SIMULATIONS AND SUBJECTIVE RATING OF ACOUSTIC CONDITIONS IN A SYMPHONY ORCHESTRA. A CASE STUDY

M Skålevik AKUTEK and Brekke & Strand

1 SUMMARY

Acoustic conditions in a symphony orchestra on concert hall stage are very different from those on the empty stage. Since inter-orchestral sound transmission and other acoustic conditions with the orchestra present is easier to simulate than to measure, a method for simulations in Odeon models of orchestras in different rooms was developed by this author. This method was applied in the Grieghallen Renewal Project, which involved changes in concert hall, orchestra pit and rehearsal hall. Prior to changes, the resident orchestra was invited to give their overall rating of the existing venues, in addition to several well-known venues visited on tour. Acoustical conditions in the rated venues were simulated and compared with ratings. Several metrics were investigated, and their correlation with subjective ratings varied between r^2=0.09 and r^2=0.85. It turned out the orchestra clearly preferred to play in conditions where the an-echoic component and the reverberant component of the inter-orchestral sound-transmission where equally strong, |Ga-Gr|=0. Any deviation from equality was associated with reduced preference, with correlation coefficient r=-0.92. Several interesting implications and interpretations of the result are discussed in the paper.

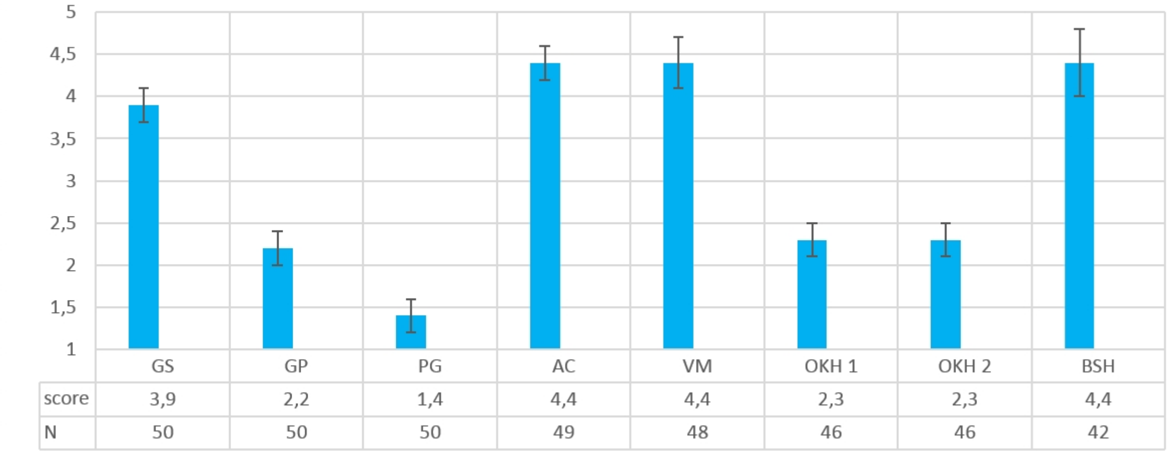
2 DESCRIPTION

2.1 Circumstances

Grieghallen (Grieg Memorial Hall) in Bergen, Norway, home of Bergen Philharmonic Orchestra (BPO) was inaugurated in 1978. After 34 years of wear and tear, the Grieghallen Renewal Project started in 2012 and completed in the 2015, the year of BPO's 250th anniversaries (BPO is one of the oldest orchestras in the world). The renewal included new seats, a new stage floor, a new orchestra shell, a new and larger orchestra pit in Griegsalen, the 1500 seats main concert hall, and a complete renovation of Peer Gynt, a smaller multi-purpose hall which BPO use for rehearsals now and then. This author was the acoustic consultant of the renewal project, and the owner of Grieghallen was the client. For the acoustic consultant, the task was to maintain the acoustic conditions for BPO and audience in Griegsalen, to provide for good acoustic conditions in the new orchestra pit, and to markedly improve the acoustical conditions for BPO during rehearsals in Peer Gynt.

2.2 Subjective data

It was natural to base all requirements and aims on BPO's preferences as to acoustics. To find out what kind of acoustics BPO liked and disliked, a survey among the musicians was carried out. In an online questionnaire, all members of the orchestra were asked to assess the acoustics on stage in Griegsalen, in the orchestra pit in Griegsalen, during rehearsals in Peer Gynt, and in several other concert halls in the world where they have played. The question made clear that they were to assess the performers conditions – not the listeners conditions: "Assess the acoustic conditions for orchestra play in these halls". Scale from 1 to 5. Among a total of 50 respondents it turned out that most of them were able to assess the following venues: Griegsalen stage (GS), Griegsalen Pit (GP), Peer Gynt (PG), Amsterdam Concertgebouw (AC), Vienna Musikverein (VM), Oslo Konserthus (OKH), Boston Symphony Hall. Since 2004, OKH have had an orchestra canopy and were assessed in its two versions – OKH 1 (before 2004) and OKH 2 (after 2004). We therefore consider 8 different venues. Average assessment scores and number off assessors per hall can be seen from diagram and table in Figure 1. In the following it is described how these scores can be explained by acoustical parameters predicted by simulations in 3D-models of each of the 8 venues.



	GS	GP	PG	AC	VM	OKH 1	OKH 2	BSH
score	3,9	2,2	1,4	4,4	4,4	2,3	2,3	4,4
N	50	50	50	49	48	46	46	42

Figure 1 Average assessment scores in 95% confidence intervals, and number of assessors (N).

2.3 3D models for simulation

In search for room acoustical properties that could explain why some of the venues are better liked or less liked by the orchestra members, simulations were performed in 3D models of each of the 8 venues. For this purpose, the computer software ODEON 11 was used. To all possible extent, the models were adapted to the actual conditions under which the musicians had assessed the halls, including the occupied stages and audience seating areas in the various concert halls. The orchestra models were basically a copy of the orchestra model in the GS model, but adapted to fit in to the constraints and the rake of the various concert hall stages. All orchestra models were in the form planes of total area in the interval 98-101m2, with absorption spectrum given by the factory setting “11000 Orchestra” and scattering coefficient 0.7. In GS, GP and PG, the absorbing plane is just above the floor plane. In GP (Griegsalen orchestra pit), the seating layout is naturally different from the one on stage, and the model was adapted to fit the geometry of the pit as it was prior to 2012. It was assumed that the orchestra would all available floor, and the resulting area of the orchestra model was 112m2.

2.4 Source, receivers and parameters in the simulations

In addition to the default parameters calculated by Odeon, we wanted to simulate and measure the inter-orchestral sound transmission. For this purpose, the orchestra was divided into a receiver grid of 1.5m*1.5m resulting in 43 receivers (in the orchestra pit, this was achieved by a grid of 1.6m*1.6m) at height 1.2m above the absorbing plane. A source was positioned between typical positions of Conductor and Concertmaster at height 1.0m above the absorbing plane. A set of 43 G values from the 43 source-receiver combinations in each venue was acquired. We calculated the set of G_d, i.e. the direct (non-reverberant) part of G, and the set of G_r, i.e. the reverberant part of G. The idea was to be able see any explanations of the musicians’ preference in not only the total G, but in G_d, G_r, or in the balance between the reverberant and non-reverberant parts, G_r - G_d.

2.5 Objective data – simulated room acoustical parameters

Results from the simulated measurements in terms of average of the 43 source receiver combinations are given in Table I. Parameters are denoted in the heading of each column. “X” is a set of reference values that will be described below. More parameters were calculated, and the selection of the parameters included will be explained further below. The data was used as input in the investigation of potential correlation between the parameters (the objective data) and the assessment scores (the subjective data) presented above. Note that for reader friendliness, all dB-values in the table are rounded to nearest integer, thus the column G_r - G_d is not always equal to the difference between its rounded terms.

Table I Results from simulations in the various venue models. “X” is a reference. See text.

Venue	G_r-G_d [dB]	G_r [dB]	T_{30} [s]	G_{late} [dB]	ST_{late} [dB]	G [dB]	ST_{early} [dB]	G_d [dB]
GS	1	8	1,7	2	-18	11	-15	7
GP	5	10	1	-4	-25	12	-14	5
PG	6	13	1,4	9	-13	14	-12	7
AC	-2	5	2,1	1	-20	9	-19	6
VM	0	7	2	2	-18	10	-12	7
OKH 1	-3	4	1,5	0	-21	9	-16	7
OKH 2	-3	3	1,6	0	-21	9	-18	7
BS	-1	5	2,2	0	-22	9	-19	6

X	0	7	2,2	2	-19	10	-20	6

2.6 Correlation between subjective and objective data

In search for any correlation between the acquired sets of subjective data and objective data, it was assumed that for each parameter in Table I there exists an unknown optimum value. Any deviation, positive or negative, from the optimum value would be associated with reduced preference. The more deviation, the less preference. The optimum values in row “X” can be found by running an iteration process for each parameter, e.g. starting with with G. First suggest an optimum value G_X for G. For each venue, calculate how much G deviates from G_X, in terms the absolute value $|G-G_X|$. Then calculate the correlation between these values and the assessment scores above. Then suggest other G_X and recalculate correlation. Repeat until the highest possible correlation occurs. Example: If we suggest G_X = 10dB, then the values in the G-column in Table I would deviate from 10dB with the amount given in the G-column in Table II, and the correlation between these deviations and the subjective scores would correlate by r=-0.70 and r2=0.49. We have not found any G_x that produces higher correlation than this.

Table II Absolute deviations (in JND) from the X-values in Table I, and correlation r and r2 between deviations and Score. Tables present dB and JND values rounded to nearest integer only.

Venue	G_r-G_d [JND]	G_r [JND]	T_{30} [JND]	G_{late} [JND]	ST_{late} [JND]	G [JND]	ST_{early} [JND]	G_d [JND]	Score
GS	1	1	4	0	1	1	5	1	3,9
GP	5	3	11	6	6	2	6	1	2,2
PG	6	6	7	7	6	4	8	1	1,4
AC	2	2	1	1	1	1	1	0	4,4
VM	0	0	2	0	1	0	8	1	4,4
OKH 1	3	3	6	2	2	1	5	1	2,3
OKH 2	3	3	5	2	2	1	2	1	2,3
BSH	1	1	0	2	3	1	1	0	4,4

r2	*0,85*	*0,74*	*0,71*	*0,64*	*0,51*	*0,49*	*0,22*	*0,09*	*1.0*
r	*-0,92*	*-0,86*	*-0,84*	*-0,8*	*-0,71*	*-0,7*	*-0,47*	*-0,29*	*-1.0*

Then, do the above iteration process for all parameters, one column at the time, in arbitrary sequence. The results after completed iteration processes are seen in Table II where the deviations are expressed in terms of Just Noticeable Difference (JND) assuming 1dB is 1 JND, and 5% difference in T30 is 1 JND. The rows r and r2 are the correlation and the squared (Pearson) correlation between the JND’s in a column and the Score column, given the final optimum values in row “X” of in Table I.

Note calculations are made with several decimals, while for reader friendliness, tables show integer values only of dB and JND.

Comment to G_d: In the background data, the G_d parameter values varies between 5.3dB (GP) and 7.2dB (GS). The low value in GP is due to the odd layout in the orchestra pit. The other venues are statistically 6.8±0.3dB, partly due to variations in layout and partly due to random variations in the receiver positions generated automatically in Odeon.

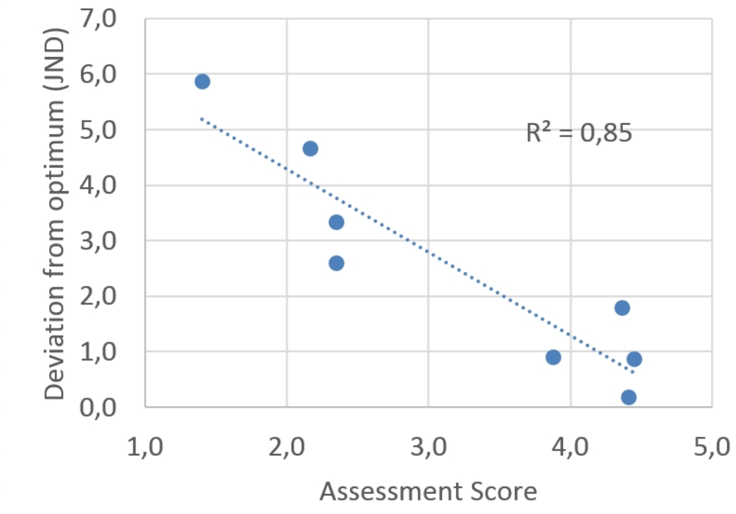


Figure 2 Plot of deviations versus Score; The less "G_r-G_d" deviates from its optimum, the higher the Objective Score, ref. Table II;

2.7 First sight comments to correlation results

In Table II the parameters are presented in the order of higher r2 correlation in columns toward the left. All default parameters in Odeon were tested, and this selection of parameters are those who exhibited the higher r2 correlation, and thereby the better explanation potential. Surprisingly, the parameter "Gr-Gd" turned out to be the one that best explained the musicians' assessment of the various venues, with r=-0.92 and r2=0.85, as graphically illustrated by the plot in Figure 2. The spread around the dashed regression line indicates an uncertainty of around ±1JND, i.e. ± 1dB.

We interpret the results as follows: When G_d, i.e. the average direct sound transmission level between Concertmaster/Conductor and other positions in the orchestra, is equal (±1dB) to the corresponding average reverberant sound transmission, as simulated in an Odeon model, the BPO orchestra musicians are likely to judge the acoustic conditions for orchestra play as "very good".

Reverberant sound transmission G_r alone correlates considerably with Score, r2=0.74, and its variation is the main source of variation in "G_r-G_d". However, though the information in G_d brings no useful explanation alone (r2=0.09), it contributes to improved explanation (from 0.74-0.85) when combined with G_r. Very much so because of conditions in the orchestra pit. Reverberant transmission in the orchestra pit, G_r=10dB, deviates by 3dB from optimum, which is not enough to explain the musicians' assessment of the acoustic conditions there. Neither does loudness in the pit appear to be extraordinary (G is only 1dB higher in GP than GS). However, the direct sound is on average weaker than elsewhere because of the elongated layout in the pit (thus longer inter-orchestral distances), resulting in a very high reverberant-to-direct balance, $|G_r$-$G_d|$=5dB, which deviates 5 JND from optimum. In such conditions, musicians hear each other mostly through reverberant sound, and relatively little direct sound is heard there.

As a preliminary conclusion, the musicians in BPO prefer a balance between reverberant sound and direct sound, G_r-G_d =0. This can be interpreted as an ensemble version of the well-known Direct-Reverberant ratio d/r=1, often expressed as Direct-Reverberant level balance, D-R=0dB.

Note: It is important to keep in mind that the findings above are valid only to simulations in 3D-models like those described above. However, in a design phase, these facts are fortunate, rather than unfortunate restrictions. On the other hand, in further work it would be interesting to investigate to what degree the findings would translate to field measurements.

3 DISCUSSION

While it is important to bear in mind that the above is a case study, its results and findings have some interesting implications. It would be interesting to apply the same approach in other orchestras and projects, to test if similar results can be found.

3.1 Direct-to-Reverberant ratio and balance

A common parameter in audio engineering is the direct-to-reverberant ratio d/r and the direct-to-reverberant level D-R=10*log(d/r). D-R is a measure of the level balance between the direct and the reverberant component in sound transmission or in a transfer function. A sound field around a sound source, where D-R>0, is dominated by direct sound, hence referred to as the direct sound region. The distance from a sound source at which the direct and reverberant sound is equally strong, D=R, is defined the critical distance d_c. At longer distances, sound transmission is dominated by reverberant sound, R>D, i.e. in the reverberant sound field. In the case of an omni-directional source, $d_c = r_r$, where r_r is the reverberant radius or the hall radius, a property of the room,

$$r_r = V/(312\cdot T) = 0.14\cdot A^{0.5}$$

where V is room volume, T is reverberation time and A is absorption area. This assumes classical diffuse conditions. In the case of stronger or weaker early reflections, d_c and r_r would be shorter or longer, respectively. The above description is the conventional way to interpret the reverberant radius and the direct and reverberant sound fields, i.e. from the source' perspective. Figure 3 is a plot of D-R plotted against distance from Concertmaster to all occupied positions, distributed over orchestra and audience in the GS model. To the average orchestra member, distance is 4.9m and D-R is 0.2dB. To the average audience member, distance is 25m and D-R is -8.5dB.

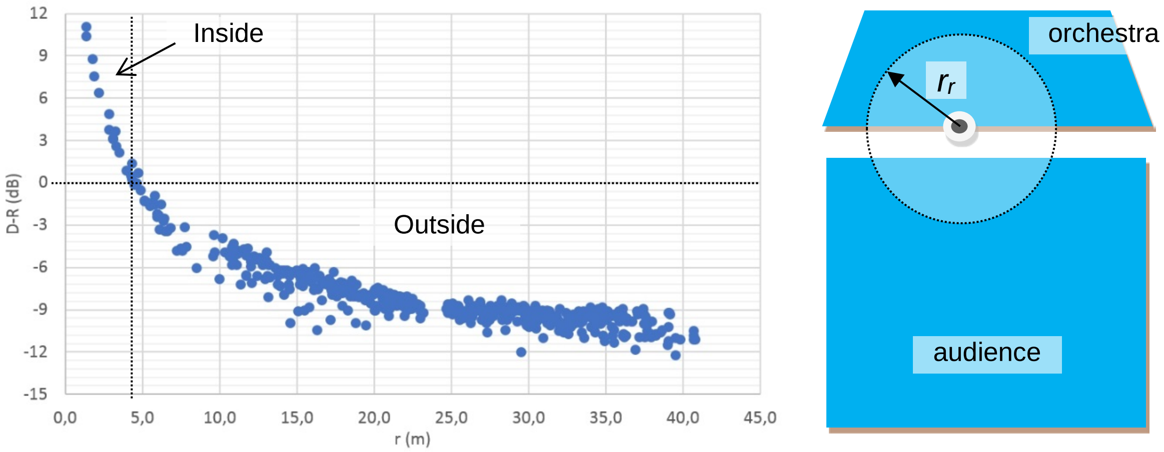


Figure 3 D-R plotted against distance from Concertmaster to all occupied positions, distributed over orchestra and audience, in the GS model. Right: Schematic plan, source (dot), dotted circle line with radius r_r (arrow) =4.5m. Inside and outside of circle corresponds to quadrants in the plot to the left.

However, for the individual musician in a symphony orchestra, it may be more relevant to take the receiver's perspective as follows. Draw a circle with radius equal to r_r, around a musician or a conductor. From the conductor's perspective, musicians' can be divided in two categories – the near group, i.e. those inside the circle, and the far group, i.e. those outside the circle, (Figure 4 right). The sound from the near group will be mainly direct sound, and the sound from the far group mainly reverberant sound. A visual analogy to the reverberant radius would be sight range in navigation, road traffic and aviation, which is a measure of how far one can see clearly. Reverberant sound would be an analogy to fog and mist which in similar manner makes it harder to separate details. Transparency, another attribute used in seeing as well as in hearing, would increase as D-R increases.

Extending from hearing to communication: A musician communicates via direct sound with the near group, and via reverberant sound with the far group. Changes in the D-R balance would mean changes to the near and far groups and the balance between them. It is hypothesised that musicians' and conductor are sensitive to such changes, and that D-R balance is a critical aspect in stage acoustics for symphony orchestras. When an orchestra is on tour, visiting one concert hall after the other, acoustic conditions may change from one day to the other. Then r_r, may vary from venue to venue, i.e. if the ratio V/T varies. If the orchestra members prefer a certain D-R balance, a change in r_r, may be unfortunate or challenging, and difficult to adapt to without ideals being compromised.

In Figure 4, simulated midfrequency (500 and 1k octave) D-R balance levels in dB are plotted against distance between Concertmaster/Conductor and 43 positions distributed in a 1.5m grid over the orchestra in the GS model. Average is D-R=0.1dB, and the reverberant radius appears to be r_r=4.5m. Near group in upper left quadrant and inside circle. Simulated measurements over the same points over the empty stage, average is D-R= -3.4dB and the reverberant radius around 2.5m.

Note that D-R is on average 3.5 dB higher without the orchestra (empty stage floor) than over the orchestra. Moreover, the difference between empty and occupied stage is bigger at short distances and smaller, mainly due to early reflected sound being more effectively absorbed at short distances than at long distances in the model. These differences indicate that D-R measurements on empty stage may not be useful when trying to understand the conditions for inter-orchestral hearing. Since such measurements would be very time and resource consuming, simulations will be the only practical option. Moreover, during planning of a new concert hall or the changes to an existing one, only simulations are available. What we need is a set of reliable criteria for the simulated measurements. On the other hand, in a research phase, real measurements would be performed to verify simulations.

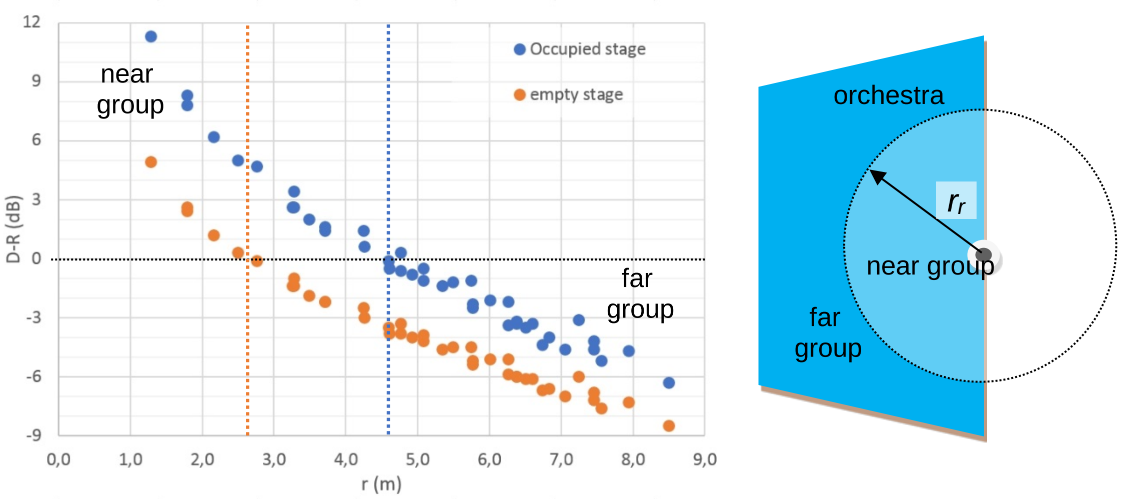


Figure 4 Direct-to-Reverberant level (dB) measured from simulations in the GS model. See text.

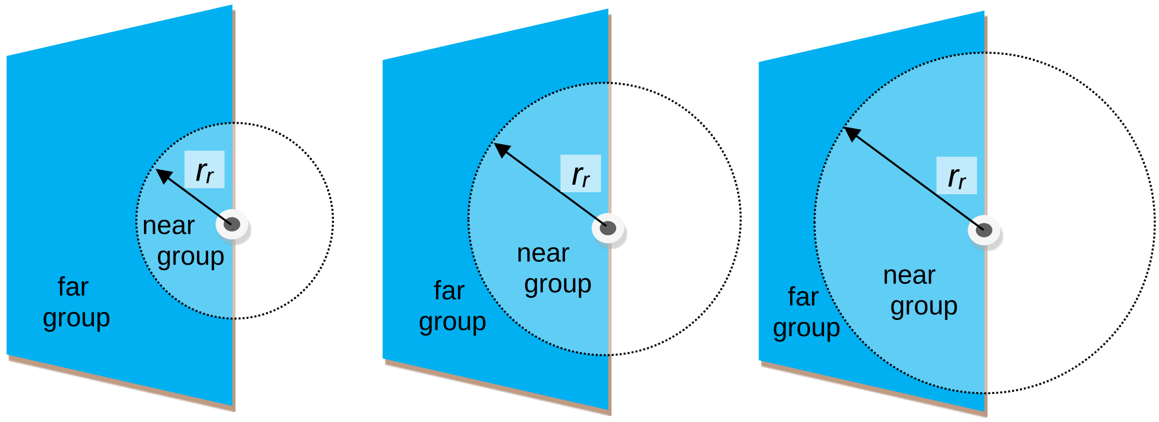
Music instruments in general can have complex directivity patterns, generally more directive toward higher frequencies. Directivity of harmonics fluctuate with time in a given direction and fluctuate over directions at a given instant. Long-time average directivity patterns can be established from measurements, but fluctuations around average can in 2/3 of the time be more than ±5dB in a violin, and more than 4dB in an oboe[1]. Importantly, the D-R can in 1/3 of the time be more than 5dB above the long-term D-R of the source. This is one of the reasons why an instrument can be localized at distances far beyond d_c.

The other reason is binaural hearing, i.e. our ability to combine information at our two ears, and in particular our ability to optimize the inter-aural cross-correlation between sounds at our left and right ear by turning our heads straight toward the source. According to Jeffress' binaural hearing model[2], sounds arriving from different azimuth angles can be separated by our hearing, even in ambient noise and other complex acoustic environments, if D-R is above some threshold. E.g. being able to separate single voices in a noisy cocktail party, hence often referred to as the cocktail party effect. Acoustically, a symphony orchestra has common features with a cocktail party where speaking voices have been replaced with playing instruments. For one, there are similar challenges with hearing. Moreover, hearing problems are often in a feedback loop with escalating sound levels, another characteristic feature of cocktail parties, as will be commented further in 3.3.

3.2 Interpretation of BPO's preference

As described above, the immediate interpretation of the results is that the orchestra in this case study prefer a balance between reverberant sound and direct sound, G_r-G_d =0, which is equivalent to the average D-R balance being zero. Further, in view of Figure 4, the balance between direct and reverberant sound translates to a balance between Near Group and Far Group, or the Near-Far balance for short. It can be seen from the "empty stage" simulations that with stronger reverberant sound, the D-R balance is lower, and the Near Group is smaller. Thus, if the D-R balance is lower than preferred, the Near Group will be smaller than preferred, and vice versa. See Figure 5.

A smaller Near Group would mean that fewer musicians hear each other via direct sound and more musicians hear each other through reverberant sound. For an individual, the count of co-players inside the Near Group would depend on the density of musicians around where the individual sits. Typically, there is a higher density in front of an orchestra than at the back. Conductor/concertmaster would have a higher instrument count in their Near Group than a percussionist in the rear row would have, typically 50 string players in the Near Group around the conductor and 30 others (woodwinds, brass percussion) in the Far Group. However, this does not change the fact that in any position, the Near Group would shrink if D-R decreases, and vice versa.



D-R too low
Near Group too small
Far group too big

D-R and Near-Far
balances as preferred

D-R too high
Near Group too big
Far Group too small

Figure 5 Interpretation of results in this case study, in terms of preferred r_r and Near-Far balance

3.3 Relating to previous research in Stage Acoustics

A review of research in the history of Stage Acoustics was presented by Gade[3] in 2010. Much of the previous work has emphasized the musicians' need to hear oneself and co-players, and how to control reflections to provide for such self and mutual hearing. Many room acoustical parameters and quantities have been suggested and tested for their ability to describe the acoustical conditions, but two parameters have so far been included in an ISO-standard, namely ST_{early} and ST_{late} , initially suggested by Gade, in the standard ISO-3382-1[4]. While ST_{early} initially was suggested a measure of the perceived acoustical support for the individual musician and indeed interpreted and practiced as such, the standard assigns the quantity ST_{early} to the aspect of ensemble conditions. ST_{late} is in the standard assigned to the aspect of reverberance as perceived by the musician.

While the way the ST-measurements are performed, 1m from the source on an empty stage, intuitively make them an obvious measurement of the room response that a soloist hears when playing her/his instrument, it is less intuitive that these measurements have much to do with what a musician on the occupied stage hears when playing in a symphony orchestra.

Inter-orchestral sound transmission as such was measured, e.g. by Krokstad et al[5] (1980), Halmrast[6] (2001) and Skålevik[7] (2007). Dammerud[8] studied inter-orchestral sound transmission in a scale model. Such investigations have not yet led to a replacement of empty-stage measurements, despite evidence of a significant impact from the presence of an orchestra. A typical observation has been the trend of a linear sound level attenuation in the inter-orchestral transmission, in contrast to the inverse square law attenuation of direct sound. Moreover, various masking effects due to sound from co-players are expected to play a role.

Since 2010, loudness issues have received more attention, and as a part of this, the level balance between sound from a musician’s own instrument and the sum of direct and reflected sound from co-musicians. This research is driven by two concerns: the noise-and-health concerns in orchestras, and the forward masking by early reflections, affecting the hearing of own instrument and other instruments. In attempts of protecting musicians’ hearing as well as improving the perceived balance between individual instruments, groups and the amount of reverberant sound added to it, it is important to know how strong these components are relative to each other, at the musicians’ and conductor’s ears. Only with this information established, one would know how to make any improvements. E.g., to reduce reverberant sound for noise & health reasons would not be adequate if reverberant sound is only a minor part of the sound exposure.

When it comes to quantifying the portions of the aforementioned sound components, the work of Wenmaekers et al[9] (2015), and the work of Skålevik[10] (2015), may have arrived at different results. While the first concluded that when playing in an orchestra, sound from own instrument plays a minor role in the noise exposure, the second concluded that sound from own instrument accounted for roughly one half the noise exposure.

Surprising as it may be, the noise-and-health concern and the mutual hearing concern in symphony orchestras may well be two sides of the same coin. Several authors have suggested that musicians would play stronger in an environment where they hear too little of their own instrument. If reflected sound is a significant portion of the sound exposure, unfortunate sound reflections may, due to their masking effect, lead to forced playing. Consequently, such unfortunate reflections may drive a vicious circle, driving the whole orchestra to play stronger, making both noise exposure and performance problems even worse because of increased spectral masking and more harsh sound (forced playing would increase the strength of the upper harmonics more than the lower ones).

Similar problems are well-known from cocktail parties, as mentioned in 3.1, where escalating hearing problems and noise exposure are indeed two sides of the same coin. The driving factors in the positive feedback loop (raised voices causes even more raised voices, and so on) are the Lombard effect, a biological reflex, and the intuitive effect, i.e. the attempt to overcome hearing problems, to be heard, by raising the voice. It is practically impossible to avoid these problems if the reverberant radius is small compared to the distance between individuals in a group that try to communicate, i.e. if trying to communicate with individuals outside the Near Group. To this authors knowledge, the similarities between cocktail parties and symphony orchestras have not been studied by other authors.

Another self-reinforcing effect can occur if sound reflections are too weak, since this could make many orchestra members compensate by playing stronger or demanded by the conductor to do so. If bass reflections are weak, i.e. low frequency G is relatively weak, musicians and conductor could perceive a lack of warmth and too much brilliance in the sound. In this case the conductor may want more power from the lower pitch instruments. However, in musical instruments more power cannot be produced without at the same time increasing brilliance and reducing less warmth to the power spectrum. Again, this makes the initial problem worse, driving the same vicious circle as described above. Concludingly, too much or too little reflections both lead to double trouble, i.e. noise & health problems AND ensemble problems as to hearing one self and others.

3.4 Recommendation

In terms of inter-orchestral D-R as discussed in this paper, too low or too high D-R values would involve the risk of escalating loudness and sound level exposure as well as worsened conditions for inter-orchestral hearing. As a preliminary recommendation, simulated average D-R over the orchestra in a 3D model, with a source in the position of Conductor/Concertmaster, should be close to zero.

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