19th INTERNATIONAL CONGRESS ON ACOUSTICS
MADRID, 2-7 SEPTEMBER 2007

Early subjective and objective studies of concert hall stage conditions for orchestral performance

PACS: 43.55.Gx

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ABSTRACT
For a study of acoustical conditions on concert hall stages, we have been lucky to be able to work with the Bournemouth Symphony Orchestra, which is based in the south of England. Their response to a general questionnaire which was circulated to the whole orchestra has produced interesting results. Objective measurements have been made in some of the halls in which they perform; impulse responses on stage and in the audience area have been collected. The orchestra players' views and the objective data have given us the opportunity to consider which objective properties of the stage and the hall overall are likely to contribute to good acoustic conditions for performers. Early results suggest that, for an optimum acoustic performing environment, there may be other important objective concerns beyond the traditional measure of Support.

1 INTRODUCTION

For the understanding of stage acoustics for musicians a major contribution was made by A. C. Gade, who proposed objective measures to evaluate acoustic support back for musicians themselves and for ensemble conditions [1], [2] (for a review of work by Gade and others on stage acoustics, also see [21]). Gade proposed two parameters: ST (Support) for the acoustic support of an individual musician and EEL (Early Ensemble Level) for ensemble conditions. ST was found to be the more successful of these two when related to orchestras' impressions of measured stages. Three revised versions of ST were later suggested: to measure ensemble, ST_{early}; for impression of reverberation, ST_{late}; and for acoustic support, ST_{total} [3]. ST_{early} measures the energy of reflections in the time interval 20 to 100 ms (relative to the direct sound) that come back to a musician seated at least 4 metres away from any vertical reflecting surface. For our research, Bournemouth Symphony Orchestra kindly volunteered to complete a questionnaire and take part in discussions. Four of the halls in which they regularly play have been measured, on stage without the orchestra present and in the audience. The relation between objective measures and the orchestra's subjective impressions has been studied.

2 BACKGROUND

The questionnaire was distributed to all the orchestra members. It covers acoustic conditions in general, non-acoustical factors and the least and most preferred hall in which they regularly play and the best hall they had ever played at anywhere. They were asked to give reasons for their preferences. The response rate on the questionnaire was 81 % with the string, woodwind and brass sections well represented, but no percussion players. The questionnaire has been followed up with a meeting with the orchestra committee.

To investigate how objective factors relate to the orchestra's impression of the acoustics, the physical dimensions and overall stage design have been studied and impulse responses have been measured on stage with and without chairs. Conducting measurements with the orchestra would be preferable due to their effect on the stage sound, but this has not been possible so far. The four stages that have been studied so far in this project are: The Lighthouse, Poole (PL), The Anvil, Basingstoke (BA), Colston Hall, Bristol (BC) and St David's Hall, Cardiff (CD). The impulse responses have been collected using an omni-directional loudspeaker (dodecahedron) with source-receiver distances from 1 to 9 metres. These have been analysed to give objective parameters, including measures of Support (ST), as proposed by A. C. Gade [1] and a modulation index as proposed by Naylor [4] using a modulation frequency of 4 Hz (leading to reflections arriving at 125 being most detrimental to intelligibility). ST has been derived from measurements taken 1 metre from the source, while the other parameters have been based on measurements with a minimum source-receiver distance of 4 metres.

Other authors have suggested that sound reflections arriving between 35 and 250 ms after the direct sound may have a detrimental effect on the clarity of sound on stage [14], [15], [16]. If the sound is unclear ('muddy'), it will be difficult to judge timing and pitch. Unclear sound can result from both a large build-up of late arriving reflections compared to early reflections or strong discrete reflections. There are uncertainties related to both the lower and upper limit of reflection delay that are detrimental to clarity. Based on these findings, forward integrated impulse responses have been calculated, as used by Yamada, Hadaka and Suzuki to detect audible echoes [18]. The forward integration is performed by integrating the squared pressure impulse response with an exponential decaying integration function. From [18] this can be expressed as:

$$P(t,\tau) = \int_{-\infty}^{t} p(u)^2 e^{-(t-u)/\tau}\, du\,, \qquad (1)$$

where p represents the pressure impulse response and τ is the time constant. A time constant of 10 ms has been used to avoid too much influence by the direct sound and very early reflections on the response from 20 to 130 ms. We are also assuming that listening among musicians may have a shorter time constant than normal listening (up to 40 ms) [5]. This results in a reverberation time of the integration function itself of 0.14 s. The direct sound and floor reflection in the impulse response have been attenuated by 0.75 to 1.25 dB loss per m (0.5 to 2 kHz) based on [7], [8]. The overall level is normalized to maximum integrated level. From the resulting integrated response, a corresponding RT (60 dB decay) has been calculated using linear regression in the time interval 20 to 130 ms and this value has been called the EMDT (Early-Mid Decay Time).

3 RESULTS

3.1 Orchestra questionnaire and dialog

The performers' impression of stage acoustics appears to be affected by how well they can hear themselves and each other, the sound from the hall, the clarity of sound without harshness and non-acoustical factors such as space available on stage, visibility, thermal conditions and backstage facilities. When comparing the best stages played at during their career, the architectural dimensions that are most distinguished from halls globally are stage width at front of stage (string section), ceiling height and stage area. The distance between musicians affects the level of direct sound within the orchestra, and achieving a good level balance could seem more important than minimizing transmission delay, within certain unknown limits.

For the orchestra member's impression of these stages, BA appears to be the favourite hall that they regularly visit (by 40 out of 55 players). BC was mentioned as the best hall ever played at by 4 string players and the best regularly played at by 13 players. CD was the favourite hall of one trumpet player and the best regularly played at by 3 string players. By contrast PL was mentioned by 5 string players as the worst hall visited regularly, despite the fact that they also play at acoustically dead theatres. A selection of comments by the musicians:

"*Clear acoustics - can hear myself clearly in section and the rest of the orchestra, so easy to balance with everyone else*", cello player on BA
"*Excellent amount of clarity and reverberation*", viola player on BA, BC and CD
"*Good ability to hear rest of the orchestra in real time*", trumpet player on BA
"Very difficult to hear other instruments or sections sitting not very far away", viola player on PL
"*Impossible to play together as it is so muddy. For the listener it makes the orchestra sound bad. Brass sound harsh, violins metallic etc.*", cello player on PL
"*Everything sounds loud and coarse on the platform*", viola player on PL

3.2 Objective measures

Table I and II below show objective measures from the four stages visited, while Figure 1 shows forward integrated impulse responses measured from the solo violin to the double bass section, which came out as the most variable response between the four stages.

Table I.- Objective parameters on stages with chairs plus stage dimensions below

Parameter	Meas. dist. (m)	Average 250 – 500 Hz				Average 1 – 2 kHz			
		PL	BA	BC	CD	PL	BA	BC	CD
RT (s)	>4	2.2	2.0	2.2	2.0	2.1	1.9	1.9	1.8
EDT (s)	>4	1.8	1.3	2.5	1.7	1.8	1.3	2.0	1.8
C_{80} (dB)	>4	3.5	5.2	3.0	4.6	3.2	5.9	4.3	5.0
G (dB)	>4	11.0	11.4	9.0	9.4	10.7	11.2	9.7	9.2
T_s (ms)	>4	89	73	102	71	86	60	77	61
MTF_{4Hz}	>4	0.54	0.60	0.56	0.61	0.50	0.63	0.59	0.62
EMDT (s)	>4	1.1	0.5	0.9	0.8	1.9	0.6	1.3	0.9
		Average 250 – 2000 Hz							
ST_{early} (dB)	1	-13.8	-12.5	-17.1	-17.1				
ST_{late} (dB)	1	-14.6	-16.0	-16.3	-17.0				
		PL		BA		BC		CD	
Width @ strings (m)		27.0		18.4		18.0		19.5	
Height (m)		9.6		16.3		11.3		19.0	
Stage area (m^2)		120		163		111		189	

Table II.- Objective parameters in the audience, mean values in unoccupied hall

Parameter	PL	BA	BC	CD
RT (dB)	2.3	2.0	2.2	2.0
EDT (s)	2.2	1.9	2.0	2.0
G (dB)	6.8	5.4	4.5	2.7
C_{80} (dB)	-1.8	-0.6	1.1	0.2
LF	0.20	0.23	0.15	0.18

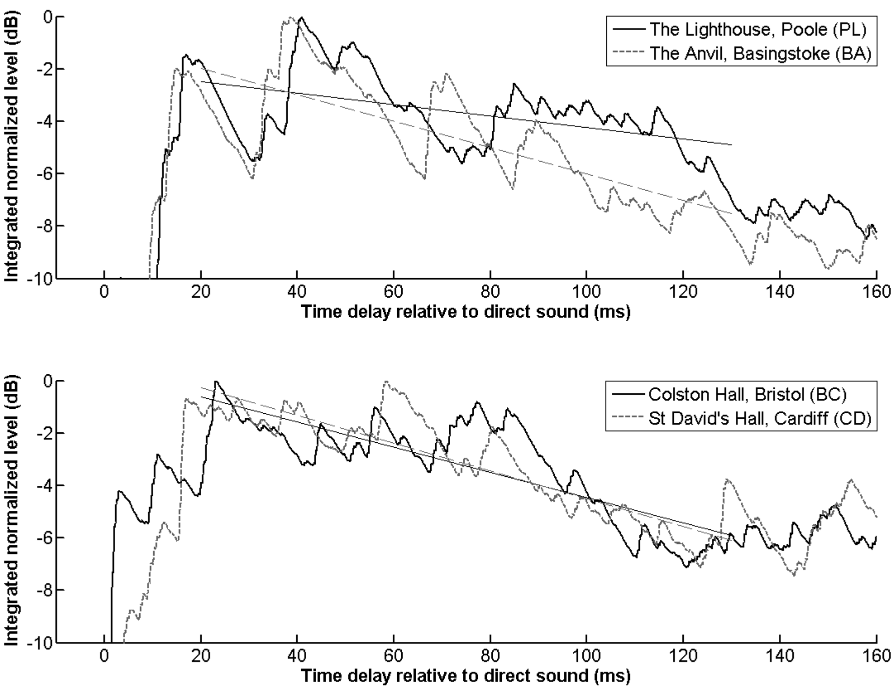

Figure 1.-Forward integrated impulse responses 1 kHz (from solo violin to double bass section)

The decay times (corresponding RT) on the integrated responses from 20 to 130 ms presented in Figure 1 are: 2.7 s in PL, 1.2 s in BA and BC and 1.1 s in CD.

4 DISCUSSION

From the subjective results, BA appears to provide the orchestra with the best conditions, BC and CD are also mentioned as good halls. PL apparently has the least preferred acoustical conditions among the purpose-built concert halls which the orchestra regularly plays at. One of the reasons given for this rating was balance and clarity of the whole orchestra. Measured parameters in the audience area confirm that all four halls have reasonable acoustical conditions for listeners. Regarding objective parameters calculated for the stage conditions, parameters normally associated with clarity correspond with the rating of BA and PL. The most significant difference is for measured EMDT. The decay time from 20 to 130 ms is 1.9 s at 1 – 2 kHz in PL, while only 0.6 s in BA. C_{80}, T_s (centre time) and MTF_{4Hz} (representing intelligibility) also indicate less 'muddy' sound in BA, but not as significant as EMDT. Measured ST_{early} values are only 1.3 dB different between PL and BA.

In terms of their stage design, the most significant difference between PL and BA is the much lower ceiling in PL and a narrower stage surrounded by audience in BA. In BA there are panels tilted downwards on the side and at the back of the stage and cornices above the audience on the side walls, as indicated in Figure 2. In BA there is a small reflector about 9 m above the strings tilted to project sound towards the audience (approximate position given in Figure 2).

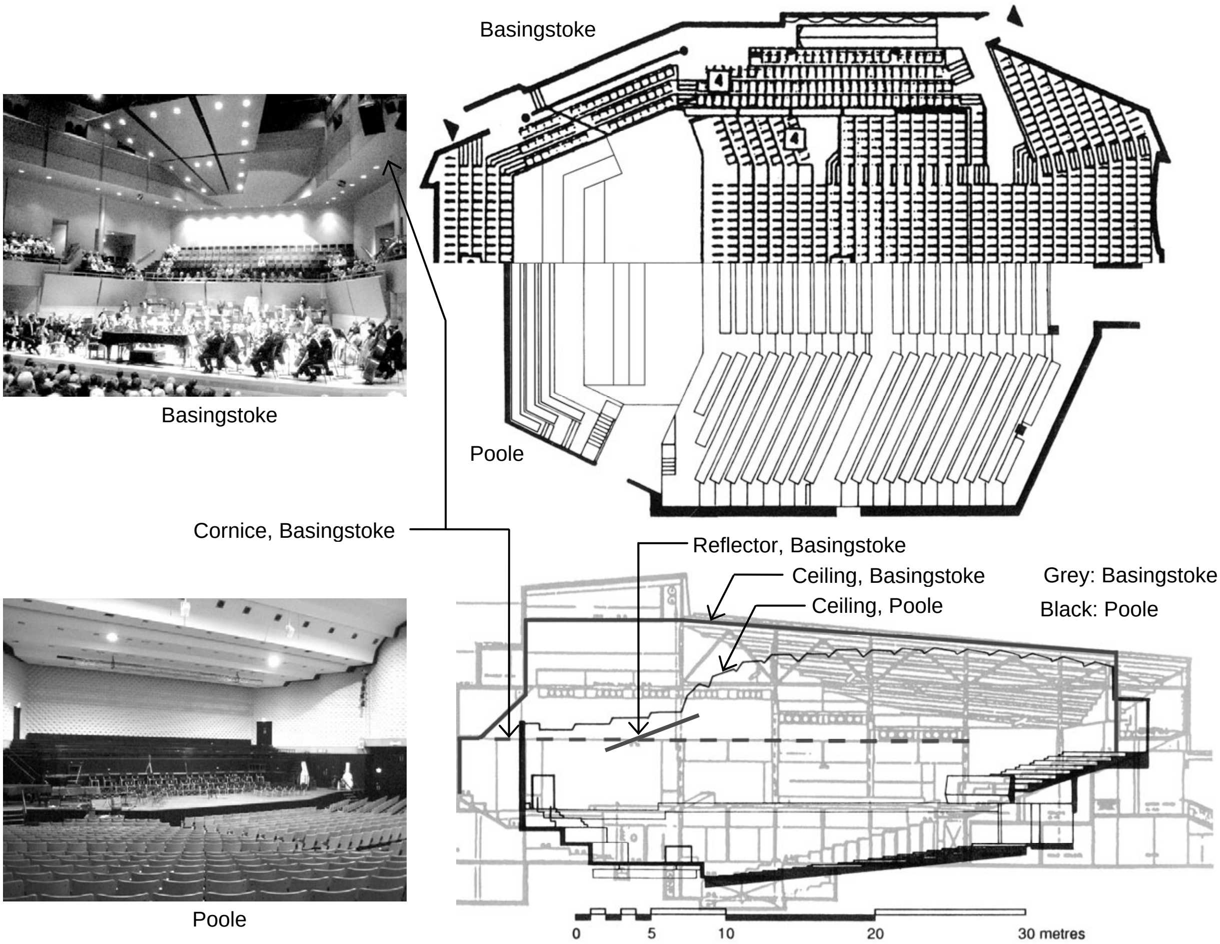

Figure 2.- Plan and cross section view of The Lighthouse, Poole and The Anvil, Basingstoke

In view of a possible preference for narrow stages with high ceilings, it is interesting to look at differences between a ceiling and side wall reflection for the balance of sound on stage. String players normally sit on the flat floor part of the stage, where there will be significant attenuation of the direct sound level across the stage. Early reflections could contribute to compensate for possible poor balance. Figure 3 compares the level of a ceiling reflection to a side wall reflection from musician B and C to musician A. For musician A, the distance to the image of musician B via the ceiling is shorter than to musician C. Hence the level of this reflection will be louder from musician B, which will not help compensating for the lower direct sound from musician C. The resulting impulse responses are shown in upper right corner of the figure. The directivity of the violin at 1.5 kHz (from [9]) is indicated for musician C with the main radiation angles shaded (the pattern is similar at 1 and 2 kHz). For the side wall reflection, the image of musician C will be much closer to musician A than the image of musician B. This reflection will be attenuated by the musicians sitting along the reflection path, but tilted elements or cornices (indicated with a and b in Figure 3) will help create a free path for this reflection. These observations indicate that a low ceiling will make the stage sound louder without improving the poor balance initially created by the attenuated direct sound across the stage. It could also affect the balance between self and others.

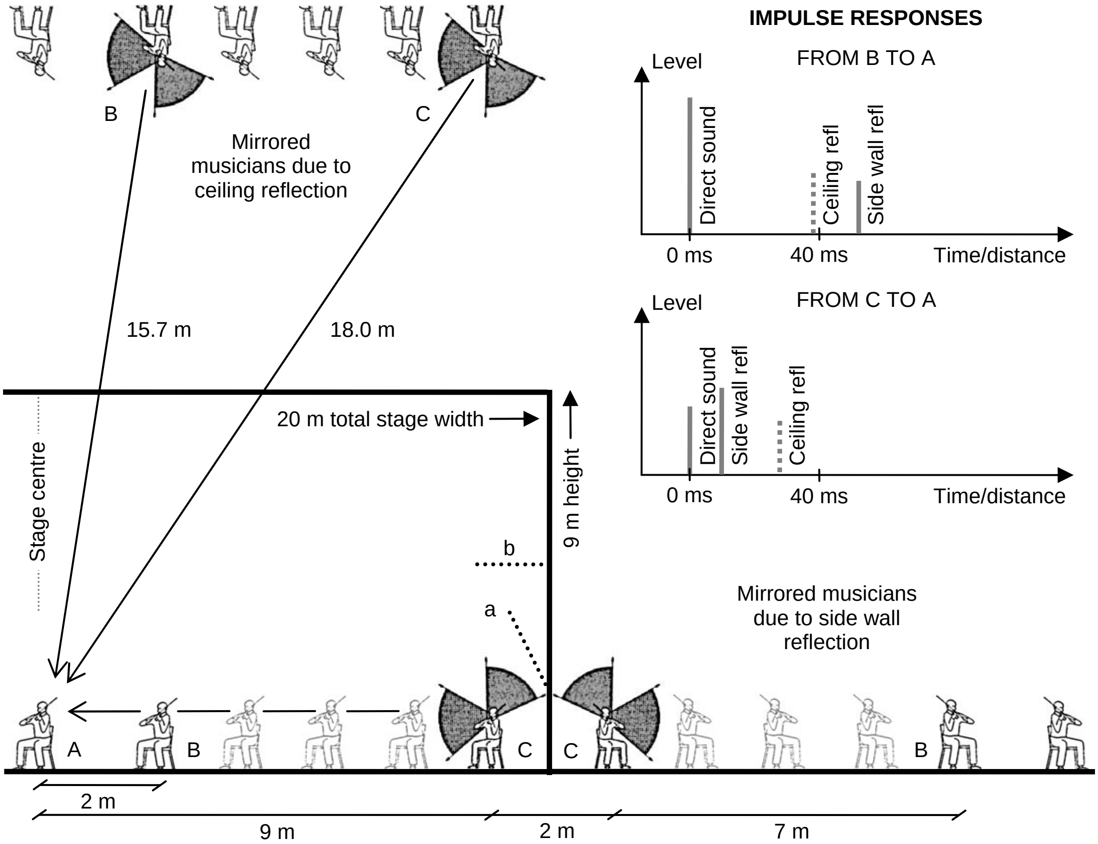

Figure 3.- Ceiling reflection versus side wall reflection (from musician B and C to A)

With risers on stage (which is the case for all the four stages studied), the direct sound from the percussion and brass section to the string section is not much attenuated. A ceiling reflection will reflect a similar amount of all the instruments on stage, while a side wall not far from the string section will reflect more of the sound from string players close to that wall. Another advantage of a side wall close to the orchestra could be the increased low frequency levels for the double basses [13]. The back wall on stage will also affect the level of percussion and brass. Kahle and Katz found that a reflecting back wall close to the orchestra can lead to balance problems [10].

Based on these observations, a low ceiling, wide stage and a back wall quite close to the orchestra (leading to a cornice reflection favouring the percussion section) may explain why the orchestra complain in PL about loud sound and poor balance. A cramped stage will also lead to high levels of direct sound from nearby musicians. Preference for a narrow, high stage enclosure was also found by Cederlöf [19] (not seen from measured ST_{early}) and D'Antonio found a preference among musicians for vertical panels with scattering elements close to the musicians with flat panels on top tilted downwards [20]. The results from our questionnaire also show that the best liked halls anywhere for the musicians had ceiling heights above 13 m.

In Figure 1, the most significant difference between PL and the three other halls is that the integrated level in PL increases at 80 ms after the direct sound and has a slow decay until 120 ms. In the other halls there are more even decays from 80 to 120 ms. For all the halls, the integrated level does not decay much before 60 ms. This may indicate that all reflections arriving before 60 ms contribute to clarity as opposed to reflections arriving between 60 to 120 ms, and that the direction of reflections arriving before 60 ms affects balance more than clarity. Reflections before 60 ms will also affect timbre [11], [12], and the lower time limit for detrimental reflections is likely to depend on the degree of diffusion and music played. The time interval between musical notes will rarely be shorter than 120 ms, and a diffuse decay of reflections starting at 60 ms may provide sufficient separation between each note. With an omni-directional source on stage without musicians it is difficult to distinguish between which early reflections are helpful or detrimental to balance. Computer modelling, which includes the effects of directivity and shadowing by musicians, is possible and may be a better strategy for evaluating balance on stage.

As long as early reflections are provided, there might be an advantage to expose the stage as much as possible to the main hall to avoid build-up of disturbing reflections for the orchestra and the audience. One observes that the stages in BA, BC and CD are more exposed to the main hall than in PL (BA and CD in particular). With a ceiling height of 18 m, a ceiling reflection back to musicians at the centre of the stage will have a delay of 105 ms. A reflector above the stage can contribute to block ceiling reflections that would otherwise be too late [17], which is likely to be of most significance for instruments that radiate most sound upwards. This perhaps contributes to better clarity for the strings in BA.

5 CONCLUSIONS

From collaboration with a symphony orchestra and studying objective measures of some of the halls they play at, side walls or side panels near the orchestra and a high ceiling appear to be preferred. The only objective parameters found to correspond well with this rating are measures usually associated with clarity. Findings indicate that the width and height of the stage affects the balance between players on stage, but the resulting balance for the musicians is not easily measured on an empty stage using omni-directional transducers. Measurements of more stages and computer modelling are needed to give further support for these findings.

6 ACKNOWLEDGEMENTS

This research program is sponsored by EPSRC (UK). We would also like to thank Bournemouth Symphony Orchestra for kind collaboration and David Griesinger, Steve Barbar, Magne Skålevik and Maria Giovannini for helpful discussions.

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