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Objective assessment of acoustic conditions on concert hall stages – limitations and new strategies

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ABSTRACT

At present the most common measures for assessing stage acoustic conditions on concert hall stages are the Support measures – ST_{early} and ST_{late}. These measures are based on monophonic omnidirectional responses obtained at 1 m from the sound source, on a stage without a full symphony orchestra (or similar group of people) present. Both objective and subjective studies have been conducted, the latter using questionnaires with several orchestras and dialogue with musicians. Objective studies involved measurements on real stages of the Support measures and other acoustic measures such as *T*, *EDT*, C_{80}, $G_{7–50}$, G_e ($G_{0–80}$) and G_l ($G_{80–\infty}$) as well as a set of proposed architectural measures. These have been complemented with analytical as well as scale and computer model investigations into sound behaviour on both empty and occupied concert stages. The major results from these studies are presented in this paper along with a discussion of alternative approaches for assessing stage acoustic conditions. One important result concerned the relevance of directions from which early reflections arrive regarding perceived ensemble conditions, an objective factor not assessed by the Support measures.

INTRODUCTION

The *ST* measures are a set of room acoustic measures originally proposed by Gade (1989a) for assessing acoustic conditions for the performers on stage. The *ST* measures were later revised by Gade (1992) and renamed to ST_{early}, ST_{late} and ST_{total}. The *ST* measures ST_{early} and ST_{late} are now included in ISO 3382-1:2009 (ISO, 2009). ST_{early} is associated with perceived ensemble conditions and ST_{late} with perceived reverberance. These measures assess the level of the acoustic response returning back to a musician on stage. The room acoustic response should be obtained by use of an omnidirectional loudspeaker and an omnidirectional microphone with chairs on stage, i.e. orchestra absent. ST_{early} assesses the total level of reflections within 20–100 ms, while ST_{late} assesses the total level of reflections with 100–1000 ms. The combined level of the direct sound and the floor reflection within 0–10 ms of the response is used as reference level.

This paper is based on results from a three-year project where acoustic conditions for symphony orchestras in concert halls were studied. See Dammerud (2009) for more details regarding approaches and results for this project. The subjective surveys within the three-year project showed that hearing others is paramount for orchestral musicians, but that hearing self and hearing a response from the auditorium is also important. Regarding hearing others, the attenuation of sound across the stage (caused by other players and objects on stage blocking the direct sound propagation path) is found to be significant. Within this project the first detailed quantitative study of the orchestra attenuation effect was carried out. Measurements showed that attenuations of about 10 dB at 2 kHz occur across a typical stage (14 m source-receiver distance, attenuation measured relative to unobstructed direct sound over the same distance). A major role for a stage enclosure has to be to counteract this attenuation to allow the furthest instruments to be heard, without introducing new acoustical problems for the orchestra.

This paper focuses on the validity of the *ST* measures and other measures commonly used in music auditoria. Overall the results suggest that both the *ST* measures and other existing measures have limited subjective relevance for orchestral musicians hearing other performers. The search for an objective measure related to hearing others has been unsuccessful. However good correlations have been found between certain objective measures and perceived auditorium response (by performers). The most valid measure from our study for auditorium response is G_l, the level (or strength) of late sound on stage for a source on stage. Based on these results, new strategies for improving the subjective relevance of objective measures of concert hall stages are presented and discussed. This discussion is followed by some considerations of what appear to be beneficial design principles for stage enclosures based on our results.

PHYSICAL VALIDITY OF ACOUSTIC RESPONSES AND MEASURES WITHOUT THE ORCHESTRA PRESENT ON STAGE

The physical validity of acoustic responses obtained without a full symphony orchestra present was investigated by use of scale modelling. 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. 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 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. Similar investigations were carried out by use of computer modelling where six different stage enclosures were attached to the same main auditorium. The main scope for these studies was to investigate to which degree the change of acoustic responses were consistent with and without a full symphony orchestra present. The changes of the following acoustic measures when adding the orchestra were studied: ST_{early}, ST_{late}, T, EDT, C_{80}, $G_{7–50}$, G_{e} ($G_{0–80}$) and G_{l} ($G_{80–\infty}$). Values of G_{e}, $G_{7–50}$ and G_{l} were calculated from measured G (Strength), C_{80}/C_{50} and the energy ratio of response within 0–7 ms compared to within 7–50 ms.

The results from these studies suggest that the acoustic response within the first 50 ms is highly affected by the presence of the orchestra (using a source-receiver distance within 6–12 m). Beyond 100 ms, the responses look similar without and with orchestra, but the results suggest that the reductions of integrated levels beyond 80 ms also are significantly affected by the design of the stage enclosure. Only a few of the acoustic measures showed reductions being close to constant when adding the orchestra under different stage enclosure conditions and designs. The acoustic measures G_{l} and ST_{late} and to a certain degree also T, C_{80} and ST_{early} show the most consistent reductions. The reductions of EDT, G_{e} and $G_{7–50}$ appear highly dependent on both presence of risers and properties of the stage enclosure.

PHYSICAL RELIABILITY OF THE *ST* MEASURES

The ST measures (ST_{early}, ST_{late} and ST_{total}) assess the level of reflections returning back to the stage within different time intervals. According to ISO 3382-1:2009 the source must be set on stage with the microphone at 1 m distance from the (centre of the) source to simulate a musician with his/her instrument. Both loudspeaker and microphone should be at 1 or 1.5 m height. The reference for the measured sound level is the combined level of the measured direct sound and the floor reflection, summed within the time interval 0–10 ms. To keep this reference consistent, Gade recommended having no objects on stage that would reflect sound arriving within the time window for the reference level (0–10 ms). 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.

An alternative to ST_{early} is the measure $G_{20–100}$ (G within 20–100 ms) at 1 m. Whilst ST_{early} uses the direct and floor reflection energy for reference, $G_{20–100}$ effectively uses the source power as a reference. More precisely G values are based on the direct sound level at 10 m as reference averaged for 29 source rotations (according to ISO 3382-1:2009) 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_{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_{early} (totally roughly 21 dB difference). How a single measure of ST_{early} relates to $G_{20–100}$ is expressed in Equation (1), where ε_1 represents the effect of the floor reflection inclusion in the reference, ε_2 represents the variations caused by the source directivity and ε_3 represents variations due to offsets from 1 m transducer heights and source-receiver distance.

$$ST_{\text{early}} = G_{20-100} - 20 + \varepsilon_1 + \varepsilon_2 + \varepsilon_3 \quad (1)$$

From the observations above one could claim that measures based on G are likely to be more reliable compared to the ST measures. Measuring G with source-receiver distance well above 1 m will offer greater accuracy. If taking great care when obtaining ST the values of ε_1, ε_2 and ε_3 will be small. But since G over the last 20 years has become a common room acoustic measure it appears preferable to use G when relating to levels of reflected sound.

RELIABILITY OF SUBJECTIVE CHARACTERISTICS OF ACOUSTIC STAGE CONDITIONS

Subjective impressions by musicians of individual stages were collected through two different questionnaire surveys and dialogue with the musicians. The first study involved eight orchestras within England and Norway, whereas the second study investigated in the detail eight of the performance spaces one of the English orchestras performed in regularly.

To obtain the most valid and relevant judgements from the players the results from the questionnaire surveys suggest that 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, including Gade (1989b), 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.

Regarding the reliability of judgments of acoustic conditions on stage, the variations of judgments appear to relate to personal preferences and training as much as the instrument they play. When studying orchestra average value of overall acoustic impression (*OAI* – the overall satisfaction with the acoustic response on stage) the halls receiving the lowest and highest score differed significantly (based on statistical analysis – Student t test using a significance level of 5 %). For medium ranging halls, no significant differences were found between these halls from the quantitative studies. This shows that quantitative studies have clear limitations.

SUBJECTIVE RELEVANCE OF THE ACOUSTIC MEASURES

When relating the subjective characteristics to physical acoustic conditions, the study was in general split up in two parts based on the guidelines listed in the above section:

1) Subjective characteristics of conditions on stage related to the acoustic response from the stage enclosure.

2) Subjective characteristics of conditions on stage related to the acoustic response within the main auditorium.

For studying the effect of the stage enclosure all the halls included were judged by orchestras visiting these halls (and other halls) regularly and had a level of acoustic response that the players did not comment clearly negatively about. All the stages studied had a riser system installed. A majority of the stages had a riser system with the players at the back of the stage on risers (with all the string players on the flat floor).

For the first subjective study the acoustic measures T, ST_{early} and G_l were included, with values of G_l estimated from measured T and hall volume V based on Barron & Lee (1988). For the second subjective study a total of 21 acoustic measures based on monophonically measured acoustic responses were studied, including T, C_{80}, G_l, G_e, $G_{7\text{–}50}$, ST_{early} and ST_{late}. Stage average values of these acoustic measures were compared to subjective characteristics, as well as results at individual positions on stage and results versus source-receiver distance. The acoustic measures were based on measurements with an unoccupied audience area and chairs only on stage (47–80 chairs totally on stage).

The results from the two subjective studies suggest that existing acoustic measures based on monophonically measured responses without the orchestra present are mainly relevant regarding the following: the level of the acoustic response provided by the main auditorium to the stage and by the stage enclosure. In particular the late acoustic response (beyond 80 ms) appears relevant. Measures related to level of the early acoustic response provided by the stage enclosure were not found to be significantly relevant to subjective characteristics.

The results also imply that the acoustic measures which were found most valid in objective physical terms (relating to the conditions experienced by the players) also correlate best with subjective characteristics of overall acoustic impression (*OAI*) and sound levels. The exception appears to be ST_{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.

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 low reliability appear to refer mainly to the level of early reflection vary significantly at different locations on stage, and the low validity appear to refer mainly to the orchestra significantly attenuating early reflections.

• For ST_{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.

Based on the above and other investigations conducted during the project, the relevance of existing measures based on monophonic responses on stage without the orchestra present appears to be as follows:

• The level of late acoustic response provided by the main auditorium to the stage appears relevant for perceived 'bloom' (acoustic support) and 'projection' (acoustic communication with the audience) among the players. 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. 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.

• To what degree the stage is acoustically exposed to the main auditorium 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 $G_e/G_{7\text{–}50}$, 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 (without the orchestra present) can used to calibrate the models if studying existing stages. Measures based on measured G have within this project been found highly reliable.

The results suggest that average values within 500–2000 Hz and at single octave bands from 125 (63 preferably) 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 (preferably above 8 m if having the transducers 1.2 m above the stage floor) 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) by using a source-receiver distance well above 1 m. The use of source-receiver distances above 6 m will in general also focus on paths within the orchestra where the acoustic response from the stage enclosure appears most critical.

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).

NEW ALTERNATIVE STRATEGIES

From the questionnaires and qualitative studies of the stage enclosures judged by the orchestras it became clear that it would be relevant to study the direction of reflections provided on stage. The directions of early reflections appear relevant for the ability to hear the other players clearly, while the directions of late reflections and reverberation appeared relevant for impression of acoustic support ('bloom') and acoustic communication with the audience ('projection'). The way a symphonic orchestra is organised on stage imposes low 'within-orchestra' sound levels without any stage enclosure present – players far apart on the flat floor experience very low mutual sound levels (typically string players). These low within-orchestra sound levels are competing with high levels from typically percussion and brass, and could end up being completely masked perceptually. One of the important aspects of the stage enclosure appears to be to effectively compensate for low within-orchestra levels without the introduction of more competing sound. The competing sound can also perceptually mask the acoustic response from the main auditorium. This led to the concept of discriminating between 'compensating' and 'competing' reflections provided by the stage enclosure.

To incorporate quantitative measures related to the direction of dominating early reflections, a set of architectural measures were developed. These measures would also to a certain degree give an indication of the direction of late arriving reflections and to what degree the stage is acoustically exposed to the main auditorium. Figure 1 illustrates how the architectural measures were obtained.

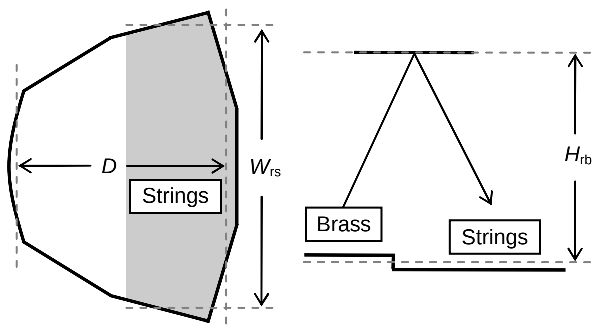

Figure 1. Plan and long section of a generic stage showing the method for obtaining the proposed architectural measures.

• 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.

In both subjective studies, these architectural measures were found to correlate significantly with subjective characteristics, such as the ability to hear one's own instrument, hearing other players and overall acoustic impression (*OAI*). The architectural measures also correlated significantly with *OAI* for 20 purpose-built concert halls (including ten halls from the first subjective study, six from the second subjective study and five halls from Cederlöf (2005)); these 20 halls had a wide range of different stage enclosure designs. These results support the concept mentioned above regarding compensating and competing early reflections provided by a stage enclosure (based on all the string players sitting on the flat floor for a majority of the stages studied). The architectural measures offer useful rules-of-thumb, but are not a replacement for objective 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. The apparent likelihoods for resulting *OAI* based on measured G_l, and H_{rb} and H_{rb}/W_{rs} are shown in Figure 2. *OAI* is here ranging from 1 to 10. 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*. Only when G_l is within the optimum range it will be relevant to study H_{rb} and H_{rb}/W_{rs}, leading to *OAI* below 4 being very unlikely when studying H_{rb} and H_{rb}/W_{rs}. Within the optimum ranges there is a significant spread in possible values of *OAI*, but the lowest values of *OAI* is likely to be avoided.

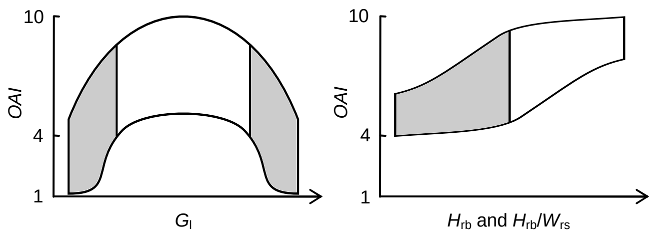

Figure 2. Tendencies of *OAI* relating to the acoustic measure G_l and architectural measures H_{rb} and H_{rb}/W_{rs}. The white areas define *OAI* within 4–10 regarding G_l and within 7–10 regarding H_{rb} and H_{rb}/W_{rs}.

The significant spread of *OAI* 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 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.

For detailed studies of the acoustic response from the stage enclosure the results from this project suggest that the orchestra must be included and that directional information is relevant regarding both early and late acoustic response on stage. Studies of acoustic responses with the orchestra present can be cost-effectively studied by use of scale or computer models. The results from the computer modelling show significant differences in level and time arrival of compensating and competing reflections provided by different stage enclosures. The differences in acoustic responses between the different stage enclosure designs were found more significant with the orchestra present compared to absent. In computer models the direction of reflections can also easily be studied and acoustic measures based on omnidirectional responses may prove more valid when being based on responses with an orchestra present. Measurements on empty stage, like G_e and G_l will be relevant for calibrating models of existing stages.

In general the quantitative methods, both objective and subjective show significant limitations regarding discrimination between mid-ranging halls. The limitations may be explained by the objective measures only providing a simplified representation of the acoustic conditions experienced by the players. Additionally, perceptual effects like level masking and temporal masking, the precedence and the cocktail-party effect appear relevant for the players' impression of hearing all other players clearly. These effects are not easily quantifiable. 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. The quantitative methods included in this study appear most useful for detecting acoustic conditions that will lead to the worst cases and detecting a potential for optimal conditions. For discrimination of mid-ranging halls qualitative information appears essential, like discussing the perceived conditions with the players, studying the properties of the stage enclosure and resulting echograms with orchestra present in detail. 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.

DESIGN OF STAGE ENCLOSURES

In design terms, though an overhead reflector above a stage might seem potentially useful, it would appear not to help hearing of others. To hear an individual musician, it is necessary that their sound is not perceptually masked by that from other musicians, such as those closer by. It appears that a lower overhead reflector does nothing to make the distant musicians more audible relative to those nearer to the listening musician. Indeed we have evidence that a large, flat and horizontally oriented overhead reflector at low height just increases the sound level, reduces the audibility of the acoustic response from the main auditorium as well as reducing the clarity of sound on stage – all acoustic conditions which the musicians in one particular hall disliked.

The preference for a narrower stage width suggests that reflections from the side help audibility of distant musicians, in particular for string players sitting on the flat floor. Also the low frequencies of the double basses are enhanced by having reflecting surfaces close to the double basses. Having the top sections of the side walls vertically tilted will also provide unattenuated early reflections across the stage, that effectively compensate for low within-orchestra sound levels. The need for compensating reflections provided by the stage enclosure will depend on the design of stage risers. If the outmost string players are on risers – for instance by use of a circular riser system – the need for compensating reflections is likely to be reduced (not studied in the detail in this project).

Vertically tilted sections may also be useful regarding the audibility of the acoustic response from the main auditorium: tilted sections (as well as outward sloping side walls and ceiling) are found to contribute to reduce the build-up of reverberant sound within the stage enclosure and may also help project late reflections from the main auditorium towards the musicians. By making the enclosure high, the negative effects mentioned in the previous paragraph appear to be lowered as well as keeping the late acoustic response on stage sufficiently coupled with the late acoustic response from the main auditorium. Meyer (2008) has also proposed that a narrow, high enclosure appears to be the most beneficial for conductors.

For cases where for instance the enclosure is very wide or an orchestral enclosure is not well linked to the main auditorium (like for a proscenium stage), carefully designed overhead reflecting surfaces (reducing the height on stage) may improve conditions even though they may not fully compensate for reflecting surfaces at the sides that are too remote from 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 in this project) appear to be the balance of compensating and competing reflections, build-up of late reflections within the stage enclosure as well as projection of the late acoustic response from the main auditorium towards the players. Projection of late reflection from the main auditorium towards the stage appears particularly important for stages that are not highly exposed (acoustically coupled) to the main auditorium.

The critical aspects mentioned above are only partly monitored by the architectural and acoustic measures studied. Our results indicate that these aspects are best studied in scale or computer models by investigating the details of resulting impulse responses across the stage obtained with the orchestra present. From resulting impulse responses the level and time delay of early reflections for sound across the front half of the stage can be studied, as well as presence of competing reflections from instruments at the back of the stage and the dominating direction of the late acoustic response on stage.

Some possible improvements regarding W_{rs} may be to obtain one value of W_{rs} for reflections from 125 Hz and below, and one value for *unobstructed* reflections with orchestra present at frequencies above 500 Hz. This would better isolate the effect of compensating reflections and low frequency enhancement of the double basses in the design process – and may lead to better subjective relevance of W_{rs} and H_{rb}/W_{rs}.

CONCLUSION

In terms of acoustic measures used as design tools and for assessing existing stages, the results from the three-year project covered in this paper suggest that existing acoustic measures based on omnidirectional acoustic responses on stage without the orchestra present have very limited physical validity and subjective relevance. The level of the late acoustic response assessed in the audience area as well as on stage appears relevant for an impression of acoustic support ('bloom') and acoustic communication with the audience area ('projection'). These subjective aspects appear to be important for the players, but are mainly related to communication with the audience, not communication between players. Communication between the players (the ability to hear all other players clearly) appears paramount among the players. Ease of communication between players appears to relate to complex perceptual effects which are not easy to quantify (like level and temporal masking effects, the precedence effect and cocktail-party effect). No acoustic measures have so far been identified to assess communication between players on stage. For valid measurements on stage, it appears essential to include the orchestra. For point source to point receiver measurements, the direction of early reflections appears important for within orchestra communication. Although no acoustic measure was found to relate to hearing of others by the orchestra, a set of architectural measures were found to be relevant both to this specific issue and overall satisfaction for musicians of individual stage environments. Such architectural measures offer simple rules-of-thumb for designers.

Regarding existing acoustic stage measures (ST_{early} and ST_{late}), these measures appear mainly relevant for assessing the level of the acoustic response provided by the main auditorium to the stage and provided by the stage enclosures. In particular the level of the late acoustic response (beyond 80 ms) has been found subjectively relevant. ST_{late} was designed for assessing the late acoustic response, but G_l is found to be physically more reliable. With G_l, resulting values in the audience area can also be studied to investigate the level of the late acoustic responses provided by the main auditorium on stage (relevant for perceived acoustic communication). Values of G_l obtained with source-receiver distance above 6 m appear highly reliable and sufficiently valid in physical terms without the orchestra present to be subjectively relevant. By assessing G_l both in the audience area and on stage some indication of the direction of the late acoustic response is provided. Values of G_l can be estimated from measured T and hall volume V or calculated from measured G and C_{80} – in some cases without the need for carrying out new measurements since results for these measures already exist. The use of T and C_{80} assessed on stage has also been found subjectively relevant associated with perceived reverberance. The results for such acoustic measures without the orchestra present have been found relevant only for discovering the most problematic conditions.

The ST_{early} is found to have poor subjective relevance if only studying stages where the level of the late acoustic response from the main auditorium is apparently suitable for a symphony orchestra. The lacking subjective relevance appears to relate to the direction of early reflections not being assessed and that values of ST_{early} are obtained at 1 m distance around the centre area of the stage. No acoustic measures have been found or proposed to replace ST_{early}, but a set of architectural measures have been proposed. The architectural measures proposed are found to be a practical and subjectively relevant substitute for not having measures of acoustic conditions with orchestra present and information of direction of early reflections available. Measures of the early acoustic response based on omnidirectional responses may prove subjectively more relevant if including the orchestra and obtaining values between positions on stage where the players are highly affected or highly dependent on the early reflections provided by the stage enclosure. This can be done cost-effectively in models, where also the direction of the reflections easily can be studied.

For future investigations of the relationships between physical objective conditions and perceived conditions among the musicians, it appears essential to not be limited to quantitative studies only and that realistic and relevant physical (acoustic) conditions are studied. The results from the three-year project suggest that the presence of the orchestra on stage is important when considering acoustic conditions and that a lot of factors which are not easily quantifiable are highly relevant for perceived conditions.

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