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STAGE ACOUSTICS
– LITTERATURE REVIEW

by Jens Jørgen Dammerud

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Stage acoustics – Literature review

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1 Introduction

This literature review has been written as part of the transfer report from MPhil to PhD at the University of Bath, October 2006.

2 The orchestra and choir on stage

A symphonic orchestra normally consists of approximately 100 players. They can be categorized into four main instrument groups: strings, woodwind, brass and percussion. The strings consist of violins, violas, celli and double basses. The woodwinds consist of oboes (including cor anglais), bassoons, clarinets and flutes. The brass group consists of trumpets, French horns, trombones, and tuba. The percussion group includes timpani, vibraphone, harps and piano. (A piano can be treated as both a string and percussive instrument). Seen from the audience, the orchestra is usually arranged in the same order as listed here: strings at front, woodwinds in the middle and brass and percussion at the back as Figure 1 shows.

The choir is normally placed behind the orchestra on stage and can often have above 100 persons. Soloist singers are situated at front of the stage like any instrumental soloist (normally violin or cello).

The orchestra plan known as the American is shown in Figure 1, which is the most common arrangement today. Alternative arrangements exist as shown in Figure 2.

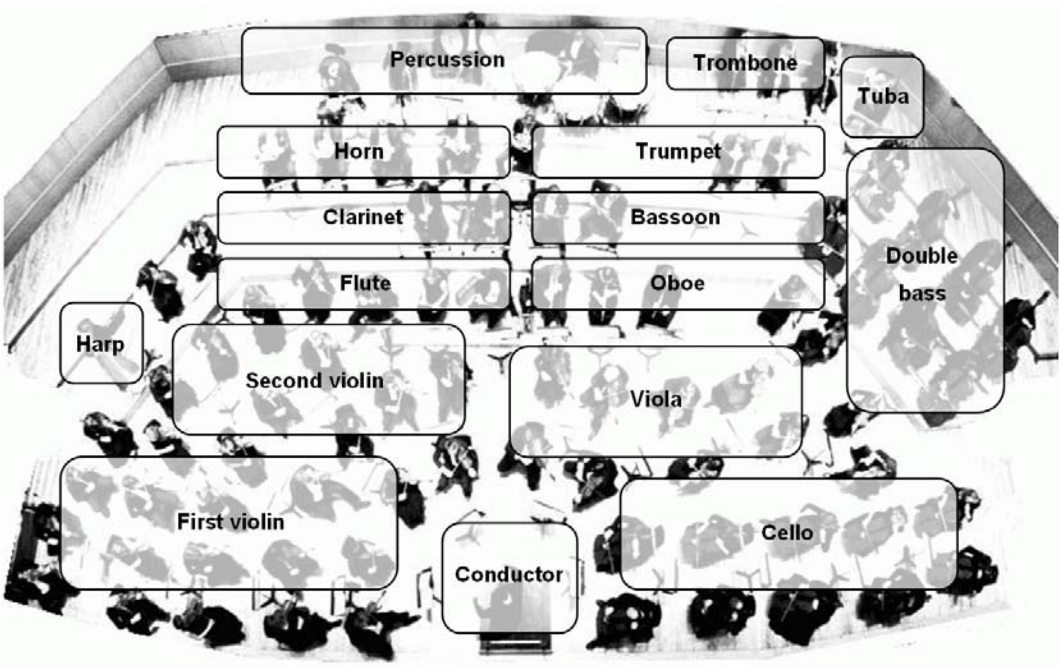

Figure 1: Orchestra arrangement, American. (Approximate positions, based on Internet [58]).

The leftmost arrangement shown in Figure 2 is the American. The middle is Furtwängler's version, while the rightmost is the German (or European) arrangement. The German arrangement gives a better "stereo effect" of the orchestra with the first and second violins on opposite sides (Meyer [22]). Many symphonic works have been written with this arrangement in mind, creating a "dialog" between left and right side of the orchestra among the violins. The American is said to be motivated by the monophonic recording technique used during the '50s and it normally requires a shorter rehearsal time for the orchestra (Orestad [52]). With the American arrangement a synchronized onset of tone is easier achieved between the two violin groups since they are sitting together using this arrangement, and the stereo effect lost its value on mono recordings. Because of more demanding playing conditions for the orchestra (especially the strings, violins), the German is not the most popular arrangement. But it is popular for its stereo effect for the audience, and string players have commented that it is easier to listen outside the string group with this arrangement. But at the beginning of rehearsals many string players experience more difficulties being split up in two separate groups (Orestad [52]).

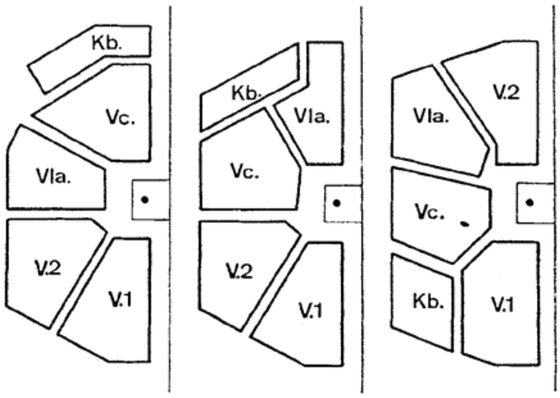

Figure 2: Alternative orchestra arrangements. From left to right: American, Furtwängler's, German.
V.1 = First violin, V.2 = Second violin, Vla. = Viola, Vc. = Cello, Kb. = Double bass
(From Meyer [59]).

The different instruments normally have their own parts and the violins represent the largest group of single instruments. The woodwinds and brass are rarely more than four on the same instrument. The strings are among the weakest sounding instruments in the orchestra and their directivity (spatial radiation pattern) varies much with frequency. The woodwinds are louder and have a more even directivity. The brass, especially the trumpets and trombones, are among the loudest instruments and become highly directional at higher frequencies as Figure 3 shows. These instruments are directed to the audience but also towards the woodwinds and strings. The player is on the opposite side of the instrument, and this causes large differences between what the player hears of his/her own instrument and what is heard by others at front.

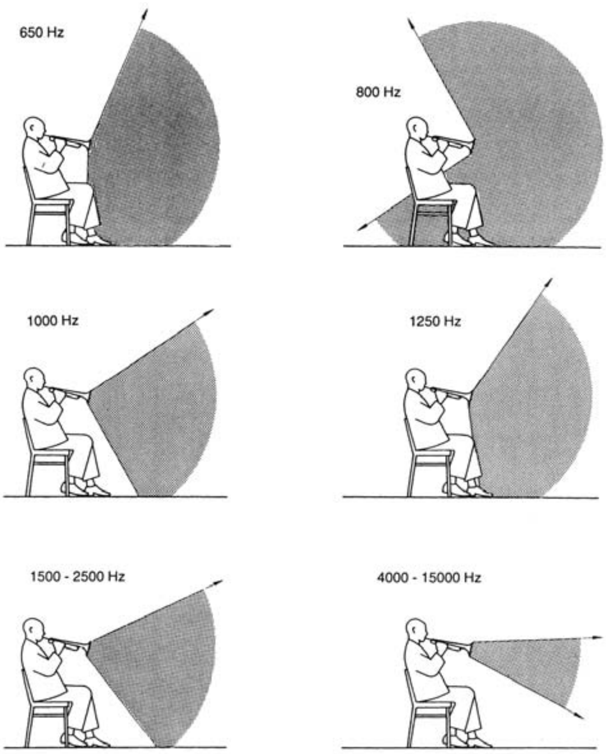

Figure 3: Directivity of a trumpet at different frequencies (Meyer [60]).

In general, the directivity of instruments increases with increasing frequency. At lower frequencies almost all instruments are omni-directional (emit sound equally in all directions), but above 500 Hz most instruments start to radiate more sound energy in certain directions. Also the transmission of direct sound (see section 3.3) of the instruments within the orchestra is varying with frequency. At low frequencies the direct sound from the different instruments diffracts (propagates around obstructions) and reaches all the musicians quite easily. At higher frequencies (from about 500 Hz here as well) the musicians, instruments, chairs and music stands start to create “sound shadows” within the orchestra. So the sound from a certain instrument can be weak at another position in the orchestra, particularly above 500 Hz, due to little energy transmitted in that particular direction and/or many objects are in the way for free propagation of the sound. This is where the stage enclosure and reflectors have an important role of providing reflections to compensate for directivity and shadowing effects (but only to a certain degree).

The sound level within the orchestra in terms of risk of hearing loss for the musicians, has received more attention recent years. The direct sound and the stage enclosure affect the sound levels within the orchestra, and different screens (absorbing and/or reflecting) within the orchestra have been introduced to try to regulate the direct sound transmission between instrument (groups) to avoid excess sound levels. An investigation of how the stage contributes to risk of hearing loss is not of primary concern in this study, but findings from this study will be seen in relation to other findings on hearing loss risk assessment for the musicians.

The time it takes for the different instruments to establish their tone (onset time) could affect the ability to hear one-self relative to the others. The direct sound from the trumpets can reach the strings group before the sound of their own instruments has established itself. But experience show that the musicians normally are able to compensate for this while they are playing (Gale [53]).

The orchestra is controlled by the conductor. The conductor tries to represent the audience and control the orchestra according to what he/she hears. At the same time the members of the orchestra are listening to each other. The adjustments of one-selves contribution to the orchestra (with respect to loudness, intonation and timing) is done based on experience following the conductor and observing visually fellow musicians and listening to the sound from one-self and the others. Due to the orchestra’s size a significant delay is added to the sound from fellow musicians (depending on the distance between the musicians). For this reason the musicians cannot base their time judgement on sound alone – the conductor and visual cues play an important role in getting the orchestra synchronized (for the audience). The musician needs to continuously evaluate what he/she is doing based on what he/she is hearing but also seeing and feeling (i.e. vibrations, overall experience). While playing, the musician looks at the conductor and the movements of the fellow musicians, follows the score (written music) and listens for important instruments relating to his/her own instrument. This makes the situation much more complicated than for the listener, who is essentially a passive listener.

If a performance is not successful for a musician it can be a consequence of the concert stage itself (due to its acoustics, size etc.) but also the repertoire, the conductor, the rest of the orchestra, the audience etc. The experience of the musicians is also closely related to emotions (making music is often a fragile situation and small details are important to make it “all work”), which makes it difficult to see clearly what was actually not working well when judging it in retrospect.

3 Floor resonance and close walls

Stringed instruments have too small a body to support the lowest notes of the instrument. This lack of resonance for the deepest notes is most significant for cello and double bass. A light-weight floor (wooden, not concrete) or a riser can assist in radiating the sound from these instruments in their lowest register. Both these instruments are resting against the floor by the use of a endpin (made of metal), and the vibrations from the instruments are transferred to the floor/riser through the endpin. These two instruments are also held against the body of the musician, so vibration from one's instrument can be picked up by other instruments (through their endpins). Instruments close to each other will respond mutually to their vibration which can be sensed by the musician holding this instrument. There are uncertainties about how significant this is for ensemble between the lower strings (cello and double bass) (Askenfelt [49]).

The floor and wall(s) close to the instruments can also contribute to raise the level at lower frequencies due to "acoustical coupling". This is due to the reflected sound being in phase with the direct sound and hence adding together constructively. For the lower sounding instruments of the orchestra, this effect can be desired since the lower frequencies play an important role for intonation for the orchestra. But for instance a hard reflecting back wall can also result in the percussion and brass being too loud (Lee [7] and Kahle and Katz [38]).

4 The sound field on stage

The main objective method for investigating acoustic behaviour in halls is through impulse response measurements. The impulse response shows how the acoustic space (or a linear system in general) will respond to an impulse source, for instance a gun-shot, bang of a drum, clapping of hands etc. The impulse response gives an overview of all the sound reflections that arrive at a certain position when an impulsive sound has been fired off. The impulse response will vary for different source and receiver positions (S and R) since the distance from reflecting surfaces will vary between different positions inside the space.

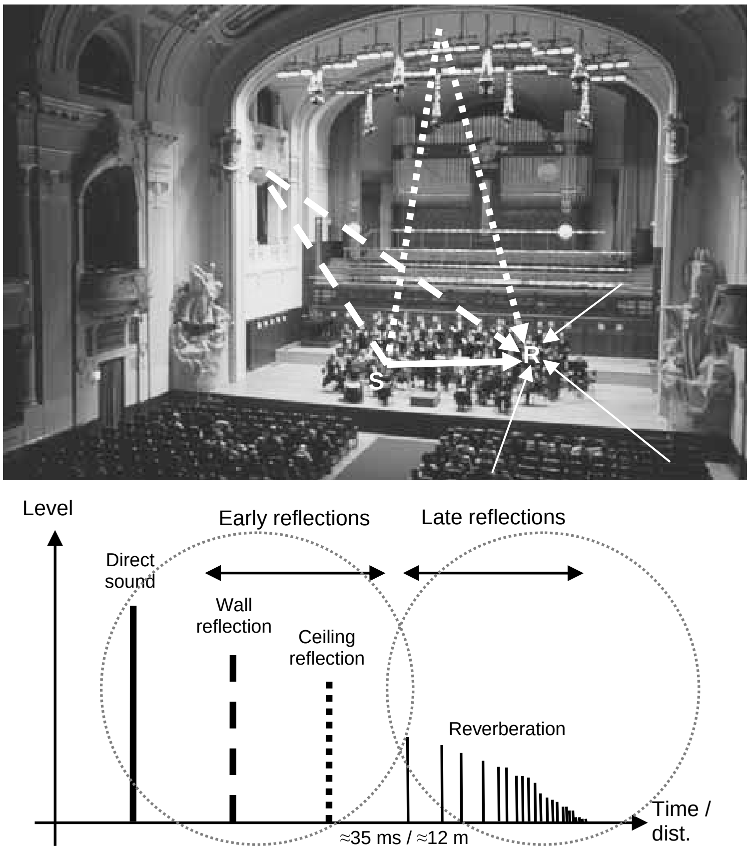

Figure 4: Direct sound, early and late reflections on a concert hall stage (S = source, R = receiver). Vertical axis represents sound level (dB) and horizontal axis represents both time and distance. (Image of Smetana Hall, Prague. Figure based on (Internet [61]).

The first sound that will arrive at the receiver position is the direct sound. This is the sound wave travelling directly from the source to the receiver without bouncing into reflecting surfaces and represents the shortest way between source and receiver. After the direct sound, the early reflections will reach the receiver. The first arriving sounds after the direct sound will be reflections of first order, which means they have only hit one surface on their way. Some waves will hit two, three, four and so on surfaces on their way between source and receiver. As the order increases the number of sound reflections that arrive at the receiver position will increase and after some time all the reflections blend together as the reverberant sound of the hall. In an ideal situation the reverberant sound field will arrive from all directions (representing a diffuse sound field).

Due to the propagation speed of sound waves (343 m/s in air at room temperature), the sound travelling along a longer path will arrive later to the listener. So the arrival time is increased as the total sound path is increased. Figure 4 illustrates the direct sound, two first order reflections and the late reverberant sound on a stage. (The line types are corresponding between upper and lower part of the figure.) A second order reflection could be heading against the left side wall, then up to the ceiling and down. This reflection would arrive after the ceiling reflection since is has travelled a larger distance.

One of the features of the early sound is that it can help creating a more solid impression of the sound source. As mentioned, musical instruments are very directional at higher frequencies which means that they will radiate differently in different directions. With only the direct sound we would hear the instrument from only one direction and the orientation of the instrument will largely affect what we hear. By also hearing the early reflections, we will also hear what the instrument radiated from its backside, sides and so on, in addition to the side facing us. This has been demonstrated for instance by Benade [10].

As listeners we by experience learned to not get confused by early reflections. When being in the woods and hearing a branch break it is to the person’s best advantage to be able to locate the sound from the direction where it actually originated. Human hearing uses mostly the direct sound to make the judgment of direction (called the precedence effect) and for recognizing the sound (what created the sound and its origin are of the main concern for survival). The early reflections will enhance the perceived loudness of the source and make a more robust impression of the source if a good combination of early reflections is provided by the environment. If only a few early reflections are provided they can cause colouration of the sound (changes in perceived timbre due to comb filtering) or they can be heard as echoes. So to be advantageous to our perception of the sound, the total number of early reflections and the level of these reflections compared to the direct sound are important. If the early reflections are too strong they will take dominance above the direct sound and if they are too weak they will not be heard. If the early reflections are too dense (many) they will cause a long EDT (early decay time) that could be perceived as muddy sound both on stage and by the audience (Griesinger [45]).

After the early reflections have arrived to (hopefully) give us an enhanced impression of the sound (without unwanted coloration or muddiness), the reverberant sound will reach us. In many respects we are not aware of the early reflections since we are naturally trained to focus on the direct sound as mentioned above. The reverberant sound is the blend all reflections from the room, it adds “liveliness” and gives the general impression of the room. If a room is perceived as “dry” or “live” is much based on the level of reverberant sound and the reverberations time of the room (how long time it takes for the room to get “quiet” when a sound is stopped). The boundary between of the perception of the source (direct and early reflections) and the room (reverberant sound) is found to be around 35 ms (sound that has travelled about 12 m from source to receiver).

Figure 5 shows a simplified stage in a concert hall and the main elements which have been found to affect the sound field on stage (see section 3.4). The side walls, the rear stage wall and ceiling enclosing the stage can be treated as the stage enclosure. The situation illustrated in Figure 5 is typical for a proscenium (recessed) stage. In a terraced or open layout concert hall, the stage will be more integrated with the hall space. The stage floor, the presence of the orchestra and eventually risers are common for all concert hall stages. Figure 6 shows a measured stage impulse response from our 1:25 scale model of a general concert hall.

The three main parts of the impulse response, the direct sound, early reflections and late reflections (reverberant sound), are indicated in Figure 6. Also indicated are the elements of the stage that are relevant for controlling these three parts and what have been found as relevant features of them. At the bottom the integration time intervals for Gade's ST parameters (see section 3.5) are also shown.

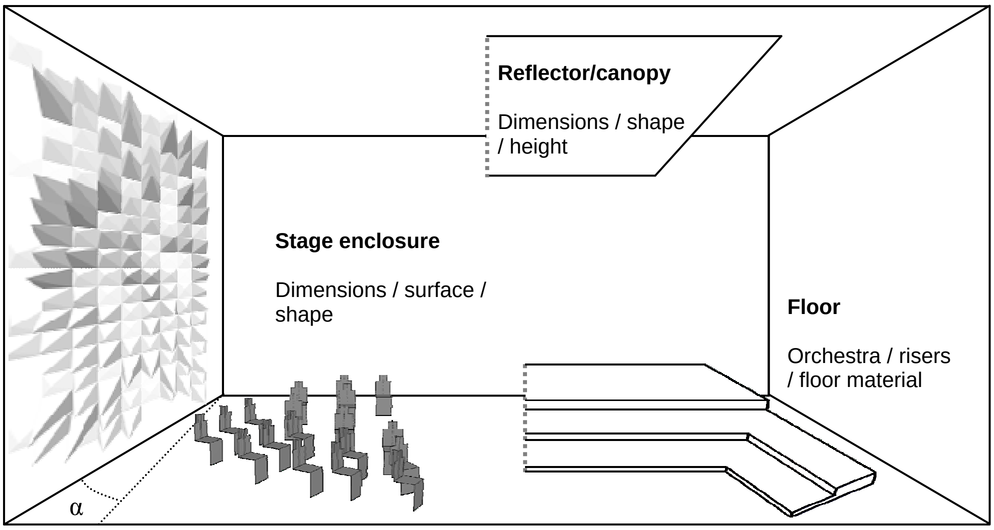

Figure 5: Elements of a concert hall stage (with splay angle is represented as α).

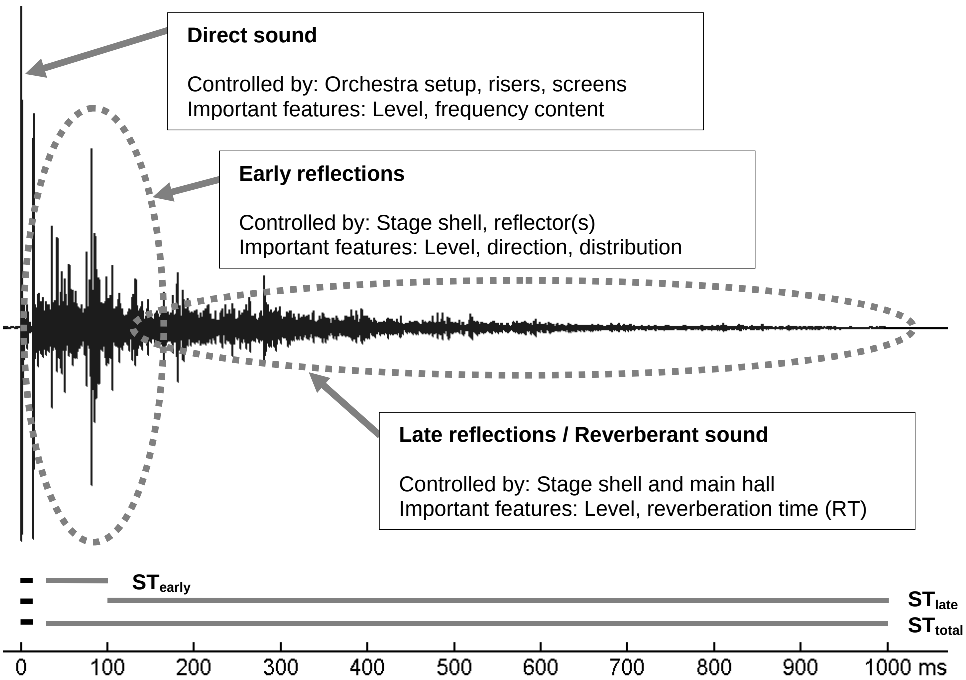

Figure 6: Impulse response on stage with ST integration time intervals indicated. (Linear pressure versus milliseconds. Linear pressure oscillates around and descending to zero).

5 Findings related to the acoustics of concert hall stages

Table 1 summarizes findings related to stage design (first part) and sound field (last part).

Attribute	Findings
Stage enclosure	- Need heavy reflecting & diffusing surfaces on the side, rear walls and if possible ceiling, Shankland [3] - Should be double amount of overhead reflections back to strings compared to woodw, Meyer and 'Serra [4] - Reflecting elements at back wall and ceiling maintain directional cues from the hall, Nakayama [12] - Level of support is controlled by the stage volume, Gade [18] - Maximum ceiling (refl.) height of 10 m, diffuse reflection, side walls as close as possible, Meyer [50] - Preference for scattered reflections from side and back walls, D'Antonio [21], Jaffe [24] - Min. volume 1000 m^3, scattering surfaces on orch. shell, max 16º splay side walls if flat, Kan et al [29] - Adding orchestra shells could increase ST_{early} on stage by up to 5 dB, Bradley [30] - Rectangular hall most, fan shaped least favoured by musicians, Sanders [33] - Trumpeters liked front stage pos. without side reflectors, strings disliked this config., Chiang et al [34] - Early energy enhanced by reducing splay angle of side walls, Chiang and Shu [35] - Preference for an absorptive back wall, Kahle and Katz [38] - A reflector behind the choir improves balance and ensemble with orchestra, Marshall [23]
Reflector / canopy	- Preferred height 7 – 10 m, Barron [1], Jaffe [24], 6-8 m if possible, Gade [16], [17] - Should consist of many small reflectors instead of one large, Rindel [19], Dalenbäck et al [26] - A low reflector above the strings can affect the balance heard by the audience, Meyer [27]
Floor / Risers	- Risers can make the brass and percussion too loud for the audience, Miller [14] - Risers can enhance lower register of celli and double bass and improve mutual hearing, Askenfelt [49]
Direct sound	- High level of direct sound strongly preferred, Krokstad et al [5] - Delay within the orch. should not exceed 20 ms (7 m) and high frequency components important, Gade [16] - Singer had best intonation when level of self was -5 to +15 dB louder than others, Ternström [48] - Important to have strong direct sound within the orchestra, O'Keefe [28]
Early energy	- The sound field characteristic of greatest importance is the spectrum of early sound, Shankland [3] - Reflections arriving 10 – 40 ms improve ensemble, Marshall et al [2] - Reflections beyond 35 ms can contribute to ensemble at lower frequencies, Meyer and 'Serra [4] - Reflections before 35 ms preferred, if weak direct sound or fast movement & long RT, Krokstad et al [5] - 0.5 – 2 kHz sound important for ensemble, below 500 Hz may be detrimental, Marshall and Meyer [9] - Too much early energy on stage can cause the orchestra to sound too quiet in the audience, Meyer [13] - Singers need early sound reflections of their formant, above 1.5 – 4 kHz, Fry [51] - Early reflections are the main factor for achieving support, Gade [16], [17] - At least 2 or 3 early reflections should arrive before 30 ms, Benade [10], [11]) - Reflections beyond 100 – 200 ms are detrimental for the orchestra, Benade [10], [11] - Singer had best intonation when level of self was -5 to +15 dB louder than others, Ternström [48] - Abs. should be added to a small stage due to the build-up of too many/dense reflections, Griesinger [45] - Early reflections are important for ensemble and support, Ueno et al [36] - Level of other instruments supported by 15 – 35 ms reflections, Meyer [22] - Strong early reflections at 5 – 20 ms can cause unfavourable coloration effects, Halmrast [31] - Singers disliked a 40 ms delayed reflection, Marshall and Meyer [9], Burd and Haslam [25] - For fast tempo solo singing a 17 ms delayed single reflection is preferred, Noson et al [32] - Musicians should only get 1st order reflections within 25 ms and late sound from the hall, Griesinger [55]
Late energy / reverberation	- Reverberation is not important for ensemble, but preferable among soloists, Marshall et al [2], Gade [16] - Late sound important for musician to "hear the sound in the hall", Nakayama [12] - Choir has a strong preference for reverberant sound, Burd and Haslam [25] - Shoe-box shaped stage will have the largest build-up of late sound, O'Keefe [28] - The brass players and the pianist were generally positive about late reflections, Chiang et al [34] - Musicians appreciated medium level of 250 ms (with "low level" early & "medium" reverb), Ueno et al [56]

Table 1: Factors appearing to be important related to stage acoustics and findings related to them.

Note: Some of the results listed in Table 1 are for chamber music.

In brief the findings may be summarized as follows: direct sound and source-receiver distance within the orchestra are important and are influenced by orchestra arrangement and risers. The risers (and a light-weight floor) also contribute to amplify the lowest register of celli and double bass and could transmit some useful vibration between these instruments. Brass and percussion are the loudest instruments, while strings which are the weakest instruments in terms of sound power. This leads to strings normally being the most demanding on acoustics for their own support. Distributed early reflections are important. Reflections arriving in the time span from 40 to 200 ms (between the time regions for early and late sound) can be detrimental. The most important frequencies are 0.5 – 2 kHz, but lower frequencies can play an important role for intonation. Especially for soloists more reverberation (late sound) is appreciated. Among the main uncertainties are time interval of useful and detrimental reflections, direction, distribution and diffusion of reflections, and preference for late sound. These are all controlled by the architecture of the stage and the hall itself.

5.1 Differences between instrument groups regarding support

The following overview on differences between instrument groups are based on the findings listed in Table 1 and several other papers that cover certain groups in detail.

String players have, as mentioned, been found to be most demanding on being able to hear themselves, and on hearing reverberation and the others (Gade [6], Sanders [33]).

Woodwinds seem to be less worried about hearing reverberation and themselves compared to the strings, but more than percussion and piano (Gade [6]).

The brass players have been reported to sometimes having problems with hearing the strings (Chiang et al [34]). They have also been reported to appreciate more late sound and less early reflections compared to the strings (Chiang et al [34]). In terms of hearing reverberation, themselves and the others, Gade found this group to have similar concerns as the woodwinds [6]. Gade found that the preferences for the piano and percussion players differed from the rest of the orchestra by being least demanding on reverberation [6]. But Chiang et al [34] found a preference for late reflections for pianists.

Some work has been done on preferred acoustics for singers which indicate that the singers appreciate early reflections on stage especially in the frequency region of their singing formant, which is normally located in the frequency region from 1500 Hz to 4 – 5 kHz (Fry [51]). Ternström found that singers could intonate best when the self-to-others ratio was -5 to +15 dB (level of self minus level of others) [48].

5.2 Stage properties and area requirements for musicians

Based on drawings of concert halls around the world, a table of actual stage dimensions has been compiled. Beranek’s and Barron’s books [62], [63] have been used for reference drawings. Table 2 lists average dimensions based on analysis of 85 halls.

	Width front	Width back	Depth	Ceiling height	Reflector height	Side wall splay	Area
Average dimension	20 m	15 m	12 m	15 m	11 m	14º	207 m^2

Table 2: Average properties of concert hall stages world wide.

11 (13 %) stages have a rectangular layout, 41 (48 %) have splayed side walls, 1 (1 %) has convex or concave side walls, while 32 (38%) have an open layout. This means that 53 (62 %) halls have a recessed stage, while 32 (38 %) have an exposed stage.

13 stages (15 %) have low sidewalls around the perimeter of the stage (at back and the sides, not a recessed stage), while 50 out of the 85 halls (59 %) have a reflector above the musicians.

With regard to area per musician the recommendation according to Barron [53] is:

- 1.25 m^2 for upper string and wind instruments
- 1.5 m^2 for cello and larger wind instruments
- 1.8 m^2 for double bass
- 10 m^2 for tympani, and up to 20 m^2 more for other percussion instruments

For a full 100-members orchestra (with a normal percussion section) this means a net covered area of about 150 m^2. The minimum stage area recorded (in the literature study mentioned) above is 111 m^2 (Colston Hall, Bristol, UK), while the largest stage area recorded is 397 m^2 (Sala São Paolo, Brazil).

6 Objective stage measures – ST and EEL

Based on questionnaires and interviews among musicians as well as laboratory experiments, Gade proposed objective measures for "support" and "ensemble" on stage (Gade [6], [16]). "Support" is associated with how much the hall is supporting the sound of ones own instrument, while "ensemble" is associated with the ability to perceive the fellow musicians. ST (Support) measures the level of early reflections received 1 metre from the source. This energy is seen in relation to the emitted sound energy: the direct sound (including and floor reflection) at 1 metre from the source. EEL (Early Ensemble Level) measures the presence of the direct sound and early reflections. This energy is measured with a second microphone positioned somewhere else on stage, for instance at another instrument group position, see Figure 7. Also this energy sum is seen in relation to emitted sound energy from the source (direct sound and floor reflection at 1 metre).

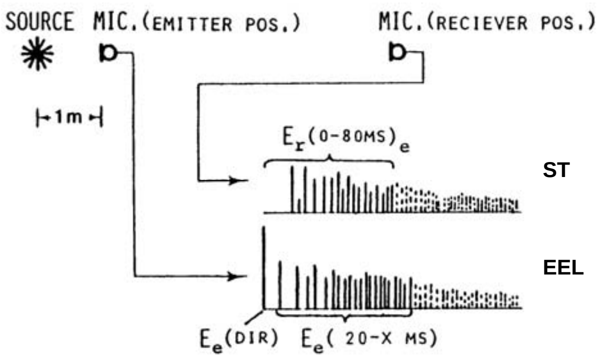

Figure 7: Principles for measuring ST and EEL. From [Gade,16].

For ST, t = 0 ms represents the arrival of the direct sound, while for EEL t = 0 ms represents the time of emission from the source. The motivation for the latter was to measure the negative effect of the delayed direct sound at the receiver position (based on Gade's findings of preferred arrival of the direct sound within 20 ms delay [17]). While the time limits for the summing of received energy can vary for ST, it is fixed at 0 – 80 ms for EEL.

These two parameters are defined as:

$$ST = 10 \cdot \log10\left(\frac{E_e(t_1 - t_2\ \text{ms})}{E_e(\text{DIR})}\right) \quad \text{dB} \qquad (1)$$

$$EEL = 10 \cdot \log10\left(\frac{E_r(0 - 80\ \text{ms})_e}{E_e(\text{DIR})}\right) \quad \text{dB} \qquad (2)$$

E_e(DIR) is measured over the period 0 to 10 ms. Arithmetical averages are taken for the octave bands 0.25 – 2 kHz for ST and for the octave bands 0.5 – 2 kHz for EEL.

ST is represented in three different forms (with different values of t_1 and t_2): ST_{early} describing "ensemble", integrates the sound in the time interval of 20 – 100 ms (relative to the direct sound). ST_{late} representing impression of reverberation integrates the sound arriving between 100 – 1000 ms while ST_{total} has $t_1 - t_2 = 20 - 1000$ ms and represents "support". The time limits are illustrated in Figure 6. (Previous versions, ST1 and ST2, are no longer used.) Stage occupancy is important for the measurement according to Gade [20]. An empty stage will represent the situation for a small ensemble, while chairs and music stands should be included when measuring for the orchestra situation. See the section below for more details on how to measure these parameters.

Only the ST parameter which takes the early reflections returning to the musician into account (not the direct sound transmission) has been shown to be well correlated with subjective evaluation (Gade [17]). ST was found to correlate well with the judgment of "support" and quite well with judgments of "ensemble". Since EEL was not found to correlate well with subjective data, it has not been much used recently.

6.1 How to measure ST and EEL

Gade has listed recommendations for measuring ST [20]:

- the platform should be occupied with chairs and music stands
- all objects in a 2 metre radius from the transducers should be removed
- the transducers must be placed at least 4 metres from reflecting stage surfaces to make sure these surfaces are include beyond the 20 ms integration limit
- on smaller stages the 20 ms limit must be reduced and all furniture removed (since many reflections will arrive before 20 ms)
- distance from sound source to microphone set to 1 metre and the height of both set to 1 metre above the stage floor
- calibration is needed for the frequency bands where the sound source is not adequately omni directional (see [20] for more details)

Jeon and Barron [39] confirmed these guidelines with scale modelling experiments for a particular hall in Seoul, South Korea.

The list given above is, as mentioned, for ST. No such detailed list has been published for EEL.

6.2 The validity of the ST parameters to evaluate stage acoustics

As described ST_{early} measures the total energy of early reflections present between 20 and 100 ms while ST_{late} measures the total late sound energy arriving between 100 and 1000 ms (and ST_{total} the sum of these two).

When trying to judge the validity of the ST parameters to evaluate stage acoustics for the musicians, we have to relate the definition of ST with the findings listed in Table 1 and summarized in section 3.4. The opposing views that have been found with regard to useful early reflections make it at this stage difficult to conclude on the validity of ST.

When it comes to how the early and late reflections are perceived by the musicians, there are many unanswered questions. Which directions are the most important for the early reflections to arrive from (above, from the sides or back)? With ST there is no discrimination between directions of the early reflections. And does the time region for useful reflections depend on the distribution of the reflections? Reflections arriving at 5 – 20 ms can result in unfavourable coloration effects, but only if a few early reflections appear in this time region (Halmrast [31]). In Gade's laboratory experiments with musicians, only a few early reflections were used [16]. It is possible that coloration effects or other unfavourable effects of few early reflections in this experiment biased the musicians' preference for delay of the early reflections. There has been some experimentation with other time limits for the summing of early energy. Chiang et al [34] used time limits from 7 to 100 ms, but this alternative version was found in chamber music halls to correlate highly with ST_{early} when relating to judgments by the musicians. Ueno et al [56] have developed their own system for generating different sound fields for the musicians electro-acoustically (in anechoic chambers like Gade) and results from their studies can reveal more information on useful and detrimental reflections.

6.3 The reliability of the ST parameters to evaluate stage acoustics

For measuring ST, the relative placement of the transducers is defined. This serves to give a stable reference of the sound energy emitted. However the measured value is quite sensitive to source directivity (not being perfectly omni-directional) and, since the microphone is only 1 metre away from the source (and the floor), deviations in relative transducer position. The early reflections are affected by the objects on stage (chairs, music stands) but results by O'Keefe indicate that ST varies by 1 dB at higher frequencies and 0.5 dB at lower frequencies measured on an empty stage versus a stage fitted with chairs and music stands [57]. Gade found reproducibility of ST_{early} and ST_{late} to be about 0.2 dB for position and frequency averaged values (with three different positions on stage) [20].

Gade has given recommendation for improving the reliability by calibrating and compensating for irregularities in the source directivity [20].

6.4 The validity of the EEL parameter to evaluate ensemble

The main difference between ST and EEL is that EEL includes the direct sound and the delay of the direct sound, whereas ST only includes the early reflections. The influence of the direct sound seems to make objective investigations of perceived "ensemble" more complicated than perceived "support". This is supported by Gade's finding that EEL did not correlate well with musicians' impression of "ensemble" [17]. ST succeeded better than EEL at measuring "ensemble" even though EEL was designed to measure "ensemble".

The transmission of direct sound within the orchestra is difficult to measure for two main reasons: musical instruments are highly directional and the musicians (and other objects on stage) affect the direct sound by casting sound shadows. Both factors are most significant at the high frequencies which have been found to be important for achieving good ensemble (0.5 – 2 kHz). For the discussion of the validity of the EEL parameter, it is important to see how well an omni-directional source on a more or less empty stage represents the real situation.

6.5 The reliability of the EEL parameter to evaluate ensemble

The reliability of the EEL measure is much affected by the same factors affecting reliability of ST. But in addition objects on stage between the source and receiver will affect the measured direct sound and the actual arrangement on stage during measurements will have a more important role compared to ST. Based on this, the reliability of EEL could be expected to be poorer than ST, when measuring on a stage without the musicians present.

6.6 Other objective measurement approaches

Gade's investigations of the influence of direct sound and early reflection were based on laboratory experiments. Others have used objective measures with musicians on real stages.

To investigate the importance of diffusion on stage D'Antonio [21], different scenarios were tested for a chamber group and a symphonic orchestra. The produced sound was recorded at stage and in the audience using different microphone system (among them in-ear microphones at the musicians' ears). The musicians' experiences were collected through questionnaire and the recorded sound was judge by listening tests.

Halmrast has proposed a method for measuring the comb filtering effect caused by interference between the direct sound and early reflections within the orchestra [31]. This is done with the musicians present on stage.

Self-to-other ratio has been measured for singers in choirs (in-situ) (Ternström et al [54], Ternström [48]). To find the level of one-self and others, the sum and difference between two microphones located at the singer's ears have been taken. The sum of the two signals was used to represent the level of self (since the distance from the mouth to both ears is the same), while the difference of the two signals was used to represent the level of others. (This method cannot easily be used for musicians, since their instruments are not point sources, like the mouth can be approximated as, and the instrument is not placed at an equal distance to both ears.)

7 References

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