

6) Dynamics – How easy is it to achieve an expressive sound in pianissimo passages?

Easy ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Difficult

7) How do you experience timbre at your position on this stage?

Natural ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Unnatural

If unnatural, please describe the sound. For your own instrument, whole orchestra or any specific group?

\_\_\_\_\_

\_\_\_\_\_

8) How do you find the acoustic response from the hall (resonance of the room)?

Live, reverberant ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Dead, no response



## Basingstoke – The Anvil

If reverberant: does this make a positive contribution to good blend, overall sound etc. or does it lead to confusion or other negative effects?

Reverb positive	<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4	<input type="checkbox"/> 5	Reverb negative contribution
-----------------	----------------------------	----------------------------	----------------------------	----------------------------	----------------------------	------------------------------

If reverb makes a negative contribution, please describe the sound:

---

9) Reflections – Are there any specific reflections or echoes audible to you from the hall to your position in the orchestra?

Clearly audible	<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4	<input type="checkbox"/> 5	Not audible
-----------------	----------------------------	----------------------------	----------------------------	----------------------------	----------------------------	-------------

If audible: does it contribute to good sound on stage or is it annoying? Can you say something about the direction and the delay of these discrete reflection(s)/echo(es)?

---

10) Balance – Do you struggle to hear some instruments or groups in this hall?

Severe problem	<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4	<input type="checkbox"/> 5	Not a problem
----------------	----------------------------	----------------------------	----------------------------	----------------------------	----------------------------	---------------

If yes, which instrument(s) or group(s) do you struggle to hear?

---

11) Balance – Do some instruments or groups become too loud for you in this hall?

Severe problem	<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4	<input type="checkbox"/> 5	Not a problem
----------------	----------------------------	----------------------------	----------------------------	----------------------------	----------------------------	---------------

If yes, which instrument(s) or group(s) become(s) too loud?

---

12) How clearly can you hear the instruments you need to hear?

Easy to hear details	<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4	<input type="checkbox"/> 5	Struggle to hear details
----------------------	----------------------------	----------------------------	----------------------------	----------------------------	----------------------------	--------------------------

Which are the most important instruments for you to hear clearly (in this hall)?

---

13) Overall impression for you as a performer of the acoustical conditions of this hall

Very poor	<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4	<input type="checkbox"/> 5	Very good
-----------	----------------------------	----------------------------	----------------------------	----------------------------	----------------------------	-----------

Any comments related to the questions above, or other comments about this hall:

## Appendix C

# Frequency response of panel reflections

This appendix discusses the frequency response of reflection off finite surfaces, like free-standing/-hanging surfaces or smaller surfaces attached to other large surfaces. Such surfaces will typically be overhead reflectors and panels at the back and sides of the stage enclosure. The effect of attaching the surface to another large surface, horizontally or angled, is discussed.

Based on earlier work by [Cremer \(1954\)](#), [Rindel \(1991\)](#) has published a simple theory that enables calculation of the diffraction effect for reflections from free-standing finite surfaces. The diffraction effect leads to the level of reflection being low below a certain limiting frequency,  $f_0$ . Only situations where one dimension of the reflector is large are here considered, so that diffraction effects are determined by the other (finite) dimension only. Equation (C.1), from [Barron \(1993\)](#) based on [Cremer \(1954\)](#), shows how to determine the limiting frequency  $f_0$  of free-standing finite surface. The variable  $c$  is the speed of sound,  $s$  and  $r$  are the distances from the source to reflecting surface and from the reflecting surface to the receiver correspondingly,  $D$  is the depth of the reflecting panel and  $\theta$  is the sound incidence angle of the reflection relative to the reflecting surface.

$$f_0 = \frac{c}{\left(\frac{1}{s} + \frac{1}{r}\right) \cdot (D \cdot \cos \theta)^2} \quad \text{Hz} \quad (\text{C.1})$$

To confirm this relation between panel width, source-receiver distance and  $f_0$ , a scale model was developed using the same scale modelling facilities as described in Chapter 4. The purpose of this investigation was also to study the effect of attaching the free-standing surface horizontally to a significantly larger vertical surface. The reflection via both the large vertical surface and the attached panel is normally called a ‘cornice reflection’ (or alternatively a ‘cue-ball reflection’). Figure C.2 shows the measurement configuration. The geometry was set upside down, so the transducers could be freely hung, which helped reducing the level of reflections disturbing the measurement of the response from the horizontal panel. The source

was set 8 m and the receiver/microphone 7 m horizontally from the vertical large surface. Panel heights of 3, 4, 5, 5.5 and 6 m ( $h_1$ – $h_5$ ) and panel depths of 1 and 2 m ( $d_1$ – $d_2$ ) were investigated. The vertical distances given refer to a virtual floor at the same level as the mounting disk of the spark source. See [Barron & Dammerud \(2006\)](#) for more details on this investigation.

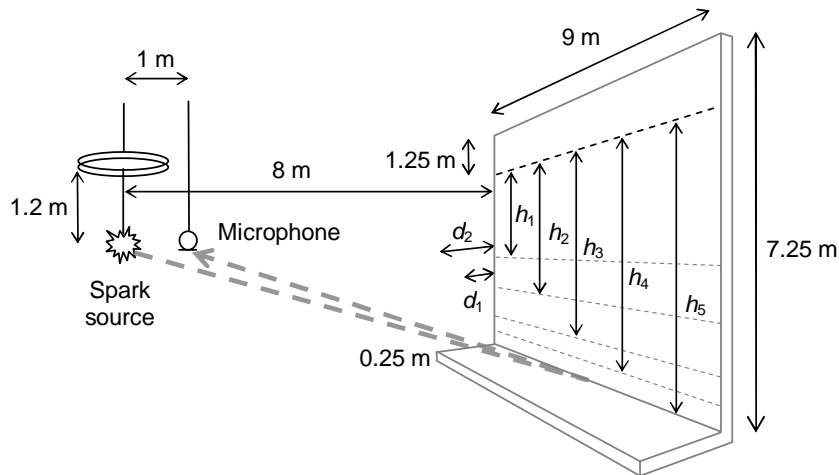


Figure C.1: Scale model measurement configuration for cornice reflection investigation.

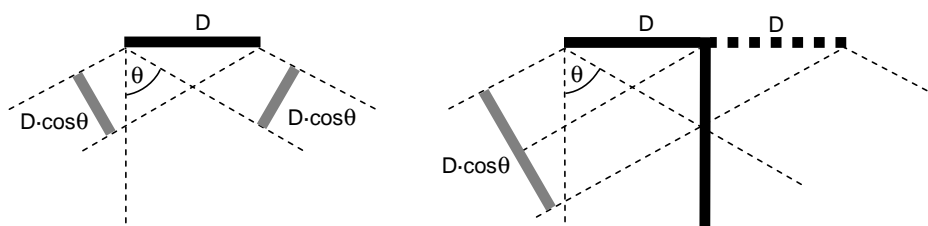


Figure C.2: Apparent width of panel with wall absent and present.

When observing the limiting frequency for the cornice reflection, the limiting frequency is a quarter of what one would expect from reflection off the horizontal panel alone. This suggests that with a large vertical panel, the reflection is effectively off a double width horizontal panel, as shown in [Figure C.2](#).

[Table C.1](#) shows the resulting limiting frequencies,  $f_0$ , for the different panel heights used, and assuming that the apparent width of the panel is doubled when being attached to the large vertical surface. The agreement with the theory based on [Equation C.1](#) is very good, which to a large extent confirms that the apparent panel width is doubled. The frequency response of the spark source limited which limiting frequencies could be confirmed experimentally – the theoretical limiting frequencies 3122 and 6809 Hz are outside the bandwidth of the spark source.

By angling the horizontal panel up as illustrated in [Figure C.3](#), the apparent depth  $D$  will be increased, but the specular image source will disappear for the musicians. If angling the panel so it faces the musicians (typically 15–19°), the term  $\cos \theta$  will be equal to 1. For source and receiver at 8 m distance the limiting frequency will for such a case be 1372 Hz with a 1 m wide tilted panel. If the panel is 2 m wide, the limiting frequency becomes 343 Hz. Such a panel

Table C.1: Limiting frequencies.

Cornice height (m)	Limiting frequency (Hz)			
	Cornice depth = 1 m		Cornice depth = 2 m	
	Calculated	Measured	Calculate	Measured
6	1434	1450	358	380
5.5	1643	1740	411	350
5	1945	1950	486	550
4	3122	–	781	850
3	6809	–	1702	1800

can be 1.5–3 m above the stage floor. Corresponding limiting frequencies with a horizontally oriented panel are significantly higher. The limiting frequencies found for such angled panels do not include the effect of the tilted panel being attached to the vertical wall. A 2 m wide panel might not be realistic in practise – a 1.5 m width could be more relevant. A 1.5 m wide panel will lead to a limiting frequency of 610 Hz. This limiting frequency is for the source and receiver 8 m from the reflecting panel. For players at opposite sides of the stage, the distance to the source will typically be 2 and 17 m. The change of source and receiver distance leads to the predicted  $f_0$  being 614 Hz instead of 1372 Hz for a 1 m wide panel. This suggests that a tilted section, minimum 1 m wide, will provide necessary compensating reflections for string players across the stage. Results from Chapter 4 show that compensating reflections are most needed at frequencies above 500 Hz.

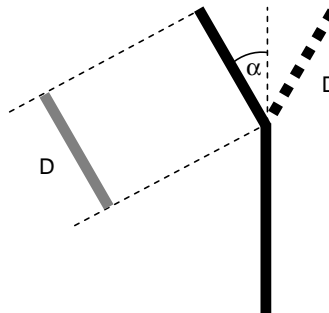


Figure C.3: Configuration with tilted section.

For more information with regard to frequency limits for reflector arrays, see [Skålevik \(2006\)](#).



## Appendix D

### Comb filtering

This appendix covers a study of potential comb filtering effects on stage with respect to width and height of the stage enclosure. [Halmrast \(2000\)](#) carried out measurements of impulse responses across the stage with a full symphony orchestra present. He found that if measured responses showed comb filtering in the frequency domain, it would indicate negative colouration effects perceived by the players on stage. The observed comb filtering was due to an early reflection from an overhead reflecting surface interfering with the direct sound (within-orchestra) sound. If the delay between the direct sound and this reflection was 5–25 ms, the perceived negative effects appeared to be most prominent. This time interval found was associated with the critical bandwidth of our auditory system. In addition to the frequency distortion introduced by the comb filter, the musicians may also respond to the ratio of direct to reflected sound being low at the frequencies where destructive interference occurs (not mentioned by Halmrast). When studying stage enclosures without overhead reflecting surfaces, similar comb filtering was not detected and the colouration effect from side reflecting surfaces was reported to contribute positively to the sound from the instrument close to these surfaces (like double bass). The results from Chapter 5 is here used to estimate at what source-receiver distances this is likely to happen for different widths and heights of the stage enclosure. The resulting distances found are compared to the finding by [Halmrast \(2000\)](#).

Table [D.1](#) shows the distances at which the estimated within-orchestra level at 1 kHz is equal to the analytical 1<sup>st</sup> order reflection level for the ceiling and the wall reflections. These distances are based on Figure [5.3](#). The corresponding delays between direct sound and reflections are based on Figure [5.5](#). The unfavourable comb filtering observed by Halmrast was with an overhead reflecting surface 7.5 m above the stage floor at a source-receiver distance of about 9.5 m. The estimated distance this would occur at with a 7 m high ceiling is at 11.4 m from Table [D.1](#). The comb filtering will mainly be based on the total level of the direct sound and the floor reflection. In Chapter 4 the combined level of the direct sound and floor reflection was found to be typically 2 dB below the within-orchestra sound level at 10 m distance on flat floor. If subtracting 2 dB from the within-orchestra level, the estimated distance where comb filtering could occur will be at approximately 9.4 m distance instead of 11.4 m distance (from Figure [5.3\(a\)](#)). This estimated distance agrees well with Halmrast's measured distance.

Table D.1: Reflection delays for ceiling and side walls.

Reflection	Height/width (m)	Distance (m)	Delay (ms)
C	$H = 7$	11.4	15
	$H = 15$	14.5	39
$W_2$	$W = 18$	9.6	6
	$W = 26$	13.5	29
$W_2$	$W = 18$	12.9	24
	$W = 26$	14.4	38

For a low ceiling reflection ( $H = 7$  m) the time delay of the reflection is in the middle of the delay range Halmrast found as most unfavourable. The minimum ceiling height to move the delay of the ceiling reflection out of the 5–25 ms time region is 9.3 m. With  $W = 18$  m the delay of wall reflections  $W_1$  and  $W_2$  are also within Halmrast's time region, but at the outer regions of his interval. Such side reflecting surfaces were by Halmrast found to contribute positively to the orchestra sound. With players on the sides of the stage being on risers, the distances at which the comb filtering occurs will move to larger distances due to raised within-orchestra (direct) sound level. The ceiling reflection delay will not change much for increased distance and for wall reflection  $W_2$  it will not move at all. For reflection  $W_1$  the delay could with risers be in the middle of the 5–25 ms range and could from Halmrast's results lead to unfavourable effects if the side walls are not diffusing.

For a 22 m wide stage and an orchestra width of 16 m, the players on the outer regions of the orchestra will receive unattenuated reflections from the side walls being about 3 m away from them. This reflection will arrive about 17 ms after onset of own note (the direct sound). If the time arrival relative of the reflection is more relevant for perceived colouration effects than comb filtering in the frequency domain, this could mean that such a wall reflection could result in unfavourable colouration of the sound of one's own instrument – especially if the wide side walls are not diffusing. Even if purely speculative, the observations regarding delay of own sound would suggest that a stage with a high ceiling and narrow side walls could be less prone to colouration effects, but that the significance of the disturbance is depending on the diffusing properties of the stage enclosure.



## Appendix E

# The lateral fraction measure applied to two stage enclosures

Computer models of two real stage enclosures were created to study values of  $LF$  on stage, using CATT-Acoustic. The two stage enclosures were from eight of the halls regularly visited by Bournemouth Symphony Orchestra: The Lighthouse, Poole (PL) and The Anvil, Basingstoke (BA). Figure E.1 shows models of these two enclosures using one source position and ten receiver positions.

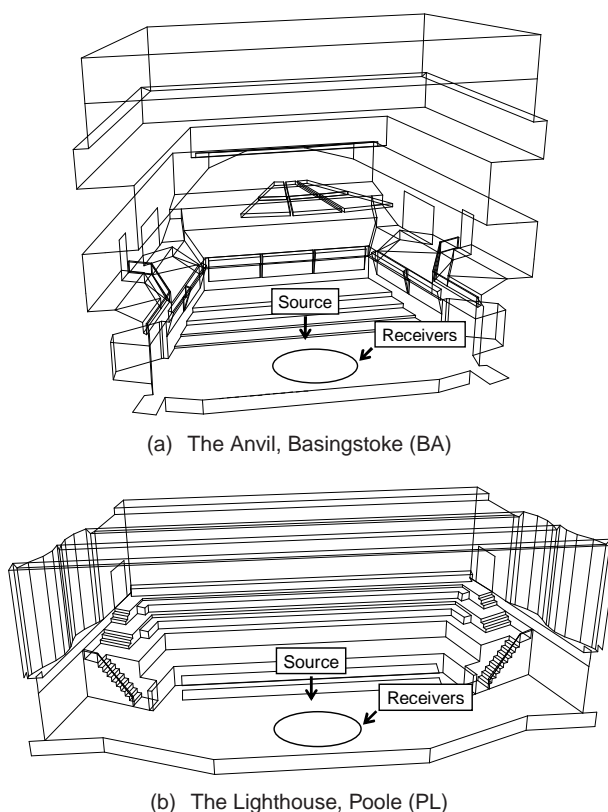


Figure E.1: Computer models of the stage enclosures in BA and PL, with source and receiver positions indicated. (The two figures are not exactly in scale relative to each other.)

The source was set at the middle of the stage, 6 m from the stage front. The receivers on stage are  $-1$ ,  $0$  or  $1$  m from the middle of the stage and  $1$ ,  $2$ ,  $2.5$  or  $3$  m from the stage front. The modelling of the two stages was initially done with an empty stage and ideal omnidirectional source. The computer models (including the complete hall geometry) were verified by comparing results for  $T$ ,  $C_{80}$ ,  $G_I$  and  $ST_{early}$  measured in the real halls (empty stage), showing good agreement. The major problem with measuring  $LF$  without players present is that some of the reflecting surfaces will be obstructed by the orchestra, in particular the section of the side walls less than  $2$  m above the stage floor. For this reason, the most valid option will be to investigate  $LF$  with an orchestra present. The two halls were also modelled with orchestra on stage (with orchestra modelling done as described in Chapter 6).

For an empty stage condition, the results show average value of  $LF$  (averaged  $1$ – $2$  kHz) equal to  $0.043$  on the stage in BA while  $0.012$  in PL. The generally low values are as mentioned caused by the large distance to the side walls compared to the source-receiver distances. The ratio of  $LF$  at these two stages is  $1:3.0$ , which is a significant difference. In BA the side walls are closer and the main ceiling higher compared to PL, resulting in higher values of  $LF$  at the centre of the stage. The architectural measure corresponding to  $LF$  in a simplified manner is  $\frac{1/W_{fs}}{1/W_{fs}+1/H_{fs}+1/D}$ . For BA this fraction comes out as  $0.30$ , while  $0.14$  for the PL stage enclosure – a factor of  $2.15$  between the two enclosures. This does not exactly match the factor between  $LF$  values for the two enclosures, which is most likely caused by the architectural measures only providing a simplified representation of the acoustic conditions and that the definition of  $LF$  does not correspond directly with  $\frac{1/W_{fs}}{1/W_{fs}+1/H_{fs}+1/D}$ .

When including the orchestra, the corresponding average  $LF$  value are  $0.053$  in BA and  $0.028$  in PL, a ratio of  $1:1.9$ , which is a significant change compared to the results for empty stages. This again demonstrates the importance of investigating conditions on stage with an orchestra present.

## Appendix F

# Strype's reversed orchestra arrangement

Figure F.1 shows a recording session with The Norwegian Radio Orchestra 19 May 2005, recorded by Audun Strype. For this recording session the orchestra had a 'reversed' arrangement of the different instrument sections, compared to what is the common arrangement: the string players sat at the back of the stage and the percussion players sat at the front of the stage (closest to the audience area). Such a configuration would not be possible during a concert performance (since the musicians turn their back to the audience).



Figure F.1: The orchestra arrangement used by Strype for sound recordings of a symphony orchestra. From a recording session in Store Studio (NRK), Oslo with The Norwegian Radio Orchestra 19 May 2005.

With a normal orchestra arrangement the percussion and brass would on this stage be close to the back wall, on risers elevating the players above the string section. With the reversed configuration the string players are instead close to the back wall and on risers, as seen in Figure F.1. The direct sound from the brass players will now propagate more into the risers instead of the string players' ears, since the string players now are elevated above the percussion and brass players. Regarding early reflections provided by the stage enclosure, there will be no reflecting surfaces close to the percussion and brass players (no competing reflections from these instruments). The back wall now instead provides compensating reflections back to the string players. These changes of compensating reflections and competing direct sound and reflections suggest that the level balance and consequently mutual hearing between string, brass and percussion will be improved.

It has been difficult to obtain individual comments from the players and conductor regarding this arrangement. The general impression, based on experiences reported by Strype and a few of the players, is that the reversed arrangement helped mutual hearing between the players. This supports the findings from this study regarding the balance between the different instrument groups being controlled by compensating reflections and competing direct sound and reflections (see Chapter 5 for more details).

Below are listed two recordings where Strype's orchestra arrangement was used, with details on the orchestra arrangement (provided by Strype):

The Norwegian Radio Orchestra, conductor: Rolf Gupta, "Lights Out".

Released on Aurora (MOP-ACD-5048).

Strype's arrangement was used for the whole recording.

Bent Sørensen, Oslo Sinfonietta and Cikada, conductor: Christian Eggen, "Birds and Bells".

Released on ECM (ECM New Series 1665).

Not a full symphony orchestra. Percussion placed next to the front row of the audience seats with the conductor and soloists as close to the stage back wall as possible.

## Appendix G

# Improved acoustic conditions on two Norwegian stages

The two Norwegian symphony orchestras who participated in the survey covered in Chapter 3 were Oslo Philharmonic Orchestra and Trondheim Symphony Orchestra. Their home venues have recently had their stage enclosures modified, and the players were asked to comment on the changes they have experienced with regard to acoustic conditions. The information provided here is limited, but description of the overall changes made and the experiences reported by the players, are useful for comparisons with the major results from this research project. These two venues are judged by the home orchestra. Such judgements were in Chapter 3 found to be less valid compared to judgements made by players visiting several different halls regularly, since the players tend to adapt to certain fixed acoustic conditions. Therefore, emphasis is here on relative changes experienced.

### G.1 Oslo Concert Hall, Oslo (OCH)

The original stage enclosure in OCH was wide, high and deep. Over the last five years the following changes were made: the wall in the mid stalls section joining the balcony and stalls section were made scattering. On stage an overhead reflector was (in 2004) introduced. Adding side reflecting surfaces was not easy on this stage in practical terms. The new reflector is close to transparent at low frequencies and reflective and scattering at higher frequencies; see Skålevik (2007) for more details. With the reflector introduced the height to a reflective surface was reduced from 12 to 7.5 m. The old and new enclosures are comparable to the enclosures named WH and WHR respectively in the computer modelling study (Section 6.6). The architectural measures for the current stage enclosure is available in Section 3.6.2.

Based on the comments made by the players, conditions are found to be significantly (though not very drastically) improved after the two changes are made to the hall. Several players comment that the clarity of sound is most noticeable improved and the ability to hear other

players is slightly improved. The players still find that the stage lacks bass and warmth. The history of this hall may have led to biased opinions among the players. The acoustic conditions on stage were strongly disliked before changes were made over the recent years. But the Oslo Philharmonic Orchestra has over the last years been touring worldwide, which could have helped the players putting the conditions in OCH into a perspective.

The results from this project suggest that an overhead reflector array (transparent and scattering) in a wide and high stage enclosure will improve the temporal clarity of sound, but that the balance problems (hearing others) will not be much improved. These results agree well with what the players in Oslo Concert Hall have reported. The scattering added to the wall in the mid stalls section appears beneficial regarding temporal clarity (reducing the level of the specular reflection from this surface back towards the stage).

## G.2 Olavshallen, Trondheim (TOH)

The Olavshallen in Trondheim is a multipurpose hall with a stage tower and proscenium opening stage. Originally the stage had three moveable vertical reflectors at the sides and three reflective (not very scattering) overhead reflectors above woodwind and strings (12.5 m long, 2 m wide) at about 7.5 m height. This hall is included in [Beranek \(2004\)](#) showing the old stage enclosure. This stage was recently (in 2006) fitted with a stage enclosure and riser system. The new stage enclosure includes side and back walls and is about 19 m wide and 10 m deep. The original overhead reflectors are unchanged. The new enclosure will be comparable to the enclosure named NL in computer modelling study (Section 6.6), but with the stage ceiling in TOH has openings into the stage tower between the three reflectors. The riser system was designed to also have the string players at back desks also being on risers.

The most significant improvements experienced by the players appear to relate to higher level of reverberant sound, a more blended sound of the orchestra and better ‘projection’ to the audience. Several players find this to be a large improvement, though the conditions with the new enclosure are not among the best the players have experienced.

Proscenium stages within this project have been reported to have problematic acoustic conditions due to a lack of reverberant sound on stage, and the players find such stages very problematic (Chapters 3 and 8). Adding side and back walls on the stage of TOH appears to result in raised level of the acoustic response from the main auditorium without decreasing the level balance or clarity of sound too much. This agrees well with the results from Chapters 5 and 6: an overhead reflecting surface was found to result in too high a level of late acoustic response within the stage enclosure itself contributing to reduced temporal clarity and audibility of the response from the main auditorium. On the contrary, side walls were found to result in the opposite effects. The risers introduced, as well as the side walls, are expected to result in improved level balance for the string players. That there still appear to still be some noticeable balancing problems could be related to values of  $D$  and  $H_{ts}/W_{rs}$  of the new enclosure being moderately low – about 10 m and 0.40 respectively.