CONCERT HALL STAGE ACOUSTICS FROM THE PERSPECTIVE OF THE PERFORMERS AND PHYSICAL REALITY

J J Dammerud University of Bath, England
M Barron   University of Bath, England

1   INTRODUCTION

A three-year study of stage acoustics for symphony orchestras in concert halls has recently been completed. The main goal of the project was to find what acoustic conditions are preferred by orchestral musicians and what objective characteristics best correspond with their views. The study involved both subjective and objective investigations. The subjective data was collected from two questionnaire studies with musicians. The objective study involved three separate types of study: measurements on real concert hall stages, measurements in scale models and investigations using computer simulation models.

Though several authors have discussed performing conditions in auditoria, the most significant studies have been by Gade. Gade's first major publication[1] described experiments in anechoic chambers with musicians performing in simulated room environments. In his second paper[2] he described three different studies: a study of three Danish orchestras playing in nine different halls, a study of one of these orchestras performing on tour in eight British halls and thirdly an experimental study trying to improve acoustic conditions on an existing stage (Danish Radio, Studio 1). These studies led to the proposal of three acoustic parameters for assessing stage acoustics, which were later revised to the following Support parameters[3]: ST_{early} ($ST1$) to measure ensemble conditions, ST_{late} for the impression of reverberation and ST_{total} for measuring support from the room for sound from the musicians' own instrument. The Support (ST) parameters sum the level of sound reflections returning back to a musician on stage from any direction, by use of 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_{early}, ST_{late} and ST_{total} are 20–100, 100–1000 and 20–1000 ms respectively.

From our study, it soon became apparent that the necessary conditions for orchestral performance may well be different to those for small chamber groups. Support measures as proposed by Gade will have some relevance for perceived conditions for the players, but our results suggest that the relevance of Support measures may be limited to assessing the level of acoustic response on stage. Based on the calibration method used for obtaining the Support values, other acoustic parameters appear more reliable for the purpose of assessing the level of acoustic response.

2   PHYSICAL CONDITIONS ON AN ORCHESTRAL STAGE

One of the major differences between conditions on stage between small and large ensembles, such as symphony orchestras, is that for large ensembles sound travelling from one player to another is significantly obscured by intervening musicians. On a stage with musicians but no stage enclosure, the level of sound travelling between one musician and another is lower than simple inverse square law behaviour, particularly at high frequencies. A full understanding of this physical behaviour is obviously important.

The presence of musicians on stage introduces screens/barriers for the direct sound and the stage floor reflection but also introduces extra reflections from nearby players and objects on stage (such as instruments and music stands). These components will be referred to here as the 'within-orchestra sound'. Sound travelling between musicians on stage was studied in a 1:25 acoustic scale model with carefully modelled musicians with the correct absorption. The measurements

showed that the effect of obstructions on stage tends to increase with frequency. At lower frequencies (below 500 Hz), the within-orchestra sound level is mainly controlled by interference effects between the direct sound and floor reflection. At 1 kHz a sound attenuation of about 10 dB in excess of inverse square law behaviour was measured for a distance of 16 m between players. This excess attenuation is reduced when players are at different heights due to risers. The accuracy of the modelling was confirmed by repeating at model scale two full-size measurements by others of sound travelling 'through' people[4,5].

The layout of musicians on stage is also significant. On many stages string players sit at the front of the stage on a flat floor; they need to be able to play as a unified group. At opposite sides of the stage, string players can be as much as 16 m apart and obstruction of direct sound etc. by other musicians will frustrate mutual hearing. Players at the back of the stage, typically 12 m from those at the front, will often benefit from being on risers. This will normally lead to sufficient mutual sound levels between front and back.

3 ISSUES OF ORCHESTRAL PERFORMING

The situation for the musicians playing in an orchestra is certainly complex and will no doubt depend on the instrument they play. Listening to other players allows the performer to check on at least three aspects which are important for ensemble: timing, dynamics and intonation. Playing in a group it is the farthest players who are likely to be the most difficult to hear, except when the source player has a loud instrument. Our two subjective studies indicated that most players prefer to be able to hear ALL other players in the orchestra clearly; string players often struggle with hearing their own group.

A major reason for requiring reflections from a stage enclosure is to compensate for excess attenuation between players who are far apart. Reflections that fulfil this function can thus be called 'compensating' reflections. The optimum location of reflecting surfaces is also influenced by the relative disposition of musicians on stage. However the sound from players at middle distance can obscure the sound from distant players. If the stage enclosure reinforces sound from middle distance players, this may increase the masking of sound from distant players. These reflections can be called 'competing reflections'. It is therefore the goal of a stage enclosure to provide compensating reflections without introducing competing reflections that are too strong. Our results also indicate that it is necessary to distinguish between reflections returning to the musicians from different directions.

4 FIRST SUBJECTIVE STUDY WITH ORCHESTRAL MUSICIANS

The first questionnaire covered musicians' impressions of stage acoustics in general and was distributed to eight different orchestras – six within England and two within Norway. In total 180 questionnaires were returned, with all four instrument groups represented – strings, woodwind, brass and percussion. This questionnaire focused on the players' experience and preferences regarding eight different aspects of stage conditions: the importance of space available to them on stage, their preferred size of stage, preferred riser configuration, how often some instruments become too loud; problems with hearing particular instruments, importance of being able to spatially separate different instruments, their awareness of reflecting surfaces close to the stage and finally the importance of hearing the reverberant sound from the audience area. They were asked to comment on statements regarding what good stage acoustics meant for them and what useful information is contained in the reverberant sound. The players were also asked to list the hall they remembered as providing the best stage acoustic conditions during their career, and try to explain why they found this hall superior. Seven of the orchestras were also asked to give a score on overall acoustic impression (*OAI*) for 7–12 listed halls they regularly perform in or have visited on several occasions.

Available objective characteristics were collected for the 22 concert halls judged by the players. These included reverberation time, T, and estimated late sound level, G_l, ($G_{80-\infty}$, based on measured T and hall volume V) for the main auditorium, and ST_{early} (only available for 12 of the halls) and a set of architectural parameters for the stage. The architectural parameters were selected based on findings relating to compensating and competing sound (as described in Section 3). Figure 1 shows how the architectural parameters W_{rs}, H_{rb} and D were obtained. The architectural parameter W_{rs} (width, reflecting surfaces strings) is found as the average width between reflective surfaces 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 the brass and string section up to a reflective surface likely to reflect sound from brass 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 (and percussion) 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}. D is found as the distance between the back end of the stage accessible to the orchestra and the average stage front line. The ratios H_{rb}/W_{rs} and D/W_{rs} were also calculated.
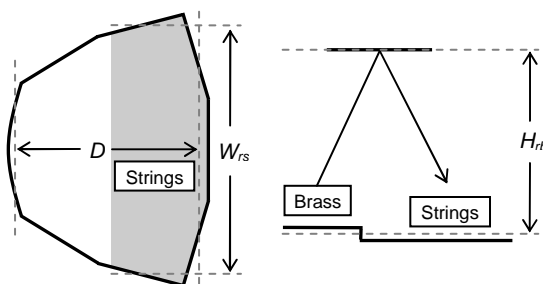

Figure 1: The method for obtaining the architectural parameters from stage drawings.

4.1   Results and discussion

The results from the general questionnaire described above suggest that almost all the players find that acoustic conditions on stage vary significantly between the halls that they perform in. Hearing all other players clearly appears to be the most important factor for describing good stage acoustic conditions. Staging conditions and the amount and quality of acoustic response from the hall appear to be essential as well, though not all players appear to see the reverberant sound as useful for ensemble playing. Hearing the reverberant sound appears to represent a means of communication with the audience and contribute to overall musical experience/judgement. The string players frequently have problems with the sound from players within their own group being too low in level (compared to other instruments) or excessively delayed. Brass and percussion instruments are reported as most frequently being too loud for string, woodwind and brass players.

Much of the analysis concerned judgements of overall acoustic impression (*OAI*). It was observed that there was, perhaps surprisingly, in general good uniformity between judgements of different members of the orchestra. There were two obvious differences in the ratings of *OAI* which suggested that subdividing the group of halls was appropriate. Musicians consistently judged stages in proscenium theatres or large nineteenth century city halls with long reverberation times with low values of *OAI* (below 4 out of 10). The comments from the players on these halls were largely related to lack of or excess of acoustic response from the auditorium. To study the effect of the stage enclosure, the halls with *OAI* below 4 were therefore excluded from the analysis.

The remaining halls were designed specifically as concert halls. A further reason for exclusion was noted in the case of halls that were judged both by visiting orchestras and the home orchestra. The results indicate that experiences by home orchestras may not be representative for the experiences of other orchestras playing in the same venue, due to the home orchestra having adapted and

learnt to handle some problematic acoustic conditions. Also for casual visits by orchestras their judgement may not be sufficiently reliable due to limited experience. Results relating to casual visits were also excluded from the analysis.

Table 1 shows results of the correlation analysis between available objective parameters and overall acoustic impression (OAI, all players). The halls included in the correlation analysis were halls with an acoustic response apparently suitable for symphonic music judged only by orchestras playing there (and in other halls) regularly. Judgements of home venues were excluded. This resulted in a total of twelve halls being included. The results show that the architectural parameters H_{rb}/W_{rs} and H_{rb} show the best correlation with OAI. The acoustic parameters T and G_l appear to be relevant for assessing level of acoustic response from the auditorium. The correlations between OAI and H_{rb}/W_{rs} and H_{rb} suggest that a narrow and high stage enclosure will provide better conditions for the players, compared to a wide and low stage enclosure. This could be related to the level of compensating and competing reflections provided. The moderate correlation between OAI and D/W_{rs} suggests that a shallow and wide stage may lead to high competing direct sound and/or back wall reflection levels and a lack of compensating reflections at the sides of the stage.

Table 1: Correlation coefficient, r, between OAI (all players) and objective parameters for twelve concert halls. Bold numbers indicate significance at the 1 % level and underlined at the 5 % level.

Var.	T	V	G_l	ST_{early}	W_{rs}	H_{rb}	D	H_{rb}/W_{rs}	D/W_{rs}
OAI	-0.24	-0.22	-0.14	0.00	-0.52	<u>0.69</u>	0.39	**0.78**	0.55

The twelve halls were split up in two groups: Group M consisted of six halls with OAI judgements within 4–7, while Group H consisted of the six remaining halls with OAI within 7–10 (out of 10). Discriminant analysis was carried out to see to which degree values of the objective parameters could be used to discriminate between these two groups. The results suggest that H_{rb} and H_{rb}/W_{rs} best discriminate between groups M and H. The transition values between the two groups are H_{rb} = 12.8 m and H_{rb}/W_{rs} = 0.58. All the six halls in Group M had H_{rb} < 12.8 m and H_{rb}/W_{rs} < 0.58.

These results and comments from the players suggest that reflections from the sides of the stage are best for compensating for low within-orchestra sound levels. By exposing the stage to the rest of the hall, the players would be able to hear the hall sound which is found to be a positive experience among many players. When the orchestra is within an enclosed stage enclosure, overhead reflecting surfaces designed to project the orchestra sound towards the audience may be beneficial for the players – competing reflections at a high sound level will not be introduced by the overhead reflecting surfaces but these surfaces can reflect reverberant sound from the hall back towards the players.

5 SECOND SUBJECTIVE STUDY WITH A SINGLE ORCHESTRA

A second questionnaire or rather set of questionnaires, was distributed to the Bournemouth Symphony Orchestra to investigate in detail the players' impressions of stage acoustic conditions for eight performance spaces where they regularly perform. The following halls in the west of England and Wales were involved: The Anvil, Basingstoke (BA); Colston Hall, Bristol (BC); Guildhall, Portsmouth (PG); The Lighthouse, Poole (PL); Pavilion, Weymouth (WP); Pavilion, Bournemouth (BP); St David's Hall, Cardiff (CD); University Great Hall, Exeter (EU). The players were asked about their experience of playing together and musical aspects in each hall; a questionnaire for each of the eight halls was completed by each musician based on their memory. A total of 24 sets of questionnaires were completed with all the four instrument groups represented – strings, woodwind, brass and percussion.

For this study a more comprehensive set of objective data was available. Impulse response measurements were obtained on these stages (with chairs, but no orchestra present) and within the audience section of the hall. Architectural parameters for the stage enclosures were also obtained,

as described in Section 4. The main aim was to find which objective characteristics best correspond with the players' subjective impressions.

Initially 15 subjective and 15 acoustic parameters were included, but after initial statistical correlation and factor analysis, the subjective parameters were reduced down to 7 and the objective down to 6. The final seven subjective parameters were: physical comfort (Co); hearing self (HS); hearing others (HO); clarity of sound (Cl); amount of reverberation (R), other instruments too loud not a problem (LNP) and overall acoustic impression (OAI). The final six objective parameters were: reverberation time (T), clarity (C_{80}), late sound level (G_l), ST_{early} and ST_{late}, plus the architectural parameters W_{rs}, H_{rb}, D and the ratios H_{rb}/W_{rs} and D/W_{rs}. G_l ($G_{80-\infty}$) was calculated based on measured G and C_{80}. In each hall the measurements carried out in the main auditorium allowed us to investigate how average values of T, EDT, C_{80} and G_l on stage correspond with those measured in the main auditorium. Computer models of one popular and one less popular purpose-built concert hall (BA & PL) were also created to study a potential use of Lateral Fraction (LF) to assess the portion of early lateral (side wall) reflections on stage (see end of Section 7.2 for results on this).

5.1   Results and discussion

Factor analysis of the results for the subjective parameters indicated that most of the subjective parameters were highly correlated, except for LNP and Co. HS, HO, Cl, R and OAI are significantly correlated with each other and these five parameters (HS, HO, Cl, R, OAI) are the main parameters related to the most significant factor from the factor analysis results ($r = 0.65–0.93$). This would indicate that enquiring about OAI only will give a reasonable representation of their perception of acoustic conditions, while LNP and Co indicate their perception of physical stage conditions.

When comparing measured T_{30} (T), C_{80}, G_l and ST_{early} with OAI, there appear to be optimum ranges for T_{30}, C_{80} and G_l, while ST_{early} shows no discrimination between the most and least preferred halls. ST_{late} was found to be highly correlated with G_l ($r = 0.97$). Figure 2 shows the results for T_{30}, C_{80}, G_l and ST_{early} at octave bands 125–4000 Hz. The shaded areas in Figure 2 indicate the ranges for the four most preferred halls (BA, CD, BC and EU). The two least preferred auditoria are proscenium stage theatres (BP & WP) which were judged with significantly lower values for OAI compared with the six other halls. For the three least preferred stages, measured G_l and C_{80} are significantly higher or lower compared to the four most preferred halls – at low frequencies or in general.
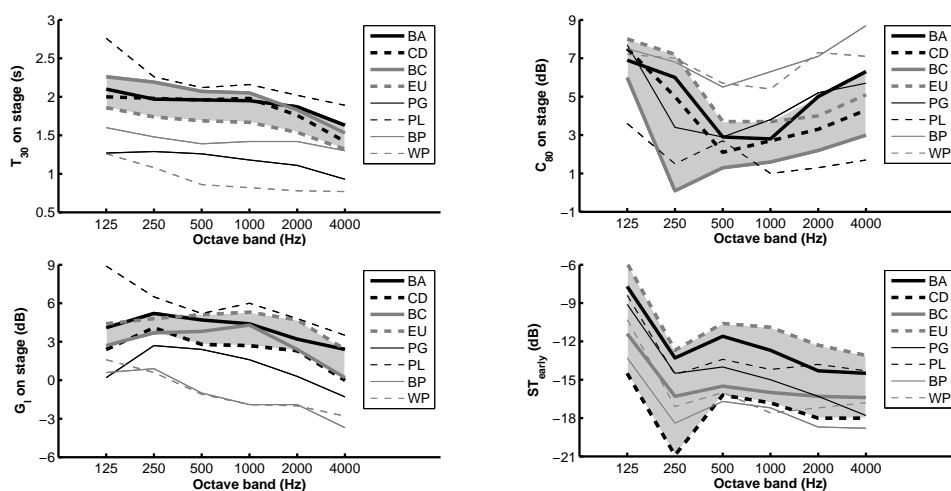

Figure 2: Octave band values for T_{30}, C_{80}, G_l and ST_{early}. Shaded areas define the ranges for the four most preferred halls.

The low scores of OAI for the two theatres (BP & WP) appear to be caused by a lack of acoustic response from the auditorium, as indicated by G_l and also C_{80} (early sound level could be too

dominating), and a lack of risers on stage. The other halls all have risers for the woodwind, brass and percussion sections. If the two theatres are omitted, the objective acoustic parameters studied no longer distinguish clearly between values of *OAI* (as seen in Figure 2). Some of the proposed architectural parameters are significantly better at distinguishing between the most and least preferred hall among the six concert halls. Figure 3 shows the architectural parameters versus *OAI*, (among all the players). Figure 3 includes correlation coefficients, *r* (1st order), between *OAI* and the objective parameters, and 1st (linear) and 2nd order (parabolic) linear regression lines for data from the six most preferred halls (i.e. excluding the theatres BP & WP). The highest correlation is seen between *OAI* and H_{rb}/W_{rs}, D/W_{rs} and H_{rb}. These results are comparable with the results from our first questionnaire study (Section 4).
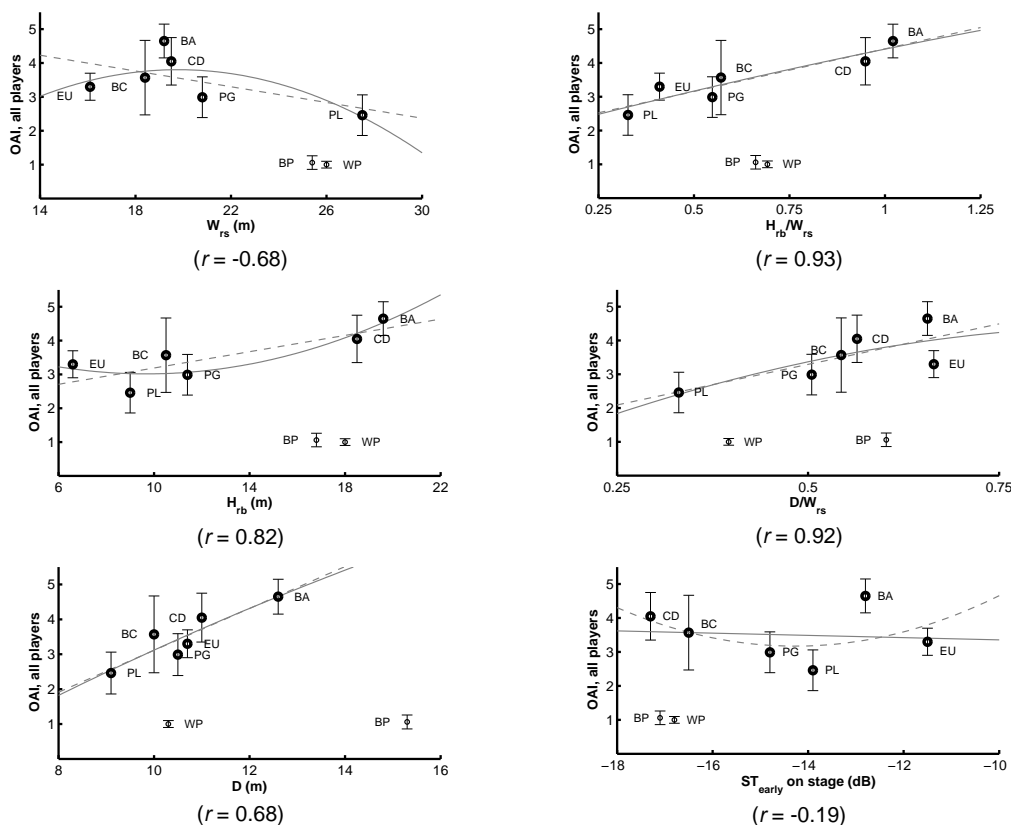

Figure 3: Architectural parameters versus *OAI*, all players. Values of *OAI* (±σ), correlation coefficient (1st order regression), *r*, and regression curves (1st order and 2nd order) are included for results with the theatres (BP & WP) excluded.

The acoustic parameters do not show significant correlations with impressions related to communication between the players (*HS*, *HO*, *CI*), but there are significant correlations between the acoustic parameters *T*, C_{80} and G_l and subjective impression of reverberation (*R*). This suggests that the acoustic parameters are most relevant for assessing impressions relating to level of acoustic response from the auditorium. G_l shows the highest correlation with *R*. The consistency of measured G_l will be affected by source-receiver distance. Our results suggest that measurements on stage should be carried out with chairs present using a source-receiver distance of 8–9 m, source height 1.0–1.2 m and microphone height 1.0–1.2 m (preferably both at 1 m). This appears to result in the most consistent results for the acoustic parameters found relevant for the impressions by the players (G_l, *T* and C_{80}). When comparing stage average results with main auditorium results, values for *T* and G_l are found to correlate highly. These parameters measured in the main auditorium could thus be used to for assessing acoustic response on stage where there is a lack of measurements carried out on stage.

6   COMPUTER MODELLING OF GENERIC STAGES

One of the main aims for the computer modelling was to study the effects of the location of reflecting surfaces close to the orchestra. A method for correctly modelling the orchestra in the computer model was developed by comparing results with our scale model investigations. Good agreement for within-orchestra sound levels was achieved at 1–2 kHz for players sitting 9–15 m apart across the stage on a flat floor. A set of simple stage enclosures were modelled to compare the resulting sound level and impulse responses within the orchestra, in particular across the string section and from a position at the back of the stage to compare the situation regarding compensating and competing sound. To investigate the effect of the location of reflective surfaces for complete halls, six different stage enclosures were studied, all being attached to the same audience section. The simple stage enclosures included: straight side walls only, top tilted side walls only, a solid flat non-diffusing overhead reflector only and a perforated diffusing overhead reflector only.

In brief our computer modelling results support the hypothesis on stage enclosure dimensions: a narrow and high stage enclosure appears to provide better compensation for low sound levels (within 0–50 ms) without introducing much competing sound or without creating a high level of late/reverberant sound within the stage enclosure itself. The results also indicate that a low stage enclosure in particular contributes to raise levels of late/reverberant sound (G_l) on stage, whereas a perforated diffusing overhead reflector can contribute to improved temporal clarity of sound.

7   ACOUSTIC PARAMETERS AND BEYOND

7.1   Validity of measurements without orchestra present on stage

A second scale model study was undertaken which involved measuring impulse responses across the stage of a generic concert hall (1:25 scale). The concert hall model had walls and the ceiling containing openings that allowed different panels to be inserted; principally this allowed walls and the ceiling to be either plane or highly scattering. Tests were conducted with two different stage conditions (with and without risers) and four different stage enclosure configurations (side walls and ceiling either plane or highly scattering). This resulted in eight different stage conditions being studied both with and without a model orchestra present on stage.

This model study indicated that the level of direct sound and early reflections on stage will be significantly higher without the orchestra present, and that only measured G_l on an empty stage may be regarded as valid compared to the conditions with an orchestra present. In particular changes in the early sound level on stage, G_e ($G_{0–80}$), appear to be too dependent on the actual staging and enclosure conditions and show no consistent general shift of value between with and without orchestra present. On the other hand changes of T and C_{80} appear to be moderately consistent between with and without orchestra present. Our results for objective measures in the eight performance spaces (listed in Section 5) show that the correlation coefficient, r, between G_e and ST_{early} is 0.92 (significant at the 1 % level). Given the dependence of G_e on stage conditions, this indicates that values of ST_{early} measured on a stage without the orchestra present will have little validity compared to the levels experienced by the players.

7.2   Temporal masking, clarity of sound and Lateral Fraction

Dialogue with several orchestral musicians suggested that the whole string group must start their note at the same time – otherwise the sound will not appear to be synchronised for the audience. Due to the delay of sound from the back of the stage, the players at the back of the stage must anticipate their note onsets to avoid being too late relative to the strings. For a string player M at the middle of the stage, this means that this player will hear the onset of sound of the percussion and

brass at the same time as onset of his/her own note, whereas the sound from other string players at the sides will be delayed depending on how far away to the side the other string players are sitting. The physical distance between players and effective delays of direct sound for a player M at the middle of the stage and a player S at the side of the stage are illustrated in Figure 4. The delays are shown relative to the simultaneous note onsets of string players M and S.
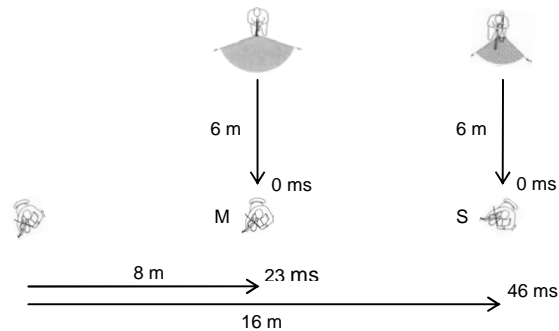
Figure 4: Distance between players and effective delay of direct sound from player at the side and at the back (top of figure) for players M and S. The delays are shown relative to the simultaneous note onsets of string players M and S, assuming the three string players at the front section start their note at the same time.

Resulting impulse responses at 1 kHz for player S for either a narrow and high or a wide and low stage enclosure are shown in Figure 5. The narrow and high stage dimensions are W_{rs} = 18 m and H_{rb} = 19 m (H_{rb}/W_{rs} = 1.06), while the wide and low stage enclosure has W_{rs} = 26 m and H_{rb} = 7 m (H_{rb}/W_{rs} = 0.27). The impulse responses included the within-orchestra response and first order reflections from the ceiling and side walls. 'Within-orch. (direct)' in Figure 5 includes all within-orchestra sound (Section 2), namely the predicted direct sound and floor reflection (both attenuated by passing through the musicians) plus incidental reflections from musicians, their instruments, music stands and chairs. The arrival time of sound events are seen relative to the simultaneous note onsets of the string players.

Narrow and high stage enclosure

(a) From player at the back of the stage to player S.

(b) From player at the side of the stage to player S.

Wide and low stage enclosure

(c) From player at the back of the stage to player S.

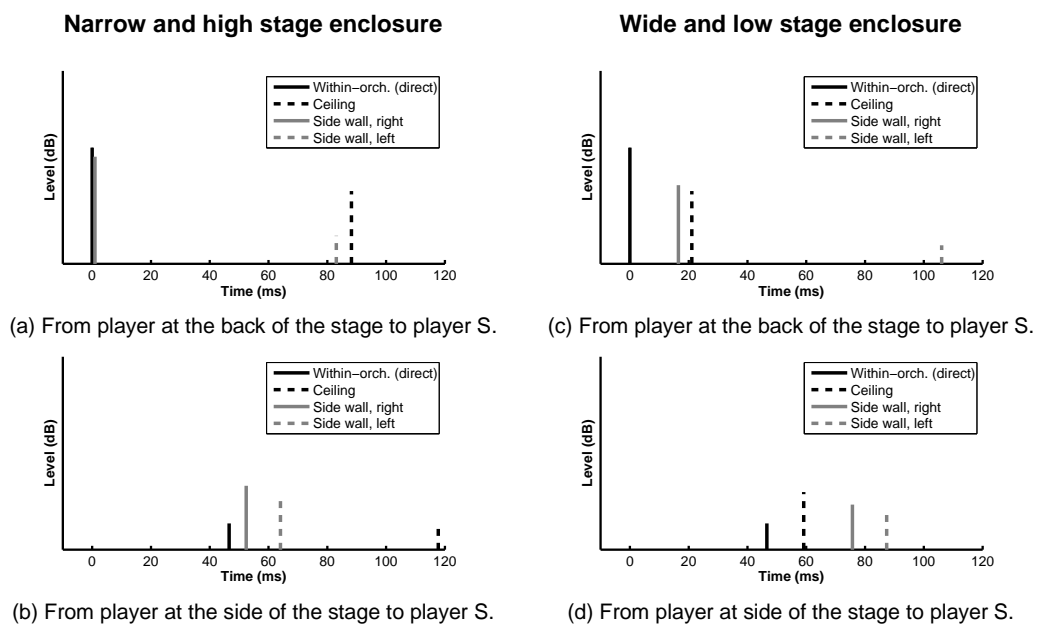(d) From player at side of the stage to player S.

Figure 5: Estimated impulse responses at 1 kHz across the stage for a narrow and wide or a wide and low stage enclosure, including within-orchestra sound (incl. direct) and 1st order reflections. Time is seen relative to the simultaneous note onsets of the string players.

The results indicate that for a narrow and high stage enclosure, there will be a time gap of about 80 ms after the arrival of the direct sound (and right side wall reflection) from the player at the back of the stage. For a wide and low stage enclosure, the ceiling reflection and right side wall reflection from the player at the back will arrive before the direct sound from the player at the (opposite) side. This suggests the following: that there is a distinct risk with a wide and low stage that sound from a player at the back will mask the sound from a player at the side; the risk of masking is much less with a narrow and high stage.

The results from the first questionnaire study indicated that being able to spatially separate the sound from different instruments is important for many players. This suggests that the cocktail-party effect may be relevant for players within a symphony orchestra, as proposed by Meyer[6] and Andersson[9]. Clarity of sound may be related to being able to hear spatial cues in order to separate different instruments/groups. Such conditions are not well assessed by existing acoustic parameters. The acoustic parameters C_{80} and D_{50} were designed for assessing temporal clarity of sound. Values of C_{80} (within 500–2000 Hz) from our second subjective study do not show a significant positive correlation with perceived clarity of sound (*Cl*).

These observations (and our results from subjective studies) suggest that present acoustic parameters based on monophonic impulse responses are not well suited for evaluating mutual hearing between players, especially without having an orchestra (or equivalent group of people) present on stage. The ratio H_{rb}/W_{rs} may offer a useful rule-of-thumb for stage enclosure design, but this is, of course, no substitute for a valid acoustic objective measure.

Since reflections from the side appear more valuable to musicians than from above, it is tempting to consider whether the measure Lateral Fraction (*LF*) used for source-broadening for audience in concert halls might be valuable to assess stage acoustics for musicians. Preliminary results from our computer modelling indicate that *LF* (or other binaural acoustic parameters) may be useful, but it is necessary that the orchestra is also modelled for valid results. Results from computer modelling of two of the purpose-built concert halls included in the second questionnaire study (BA & PL), show significantly higher values for *LF* for the most preferred stage. This was evaluated with the source at the middle of the stage and receivers around the centre front part of the stage. Currently studying complete impulse responses generated by computer modelling of stage enclosures (including the orchestra) may be the most valid way to investigate acoustic conditions on concert hall stages objectively.

8   COMPARISON WITH RESULTS OF OTHER STUDIES

The studies carried out by Gade were pioneering and contributed to a better awareness and understanding of stage acoustics for performers. Our results indicate that his proposed ST_{late} correlates highly with G_l, which has been found useful for evaluating the level of acoustic response on stage. The calibration method used for obtaining values of ST_{late} (and ST_{early}) appears less reliable compared to the calibration method for obtaining G_l (ISO 3382), leading to a preference for G_l.

On the other hand, from our results his proposed parameter ST_{early} does not correspond well with acoustic impressions among the musicians in our results. The results from Gade's first two studies of real halls[2] showed contradictory results with regard to the relevance of ST_{early} for subjective impressions. His Danish study of nine halls showed high correlation between player's impressions of ensemble conditions and ST_{early}, while his British study of eight halls indicated the opposite. The inclusion of players' judgements of home venues in his Danish study, only halls visited once included in his British study and the number of halls included in both studies may have led to misleading results.

The experimental study by Gade[2] in Danish Radio, Studio 1, involved adding tilted reflectors on the side walls, an array of small overhead reflectors at a height of 5, 7, or 14 m above the stage and

locating the orchestra at the front or back of the stage. The results suggested that tilted side wall reflectors, an array of overhead reflectors at 5 m and having the orchestra close to the back wall led to the highest score on hearing others for the orchestra as a whole. Measured ST_{early} correlated well with scores for hearing others. Brass and percussion players did not like being close to the back wall or the wall reflectors, due to increased (high) sound levels of their own sound. Having the overhead reflectors at 5 m height resulted in negative comments on sound quality from the players (but this configuration gave the highest score for hearing others). The results related to the tilted side wall sections agree well with our results, providing a higher level of compensating reflections for the string section. The results for the back wall also agree reasonably well, while the results related with the overhead reflectors and ST_{early} may be seen as contradicting ours. W_{rs} is 25.2 m in Danish Radio, Studio 1 (discussed in Beranek[7]). This could be too wide for providing compensating reflections across the stage at a sufficient sound level. The array of overhead reflectors could in such a case have beneficial compensating reflections provided that at the same time any competing reflections are not of too high a level.

Two recent Master dissertations by Cederlöf[8] and Andersson[9] and a PhD thesis by Giovannini[10] contain results which to a high degree support our findings. We have looked at the stage dimensions of the five Swedish halls studied by Cederlöf. The results from correlation analysis show that the architectural parameters, as described in Section 4, better correlate with overall acoustic impression, *OAI*, than measured *T* and ST_{early} – in particular H_{rb}/W_{rs}.

9   CONCLUSIONS

Two questionnaire surveys have been conducted with orchestral musicians. Objective studies have been carried out in full-size halls, in scale models and with computer simulation models. It soon became clear that, for symphony orchestra performance, there was much more to learn both about musicians' preferences and the behaviour of sound on concert hall platforms.

On the subjective side, it was discovered that different orchestras can respond differently to the same auditorium depending on their experience of that auditorium. For instance, there is evidence that musicians can specifically adapt to the acoustic behaviour of their home venue and can judge it more highly than an orchestra that visits the venue regularly but is based elsewhere. On the other hand, a visiting orchestra unfamiliar with a hall will often judge the hall differently to an orchestra with reasonable familiarity with the venue. For the studies described here, results of regular visiting orchestras were used.

The presence of an orchestra on stage results in the sound travelling between players being significantly attenuated between musicians who are far apart, especially at high frequencies. This effect appears to be much more significant for large ensembles like a symphony orchestra compared to smaller groups. A good stage enclosure compensates for low sound levels between distant players without significantly raising the sound levels unnecessarily on stage or by introducing too much reverberant sound within the stage enclosure itself. This balance is also affected by the stage arrangements, like presence of risers. So far, we have not found a straightforward acoustic objective measure which correctly measures this delicate balance.

What has been discovered both in our study and independently by others is that the ratio between height and width of a stage correlates with preference of musicians (higher values of H_{rb}/W_{rs} are preferred). This implies that narrow and high stage enclosures are preferred to wide and low enclosures. In particular a low reflecting surface above the stage, which might be thought to provide valuable support for musicians, can have the opposite effect of creating excessive sound levels on stage and producing unwanted masking sound for musicians. A shallow stage and reflections from the back wall on stage can have similar effects.

The optimum stage enclosure appears to have a small width for the string section, a high ceiling, moderate depth and an enclosure exposing the orchestra to the rest of the hall. The three first

factors appear to relate to balance of compensating and competing sound on stage, while the last factor appears to relate to impressions on stage of the reverberant/late sound within the main auditorium. If side walls close to the string section can not be provided, the question relating to benefits of introducing overhead reflectors will arise. Our results suggest that an array of diffusing overhead reflectors could help to improve conditions, but not to the same extent as narrow stage enclosure. If the stage is in an enclosure at the end of the main auditorium, overhead reflectors designed to project the orchestra sound towards the audience, not back towards the orchestra, may also be beneficial for reflecting reverberant sound from the auditorium towards the players.

The requirements for an objective measure to assess the suitability of orchestral stage designs are demanding. A simple measure of the amount of sound reflected back to the stage, as is the case with ST_{early}, is not sufficient. Our results suggest that existing acoustic parameters are only relevant for assessing the following conditions: level of acoustic response from the auditorium (which will also affect overall acoustic impression where levels are either too low or too high for symphonic repertoire) and to some extent temporal clarity of sound on stage. The parameters G_l, T and C_{80} appear most relevant for these purposes. No existing acoustic parameter is well correlated with overall acoustic impression for musicians for halls with suitable level of acoustic response from the auditorium. For ensemble conditions an acoustic quantity is required which is assessed with an 'orchestra' present and the source and receiver positions need to be carefully specified (particularly the distance between them). For full-size measurements, the need to measure with an 'orchestra' present means that either a compliant group of patient people is required to represent musicians or some form of modelling is necessary. Computer modelling will be the most convenient in most cases, but scale modelling at a scale of 1:25 or larger is also valid.

10   ACKNOWLEDGEMENTS

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