Acoustics for Symphony Orchestras; Status After Three Decades of Experimental Research

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In 1978, one particular paper in JASA by Harold Marshall, D. Gottlob and H. Alrutz titled: "Acoustical conditions preferred for ensemble" inspired the author and other researchers to investigate the acoustic conditions experienced by musicians on concert hall stages. The research carried out since then has involved subjective assessment by musicians playing in simulated sound fields as well as in real halls; but also purely objective investigations have been reported. After one third of a century, it seems appropriate to summarize what we have learned and where we still need more knowledge. The paper will summarize major contributions to the field, discuss the differences in opinion in view of the limitations associated with different experimental approaches, and finally address the challenges related to meeting working environment requirements recently enforced by law in Europe for limiting the sound exposure levels of musicians.

1. EARLY ATTEMPTS

Room acoustic research aiming at improving our understanding about how to design halls for the benefit of the musicians started in the late 1970-es. Before that, the literature only described musicians- architects' and acousticians' ideas and views on the subject, and only few had tried to make any objective measurements to illustrate their ideas (with V.L. Jordan [1] being a notable exception).

The first two papers reporting results from actual, subjective experiments with musicians were both published in 1978. Marshall [2] described results from a string trio playing in a simulated acoustic environment in a laboratory environment, while Barron [3] conducted experiments with a larger group (8 to 13 players) in an exsisting hall with a highly variable stage. In Marshall's setup each musician placed in an anechoic chamber played together with a "music minus one" recording of two other parts, which had been manipulated by adding early reflections with varying delay, level and spectral content, but without any reverberation. Marshall's work was focussed on factors influencing "ease of ensemble", while Barron asked his subjects about three aspects: "general impression", "ability to hear themselves and others" and "facility of playing". However, the results indicated that the musicians did not distinguish between different aspects in their evaluations. As we will soon see, this has been a problem in most investigations up to the present day.

Both papers indicated positive effects of musicians receiving early reflections – well in line with the fact, that already then many halls (e.g. Herkules Saal in Munich and the Danish Radio Concert Hall) had been equipped with arrays of reflectors above the stage. Such reflectors were described already in the early 1950'es, e.g. by Keidel [4].

Marshall found that the early reflections improved ease of ensemble playing (within a certain window both in time and level), while Barron's results spoke in favour of a low hanging reflector over the stage. Focusing on early reflections was in accordance with contemporary ideas – also promoted by the same authors - about these being important for listeners (to increase clarity and spatial impresssion).

The paper by Marshall in particular inspired my colleague and supervisor at the Technical University of Denmark (DTU), Jens Holger Rindel, to suggest stage acoustics as the topic for my PhD, which started in 1979, and our enthusiasm was strong enough to ignore the strong opinion of the responsible head of our department, the late Professor Fritz Ingerslev, that "it would not be possible to get any sensible information from musicians".

2. RESEARCH AT DTU

2.1. DEFINING A VOCABULARY

In order to be able to communicate with musicians regarding these matters, it is obvious that one has to understand the vocabulary they use to describe how they perceive - and interact with - the acoustics of the rooms in which they play.

In the late 1970-es, most of the – sparse - literature discussing musicians' room acoustic conditions did not explain clearly the underlying subjective aspects of musicans' likes and dislikes. Therefore, we decided to start our work by an attept to get an overview of the vocabulary used by musicians [5]. The approach was to interview 32 prominent performers of classical music in Scandinavia, conductors, pianists, singers, and players of various orchestral instruments, about how they would describe the different aspects of acoustic conditions on concert stages which they experienced as good or bad.

From these interviews a number of different aspects could be destilled, which we called "Subjective Parameters" and which will be written in Italic letters throughout this paper: *Reverberance*, *Support* (including *hearing one self*), *Timbre*, *Dynamics*, *Hearing Each Other* and *Time Delay*. These aspects were all mentioned by more than one interviewee as being important, and we hoped that these would cover the major concerns of musicians' room acoustic experiences.

2.2. WORKING HYPOTHESIS

In an ideal, positivistic world, one would expect to be able to find measureable, objective acoustic parameters, each of which would correlate almost 100% with one of the subjective parameters. The algorithms used to deduce the arithmetric values for each objective parameter from the sound field (impulse response) would then contain complete information about how the various properties of the sound field influence musicians' perception of the acoustics. Subsequently, one could investigate the relationships between the objective acoustics and the architectural features which determine the properties of the sound field on the stage, and the so derived architectural parameters would then contain all the information necessary for acousticians to be able to guide architects in designing concert halls with ideal acoustics for the performers.

After three decades, it seems clear that we will never reach that "Elysion"; but still this was the working hypothesis of a young, naive Danish researcher in 1979….

2.3. LABORATORY EXPERIMENTS

For creation of well controlled sound fields to be presented to musicians, it seemed obvious to apply the fine facilities at DTU regarding anechoic chambers and signal processing knowledge and equipment. Still, it was a big challenge to create a set up which could provide realistic reflections and/reverberation – also to the player's own sound (in contrast to Marshall's setup). The challenges involved both the risk of feed back, unnatural timbre (largely due to the instrumental sounds being picked up from only one direction) and the question of calibration for realistic levels.

The starting point was to record impulse response measurements on exsisting stages in order to see how much energy was returned to the stage within different time intervals after the emission of a sound impulse. The concept of the "Support"-parameters was actually conceived for these measurements. Three concert halls in the Copenhagen area were selected for these first measurements, two of which had been mentioned several times by the musicians interviewed earlier as being very different regarding *Ease of Ensemble*: The Danish Radio Concert Hall, and the Tivoli Concert Hall shown in Figures 1 and 2 respectively.

The Danish Radio Stage is characterized by a wide, fan shape in which only the rear wall and the sparse overhead reflectors distribute some early reflection energy to the stage. In Tivoli, the rather shallow stage enclosure provides early reflections abundantly; but some musicians felt that they were lacking contact with the reverberation from the auditorium. In any case, the measured values of parameters like Reverberation Time, Early Decay Time, Clarity and Support were used to set the ranges for the sound field variables in the simulation setups created in the anechoic chamber(s) at DTU.

Three different types of experiments were carried out:

- One experiment with soloists (flute and violin players) aiming at finding the threshold of perception of a single reflection of the sound from their own instrument.

Figure 1. View of the (former) Danish Radio Concert Hall.

Figure 2. View of the Tivoli Concert Hall.

- Three experiments dealt with the effects of changing levels, delays and spectra of early reflections provided to (four) flute-violin-cello trios.
- Three experiments with (ten) violin-cello and violin-flute duos (in a setup involving two anechoic rooms) investigated the effects of changing the direct sound, early reflection(s) and reverberation in the acoustic communication between two musicians representing players sitting further apart in a large orchestra.

The sound fields were created by means of the signal picked up by a highly directive microphone, which was delayed (through digital processing), attenuated/amplified and emitted back into the anechoic room through loudspeakers surrounding the musician(s). Figure 3 shows a diagram of the setup used for ensemble players.

In short, the results of these early lab experiments can be summarized as follows:

– Different instruments cause different thresholds of perception of early reflected sound from ones own instrument. For flute players, the thresholds corresponded to ST_{Early} values no lower than -15 dB, and for "strings" (violin and cello) no higher than -9 dB. This means that strings are likely not to benefit from early reflections (between 20 and 100 ms) in halls with low ST_{Early} (like DR). However, they most likely benefit from the reflection from the floor, and from a wall, if they are placed very close to it. Flute players (and perhaps players of other wind instruments) are more likely to benefit from early reflections.

– When exposed to a single early reflection with variable delay and level, the "preferred" delay depend on the level presented. (Several authors have reported results from laboratory experiments on preferred delay of "single reflections, both for listeners and performers; but ìn our opinion, this is probably without much significance in real halls, where the level of the reflections vary and where it is surrounded by other reflections – most of which can not be fully controlled anyway.)

– The trios liked a certain high level of both (five) early reflections and reverberation compared to a lower level of both components - probably for reasons of support.

– Changes in the spectrum of the reflections influence "timbre", and a wide spectrum (frequencies both above and below 1kHz) were preferred.

– For players sitting far apart,

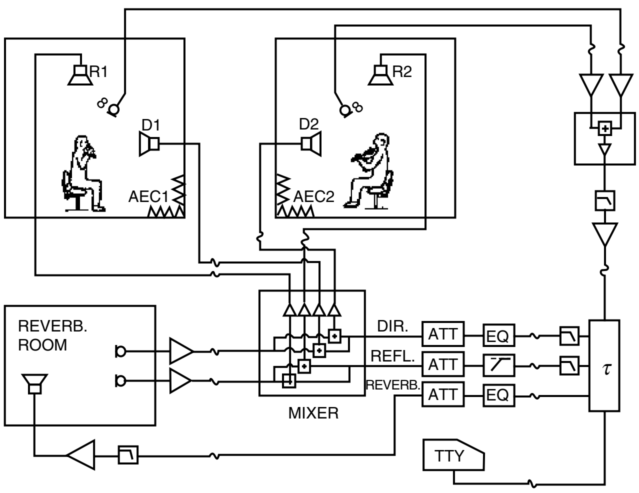


Figure 3. Set up for ensemble experiments at DTU; 1982.

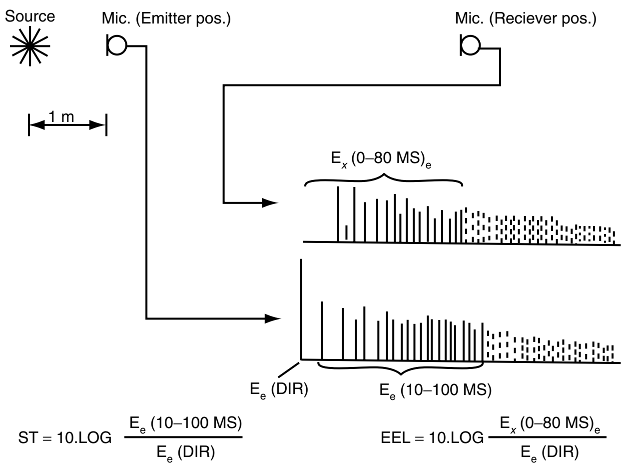


Figure 4. Definitions of ST_{Early} and EEL.

efficient transmission of early sound (both in terms of short delay and high level) between players is essential, and in particular the higher frequencies (above 1000 Hz) were found to be important.

– There were some indications that too much reverberation can make ensemble playing more difficult.

The work and results are further described in [6] and [7].

Two suggestions for objective acoustic parameters emerged from the work described above: Support, ST (ST_{Early}) and Early Ensemble Level, EEL, which are defined as illustrated in Figure 4. These parameters consider the response in level and time of the hall to the excitation by ones own instrument ($ST_{early/late}$) and to the excitation by the other player(s) (EEL). $ST_{early/late}$ measure the levels of early and late reflections relative to the direct sound at a distance of only one meter from the source. The direct sound will of course contribute to level and clarity of the perceived sound from the musicians own instrument; but it was excluded from the numerator integral because it is constant (for constant distance) and would make the measure less sensitive to the effect of the hall itself, which was what we wanted to measure.

The parameter called "ST" in the old figure above is now called ST_{Early}, while ST_{Late} and ST_{Total} were defined to measure reflection energy in the intervals 100– 000 ms and 20–1000 ms respectively; in both cases still with the direct sound (0–10 ms) as reference.

It should be mentioned that it was never investigated whether the 100 ms time limit was the optimal choices for the ST stage parameters.

Since 1997 the ST parameters have been included in an Annex of the ISO 3382 standard for room acoustic measurements [8]. This has obviously caused increased focus on their relevance – and perhaps also increased the expectations regarding what they should accomplish in terms of being able to describe the quality of orchestra stages in general – as we shall see later.

2.4. EXPERIMENTS IN REAL HALLS

We were fully aware that experiments in a laboratory without a full orchestra being present would have severe limitations, because the actual balance between what the player hears 1) from his own instrument, 2) from other instruments that he needs to hear and 3) from those which he would like to hear less loud, could not be made realistic. Therefore, we were eager to supplement the experiences from the lab with data from objective measurements and questionnaires obtained in connection with orchestras playing in real halls.

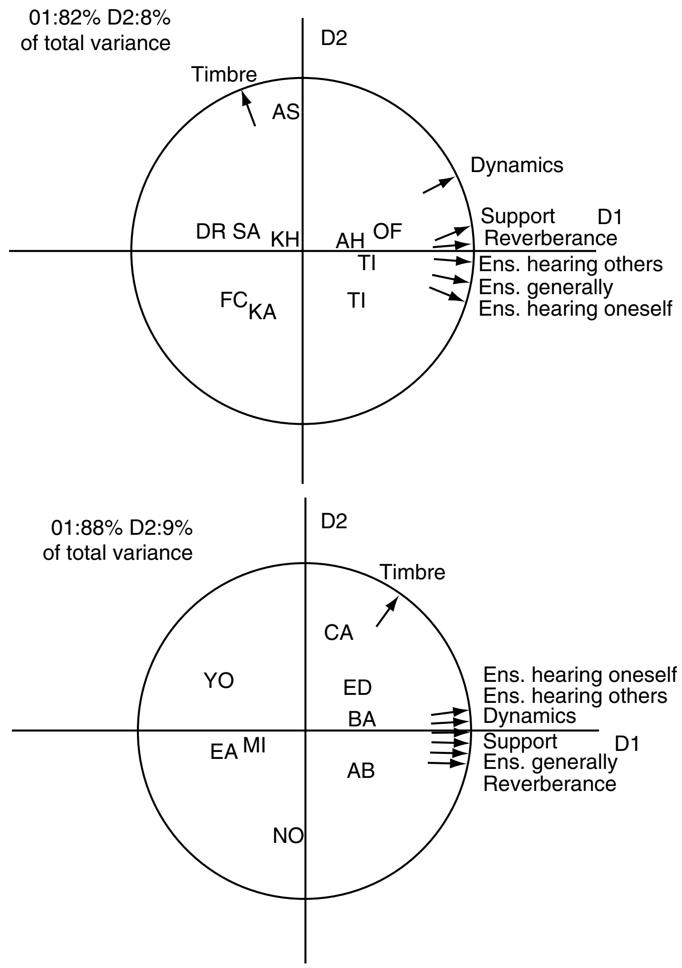
Possibilities for doing that emerged in the mid 1980'es.

Three experiments were carried out, all of which have been described in [9]:

- Three Danish Orchestras evaluating altogether nine Danish halls.
- The Danish Radio Symphony Orchestra (RSO) evaluating eight halls in the UK during a tour.
- The RSO evaluating measures for improvement of ensemble in their own (old) Danish Radio Concert Hall.

In all three experiments, the musicians reported their evaluations in questionnaires filled in right after playing in the halls (normally rehearsals without audience present) and their responses were compared with objective measurement data collected from the unoccupied halls with furnished stages.

The results of the two surveys of halls in Denmark and the UK had some results in common as well as some differences. In both investigations, the evaluations along seven scales representing "different" subjective aspects could be described by only two dimensions representing more than 90% of the variance in the subjective data (after averaging across the 20–30 musicians participating in each hall). This is illustrated in Figure 5. In both cases, the second dimension was related to *Timbre* and accounted for slightly less than 10% of the variance, whereas the first dimension accounting for more than 80% was related to all the other aspects, which were all highly mutually correlated. In other words, the musicians did not distinguish between the different subjective aspects when



igure 5. Two dimensional factor space of musicians' subjective evaluations of eight halls in Denmark (top) and eight halls in the UK (bottom).

they gave their evaluations. Thus, the first dimension might be interpreted as an "*Overall Acoustic Impression*" (*OAI*) although this was not listed explicitly in the questionnaire.

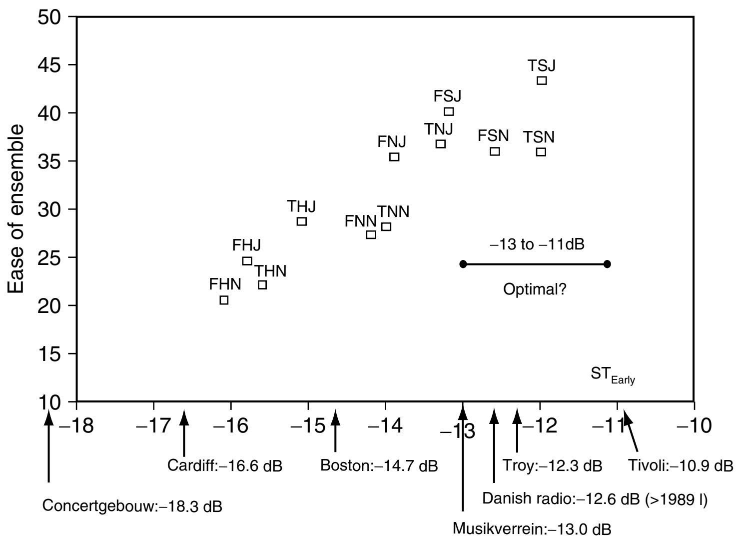
In both cases, the second dimension showed primarily a fair correlation with the variation of EDT measured on the stage with frequency:

$$EDTF = (EDT_{250\ Hz} + EDT_{500\ Hz})/(EDT_{1\ kHz} + EDT_{2\ kHz}).$$

Regarding the first dimension, "*OAI*", the objective parameters correlating with this dimension varied between the Danish and the UK halls. In the Danish halls, the highest correlation was found with $ST_{20\text{–}200\ ms}$ and with C_{80} measured at 1m distance from the source (whereby C_{80} actually represents G_{Late}), whereas in the UK halls, the main correlation was with T_{20}. It is very likely that the strong correlation with T_{20} in the UK halls was due to the halls falling in two clusters, three halls with T_{20} around 1.0 to 1.2 Sec. and five halls with T_{20} between 1.8 and 2.2 Sec. Still, it seemed as in the Danish halls the general preference was based on presence of early energy (or the balance between early and late); while in the British halls, mainly the late energy mattered.

In the experiment in the Danish Radio Concert Hall, the focus was specifically on improving ease of ensemble, which was definitely lacking. Three variables were tested: 1) Placing of the orchestra near the front or further back on the stage (closer to reflecting rear and side walls), 2) adjusting the height of the ceiling reflectors in three steps (5, 7 and 14 m above the stage floor) and 3) installing a number of near parallel reflecting side wall elements with down tilted upper parts along the flaring side walls. No attempts were made to vary the reverberation time. All 12 combinations of these variables were presented to the orchestra during a two day session, and about 70 orchestra members responded. However, this time the questionnaires contrained scales for "*Ease of hearing yourself*" and "*Ease of hearing others*" only.

The reponses from this experiment showed a very high correlation with ST_{Early} (r = 0,91) as shown in Figure 6 below – much to the satisfaction of the author, who hereby saw a proof of the relevance of early reflections and of his ST- parameter for ensemble. The figure also show the results of ST-measurements in other Halls in Europe



FFigure 6. Ease of ensemble versus ST_{Early} from experiment in the old Danish Radio Concert Hall.

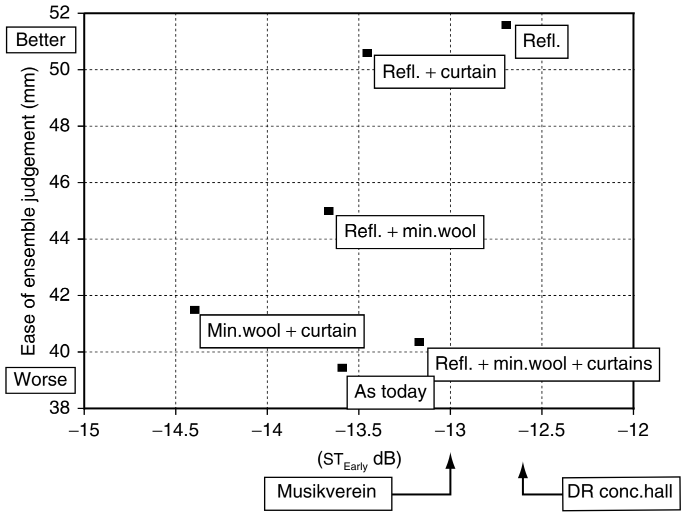


Figure 7. Ease of ensemble versus ST_{Early} from experiment in the Göteborg Konserthus, Sweden.

[10] and a suggestion for an obtimal range for ST_{Early} based on the experiences up to 1995, where we had made similar experiments and suggestions for renovation of the stages in a few other halls, in Göteborg and Oslo.

The results from the Göteborg Konserthus regarding relationship between *Ease of Ensemble* and ST_{Early} are shown in Figure 7 [11]. They were less clear; but still a certain relationship ($r = 0.51$) is seen. A major reason for the lower correlation was identified as the orchestra's strong reaction against one setting representing the situation as it was before any changes were made ("as today"), and one in which a likely error in the objective measurement caused the ST_{Early} value with curtain on the back wall to be higher than without (i.e. one would have expected the point "Refl. + Min. Wool + curtains" in Figure 7 to have been placed further to the left!).

As one would expect we have also found strong objective relationships between ST_{Early} and the main dimensions (width, height and depth) of the stage area [10]. This we even found in the case of EEL; but in none of the three field experiments, EEL came out as being significantly related to *Ease of Ensemble* or to any other subjective aspect.

As discussed in [9], it is a paradox that ST_{Early} showed high correlation with *Ease of Ensemble*. Reasons can be that it is easier to measure ST with decent accuracy than EEL and that in practice none of these parameters are anyway able to detect anything but the level of the reflected sound on stage. Thus, a valid EEL-measurement including the barrier effect of other musicians sitting between source and receiver would require the musicians to be present during the measurement, and for practical reasons that was not possible during our work in the halls. More specific and correct measurements of *Ease of Ensemble* – perhaps even describing the conditions in specific positions within the orchestra - would require that also the specific orchestra layout, the directivity of the individual instruments, the balance between different instrument groups and deeper aspects of musicians' perception of the sound on stage could be imbedded in the transducer technology, calculation algorithms and procedure. Therefore, it was felt that the information about early reflection energy on stage gained from just averaging ST_{Early} values from different positions was all we could hope for.

Further aspects and recommendations regarding measurements of ST-parameters were later given in [12]. The guide lines given regarding distance to large room surfaces and stage furniture relate to the time intervals for integration of direct sound and reflections, which again are largely determined by the limitations of obtaining both time and frequency resolution in acoustic signals.

3. RESEARCH BY OTHERS

This section will not attempt to provide a total overview of the research on stage acoustics since our work in the 80-es. Excellent, up to date overviews can already be found e.g. in Dammerud [13]. Rather, the following will mainly focus on some of the major contributions which illustrate either the challenges facing researchers in this field, or which indicate results supported by several studies.

3.1. PURELY OBJECTIVE STUDIES

Some, purely objective, studies have been carried out mainly to get more knowledge about the behavior of objective acoustic conditions on existing stages, e.g. O´Keefe [14]. Likewise, Chiang & Shu [15] made computer simulations showing how much $ST_{Early/Late}$ (and other similar measures with slightly different integration limits) can be made to change as a function of changes in geometry of surfaces around the stage and positioning of the musicians. Also the work by Dammerud [13] includes purely objective studies (in scale and computer models) of great interest; but the main interest here is to find out which parameters are actually describing musicians' room acoustic perceptions.

3.2. LABORATORY EXPERIMENTS WITH MUSICIANS

One very important contribution to a more detailed knowledge about the behavior of sound propagation and perception on stages was due to Meyer and Biassoni de Serra [16] who published results on the direction dependant threshold of perception of sound for musicians playing various instruments. Meyer used the results to suggest a configuration of over head reflectors to better consider the balance between the weak string instruments and the loud wind instruments sitting further back on the stage. Also in other papers, Meyer has provided valuable insight into the acoustic conditions on stages, e.g. [17].

Another interesting contribution – and equally different from our approach in Denmark - was made by Naylor, who studied the interval within which the balance between the sound level of the other player(s) and the level of ones own instrument: OTHER – SELF should fall for the player to be able to hear both signals well and so be able to achieve ensemble [18]. Naylor found that this ratio depends on the nature of the music regarding similarity of the self and other music lines (unison, single counterpoint, triple counterpoint or "Nonsense"). In general, he found that both SELF and OTHER could be heard sufficiently, if the level of OTHER was in the range -15 dB to -8 dB relative to SELF. Ternström, [19] has found a much similar range for preferred self-to-other levels for choir singers. In another paper [20], Naylor suggested the modulation transfer function to be used for measuring the clarity of the OTHER sounds on stages; but he found the influence of level ratios to be far more important than the clarity aspect measured by the modulation transfer function. However, if it is possible to include the level ratio as a noise component in a kind of STI measurement, this idea might be worth further attention.

Among the few other laboratory experiments reported in literature the works by Ueno are outstanding. Ueno has carried out three dimensional impulse response measurements in real concert halls, applied them as real time convolution filters in a setup with six loudspeakers in each of one or two anechoic rooms, whereby the original – or manipulated – acoustic conditions could be (re)created in 3D for musicians playing solo [21] or in ensemble [22] with another player in the other anechoic room. Thus, her setup is a modern, highly advanced version of the one we built at DTU back in the early 1980-ies, but with the possibility of creating much more realistic sound fields for the subjects. In accordance with our early experiments, Ueno found that for soloists the early reflection energy is often masked by the direct sound. She also found that a very high level of early reflection energy (corresponding to ST_{Early} in the range -7 to -10 dB) was disliked by most musicians because it masked the reverberation and made the room sound "small" and was actually not contributing to *Support*. For ensembles (two players), she found that the highest level of early reflection energy did not always promote easy ensemble. (NB: Ueno did not vary the direct sound of OTHER in her experiments, so perhaps the direct sound transmission already provided a sufficiently clear sound of the other, and so excessive early reflections just disturbed the self-other balance?) Besides, she found that a long reverberation time was liked because it helped "making music". However, loud reverberation made ensemble playing more difficult.

Lab experiments carried out so far are limited in realism because they have not reproduced the complexity of the many sounds inside a full orchestra. Also Ueno's experiments in highly advanced sound simulation set ups missed the – often masking - influence of the many other players in a large orchestra. However, her setup could actually be used to simulate a full orchestra in play back for one (or even two players) - including simulation of the room response to the sound from the active player's own instruments - if recordings within the orchestra was made using her six channel recording technique - preferably recorded with the same orchestra and repertoire in several different halls.

3.3. FIELD EXPERIMENTS WITH MUSICIANS

Chiang [23] made experiments with chamber groups (and soloists) playing in five different halls. The variables were 1) reducing the size of the stage by placing additional side wall reflectors in front of the existing side walls and 2) changing the position of the musicians (down stage or center stage). Besides observing their general preferences he also analysed the correlation between the subjective responses concerning *Hearing* self, *Hearing* others, *Ease of* Ensemble and the objective parameters $ST_{Early/Late}$ and ED100. ED100 is similar to ST_{Early} except for the time interval for integration of early reflections starts at 7 ms after the arrival of the direct sound instead of 20 ms. The purpose is that on smaller stages (suiting chamber music groups), 20 ms is too late for capturing the energy from walls close to the measurement position. The results showed a high correlation between all the response scales (like in our studies) and moderate – but highly significant - correlations between the subjective responses of *overall impression/hearing oneself* and the early reflection parameters ST_{Early}, ED100 and T20. These correlations were found for some instruments (piano in particular) but not for others. However, the correlation with the early reflection measures was negative! Perhaps because some of the ST_{Early} values presented were quite high: up to -9 dB. The optimum value was found to be around -12 dB equal to what we found for full orchestras in our studies.

In Sweden two recent MSc projects have dealt with orchestra stages. Andersson [24] studied the subjective response of a symphony orchestra to modifications on the stage in their home hall in Norrköping. The variables included changes in over head reflector density and height, covering of upper stage wall surfaces with absorbing drapes, positioning of the orchestra on stage, introduction of screens in front of brass and narrowing the stage by placing of reflectors closer to the sides of the orchestra. This experiment might have suffered from too many independent variables presented with quite small changes, as the subjective judgements contained a large amount of unexplainable (error-)variance. Consequently, their correlations with objective parameters were poor (Ease of Ensemble and ST_{Early} were even negatively correlated – likely due to confounding of several variables); but the best liked configuration involved reducing reflections from above to some degree, narrowing the stage and placing drapes on rear and upper side walls. Most likely the drapes were associated with reducing the sound level on stage, which apparently was an important issue for the orchestra. Finally it is worth mentioning, that the data also showed the influence of a possible order effect as preference increased steadily from the first to the last of 15 the configurations tested!

A similar experiment carried out by the consulting company Akustikon, Sweden (and assisted by the author) in Gävle showed similar tendencies regarding preference for an increase of early reflections from lateral directions (through tilted upper parts of side wall reflectors) and for reduced reflections from an over head reflector array.

Cederlöf [25] distributed questionnaires to five orchestras in Sweden and asked them about how they liked the acoustics in their home hall only (implying any effect of hall and orchestra being confounded). The best liked "hall" (or the orchestra which liked its home hall the best) also had highest ST_{Early}; but other factors seemed to have an effect on the *OAI* as well – which is no surprise. Overall, the relationships between the objective characteristics and the judgements were rather weak; but it is worth noticing that the best liked halls were the ones with small stages and high ceilings or substantial reflectors high above the stage. Besides, there was a strong correlation between *OAI* and the age of the hall (ranging from 1979 to 2002).

In New Zealand Sanders [26] sent questionnaires to experienced musicians to collect their evaluation of 24 halls used for chamber music. She found that the subjective responses were highly correlated (propably representing two factors at the most), and that the highest mutual correlation was found between *overall impression* and *support (for chamber music)*. Besides, it was clear that poorly rated halls had low reverberation time values and low reverberation levels.

Luxembourg et al. [27] suggested a new objective parameter: LQ_{7-40}; which describes the ratio between the early reflections within 7–40 ms after the direct sound and early reflection/-reverberation energy after 40 ms. As such, this parameter describes a kind of clarity but excludes the direct sound. However, neither this parameter nor any other measure – including $ST_{Early/Late}$ - did correlate with the subjective response by a university orchestra touring in 7 halls in the Netherlands. In a later paper [28], the data have been subject to further analysis; but no improvements in correlation with subjective data have been reported.

Giovannini [29] investigated 5 concert hall stages in Italy visited by four different orchestras (evaluating one or two halls each). The subjective answers along twelve scales could be condensed to two dimensions: one related to "precision" (*Clarity Dynamics Tempo*) the other was related to "general" aspects of the hall acoustics (*Reverberance, Envelopment, Strength*). *Reverberance* was found to be related to T20, which could be expected; but T20 was also negatively correlated with *Envelopment*. Also ST_{Early} was negatively correlated with *Envelopment* and positively related to *Timbre*, none of which would be obvious a priori. Most of the other correlations found were also lacking a logical explanation. This is likely to illustrate the problem of many independent, variables being confounded in real halls, when only a few halls are included in a field experiment. On top of this comes the large "random" variance between musician's responses, although it was concluded that – from a statistical view point - musicians could be regarded as "reliable" measurement tools. The best liked of the five halls had a rather narrow stage (18 m) and reflectors situated about 10 m above the stage. Giovannini has also reported an increase in ST_{Early} when the tilted side wall reflectors in the Queens Hall in Denmark (see Fig. 9) are activated [30].

3.4. THE WORK BY DAMMERUD

The most extensive and important single contribution to stage acoustic research in recent years is the PhD work by Dammerud [13]. This work involved objective studies of the acoustics on orchestra stages both in real halls and in scale- and computer models as well as subjective studies through questionnaire surveys among experienced orchestra musicians. The thesis also contains an excellent, updated overview and summary of previous work in this field.

Foreseeing the difficulties in reaching firm, quantitative results, Dammerud is critical towards the "normal" natural science researcher's "positivistic" belief in quantifiable measures being able to explain all aspects of relevance! Dammerud did not have access to a simulation setup in an AEC (which might have been a blessing as that would have occupied him making endless simplified/unrealistic experiments). This forced him into a more holistic approach in which several other approaches and techniques had to be combined and related to practical aspects of orchestra stage design, an approach which appear to have been most fruitful.

Dammerud has made theoretical calculations and scale modeling work to describe sound propagation within orchestras and possible masking effects of reflections. The objective studies in the scale model studied the effects of risers and of the musicians themselves on the propagation of sound within the orchestra. The results regarding the sound attenuation with distance were then used to build a "computer model orchestra", which was used in computer models to investigate the influence of several parameters: main stage dimensions, mean width and ceiling/reflector height, reflector configuration and wall diffusion.

The objective studies in computer and scale models were evaluated both in terms of variation in room acoustic parameters and by discussing details in the impulse responses in view of psycho acoustic knowledge, results from interviews with musicians and the obvious need for balance between loud and weaker instruments. In short it was found that narrow stages with splayed side walls and high ceilings will provide the best conditions both regarding balance (in time and level) between early reflections from different instrument groups and regarding the balance between early and late reflections and reverberation on stage, so that sufficient clarity is achieved.

Dammerud collected two sets of subjective data. First he sent questionnaires to eight symphony orchestras (six in the UK and two in Norway) from which as many as 180 experienced musicians responded. Besides covering about 45 halls (in terms of *OAI*), the respondees were also asked to give explanations for their likes and dislikes and to evaluate a number of non acoustical aspects of the halls.

The musicians disliked proscenium theatres for reasons of too little response, and also highly reverberant (19^{th} century) halls were disliked. In other words, a certain amount of reverberance is important to orchestra musicians.

It was also found that string players preferred curved risers (like in Berlin) probably because they cause improvements in cross stage communication. (Unfortunately such risers were not included in the scale model investigations.)

Some musicians commented that overhead reflectors could have a positive effect; but halls with low ceilings were strongly disliked!

Attempts to find correlations between the *OAI* and available objective data were made after reducing the data set from 45 halls to only 12, since the other halls were either not purpose build symphonic concert halls, they were the orchestra's home hall (from which the responses could be biased) or halls which the orchestras had only visited a few times. The analysis of this reduced data set revealed no significant relationships with acoustical parameters, only with stage geometry: the height of the ceiling or of over head reflectors from which reflections from brass are likely to arrive at the strings and in particular the ratio between this height and the width of the stage. The correlation was positive with high and narrow stages being preferred.

Dammerud also asked whether or not the musicians agreed to a number of statements that he had formulated. 81% agreed that "Acoustics for performers depends on the correct balance between hearing yourself and hearing other players". However, such an approach might impose a high risk of biasing the results - and in the end most of the preferred halls were not likely chosen for reasons of easy ensemble playing.

After the experiences from the first questionnaire survey Dammerud sent new questionnaires to members of one regional orchestra to get their evaluation of eight concert halls in the south west part of the UK, all halls in which they performed regularly. In these halls he also carried out extensive objective measurements.

When including all eight halls, he again found high (negative) correlation between "general preference" and stage width, and among the objective acoustic parameters only parameters related to the amount of reverberance, T_{30}, C_{80}, G_{Late}, and ST_{Late} had any connection with the judgements most of which were highly related to the answers along the *reverberance* scale. He concluded also, that two of the eight halls, which were proscenium theatres and had very low reverberation times, were irrelevant for the study of "proper" concert halls and should be excluded from the analysis. For the remaining six halls, he then found no significant correlation between subjective responses and objective acoustic parameters; but high correlations with stage dimensions, which again indicated narrow stages and high ceilings to be preferred.

In view of the small number of halls, on which these conclusions were based, Dammerud then combined data from his two investigations with the data from Cederlöf [25] in a new analysis of all together 22 halls; but the results were not much different from when only using data from his own six UK halls.

Dammerud's thesis contains a wealth of other interesting information, and it is outstanding in its comprehensiveness and ability to incorporate and combine knowledge from many different types of investigations, and it gives a fine insight into the acoustic concerns of experienced musicians.

3.5. RENEWED ANALYSIS OF THE DTU DATA

Dammerud's results have inspired the author to take a new look at his own old data from exsiting halls. Therefore, a correlation analysis between the old subjective data and the geometrical parameters that emerged as promising in Dammerud's work was carried out. In this new analysis, the data from both UK and DK were combined – and analysed both without and with exclusion of halls with low reverberance as Dammerud suggested. Unfortunately, G_{Late}–values were not available in our data. Neither had we asked about *OAI*; but as all the more specific evaluations of subjective aspects (except *timbre*) were made along one dimension, one can assume that also *OIA* would be highly correlated with this first dimension and with all the other aspects correlating with this dimension, such as *Ease of Ensemble* and *Reverberance*. (Both before and after exclusion of halls with low reverberance, the correlation between these two subjective aspects is 0.82, which is significant at a 3% level at least.) Therefore the judgements along these two scales were selected as representing *OAI*.

The correlations found have been listed in the table below.

As seen in the table, neither ST_{Early} nor the geometrical parameters show any connection with the subjective responses. Only EDT_p has a decent relationship (significant at a 2% level and shown in bold) with the judgements – and only as long as one leaves the full data set in the analysis. It is only natural, that this relationship disappears when the span in EDT is reduced by leaving out halls with low *reverberance* and low EDT_p. There was no indication of parabolic correlation in the data (i.e. of an optimum point or interval within the range presented).

The data behind the most "promising" relationship in DK + UK halls have been plotted in the following graph:

The main result is that the significant parameters from Dammerud's investigations, stage width or height, do not show up as being important in our data, and promising parameters from our studies do not correlate in Dammerud's subjective data.

4. DISCUSSION

4.1 FEASIBILITY OF VARIOUS RESEARCH METHODS

We have seen that two types of experiments have been applied in subjective stage acoustics research; lab experiments in simulated sound fields and field experiments in real halls. Both types have their advantages and draw

Table 1. Correlation coefficients between selected physical parameters and subjective evaluations by Danish orchestras.

# of halls	16 halls in DK/UK		10 halls in DK/UK	
Correlation between:	*Ease of ensemble*	*Rever-berance*	*Ease of ensemble*	*Rever-berance*
ST_{Early}	-0.30	-0.29	0.06	0.15
EDT_p	**0.58**	**0.61**	0.23	0.31
W_{rs}	-0.26	-0.25	-0.32	-0.29
H_{rs}/W_{rs}	0.32	0.24	0.24	0.26

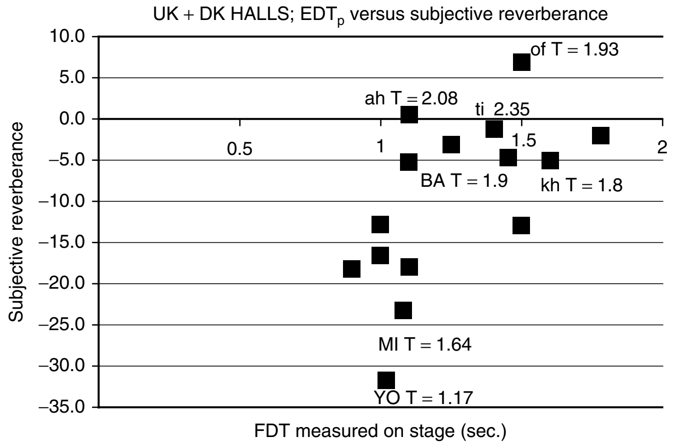


Figure 8. *Correlative values of subjective responses (likely to represent Overall Acoustic Impression, OAI) and Early Decay Time measured on the stage in 16 halls in Denmark and in the UK.*

backs.

In field experiments the musicians are exposed to the "real thing" including the entire complexity of all the sounds from the orchestra correctly modified by the acoustic features of the hall. There is no question about the degree of realism; but most often we can not control the many possible, independent variables as we wish, comparisons are difficult with long time intervals between the stimuli and likely different music has been played in the different halls. The situation is slightly different if experiments are carried out in a single hall with variable acoustics on stage; but the variation in independent variables will still be limited, and unless one pays the orchestra (roughly 30.000 Euro per day in Demark!) plus rent for the hall, one has to wait for a special opportunity - like when an orchestra wants your assistance to tune or modify their hall.

In field experiments it also matters whether the judgements are made from memory or collected right after a rehearsal or concert. The latter would seem more reliable; but requires logistics and opportunity to be realized.

The lack of common results in Dammerud's and in the Danish investigations is striking. A major reason could be that in both experiments the number of important physical variables in the halls is much too large compared to the number of halls investigated, which leaves too few degrees of freedom for common variables to appear as significant. To this should be added that obviously orchestra musicians are very limited in their ability to separate different subjective aspects in their evaluations, which means that they will probably react on those variables which caused the strongest – and in the situation to them the most important - subjective changes without the experimenter being able to identify which among the physical variables caused this judgement. In other words, one can not be sure that an evaluation along the "ease of ensemble" scale is really based on judgement of this aspect. In Cpt. 8 of his thesis [13], Dammerud also writes: "the least preferred halls receive more comments regarding poor thermal comfort"!

Surely, also the Danish investigations of 9 halls in Denmark and 8 halls in the UK represented a limited selection of halls among which only a few were dedicated concert halls, and also the experience of the Danish regional orchestra members might have been limited. (Denmark is not a big country, and collection of objective data and data analysis was very slow 25 years ago).

Later investigations are subject to the same limitations: Giovannini studied 5 halls, Luxembourg 7 (and the judgements were made by a student orchestra) and Cederlöf: 5. Dammerud managed to cover 45halls among which only 22 could be represented by valid data, upon which he made a more in depth analysis of 8 halls, of which only 6 were dedicated concert halls.

Consequently, all of our existing investigations from real halls are most likely severely limited by confounding of both objective and of subjective variables, which makes it very difficult (if not impossible) to reveal the "true" architectural or acoustic factors behind the various subjective aspects of importance to musicians. Obviously the number and selection of halls – and perhaps of orchestras as well – is very important in a field investigation, and as of now we only have data from investigations each covering a number of halls far lower than the likely number of independent (and even uncontrolled) variables.

Reasons why significant – but physically unexpected - correlations still appear in many investigations could be either confounding of variables or simply due to the size of the correlation matrix. A correlation significant at a 5% level means that the probability of a correlation higher than the one observed with purely random data is less than 5%; but if a large number of both objective and subjective parameters are included in the matrix, the probability of at least one pair showing high correlation by chance is much higher!

The logical solution to these problems would be to gather data from far more orchestras and halls. For this to happen we (researchers and consultants alike!) need to cooperate to develop a common minimum questionnaire form and common objective measurement procedures so that results from different sources can be pooled! But such an international effort would require both organization and some funding.

The simulation experiments carried out so far have been too simple by only including sound from a few musicians and not from the entire orchestra. Besides, in most cases, also the acoustic conditions have been too simple and have lacked realism. Still, this technique is probably necessary in order to be able to focus on specific objective and subjective aspects and to refine – e.g. integration intervals – in suggested objective parameters. Actually, Ueno's setup has a huge potential for improved subjective laboratory experiments.

4.2. THE SEARCH FOR OBJECTIVE ACOUSTIC STAGE PARAMETERS

Until the present day, only the support parameters have acquired a wider recognition, and since 1997 they have been included in the ISO 3382 standard. Several other measures have been suggested by researchers and consultants; but without having caught the attention of others than their original authors. In some cases this is a shame, as there is room for development of better objective parameters than the existing Support-measures.

Dammerud [13, section 7.7] states that $ST_{early/late}$ measurements are less accurate than a similar measurement based on Strength, $G_{e\ 20–100}$ or $G_{early/late}$. The only difference between $G_{e\ 20–100}$ and ST_{early} is that G uses a separate measurement of the source power as reference, while ST uses the direct sound from the same impulse response as the one from which the reflection energy is calculated.

The advantage of the G measure should be more accurate calibration plus less variation with changes in the floor reflection, source-receiver distance and source directivity. The floor reflection issues we will discuss below; but the other sources of error are not a problem in practice if some basic precautions are taken. Of course one should start with a simple$_{Early/Late}$ power calibration of the source in a reverberation room with the relative positions of source and receiver well defined and identical to those used in the practical measurements. This means: same height of the transducers above the (hard) floor, same mutual distance (microphone one meter from the acoustic center of the loudspeaker) and the the same orientation of the source relative to the microphone. Keeping these geometrical dimensions fairly constant (within one cm) is easy. One can simply attach strings and/or set markers on the speaker enclosure. The power calibration will essentially establish the directivity index of the loudspeaker in the position of the microphone (which is likely to be different from unity only in the 2 kHz octave and above), so that when measuring on actual stages one can freely ajust the level to suit the dynamic range at hand. With these precautions considered, it is difficult to imagine the calibration accuracy being poorer for ST than for G. According to Hak et al. [31] G-measurements can easily vary by one dB even when calibration and measurement is done with utmost care, and our experience is that position averaged measurements of ST can be repeated within a small fraction of a dB.

Regarding the influence of the floor reflection on ST measures, it is true that it will have an effect when the transducers are placed close to risers. Otherwise the influence of floor type is practically insignificant (for fixed transducer positions) unless the floor is carpeted!

However, G based measures do have other advantages. There is no need to exclude the very early reflections which implies that one can also do the measurements on smaller stages and even in smal practice rooms. For this, $G_{10\,-\,xms}$ might be appropriate. Garcia has applied such a measure successfully in rooms for speech [32].

One can also make the measurement at a distance from the source different from one meter, and one could then also include the direct sound in the G measurement and hereby use it for measurement of the propagation between source and receiver positions further apart, which seems highly relevant for ensemble. Hereby we actually approach the old definition EEL, the only real difference being that with EEL the integration started at the time of emission.

In Dammeruds work there was no sign of an objective range for ST_{early} as we had found; but actually this might be influenced by very high values of this parameter not being included in his data set. However, the parabolic correlation between *OAI* and ST_{early} was quite high (see [13] Fig 8.5.C) and indicates values between -13 and -11dB to be favourable. (The fact that very low values, below -16dB in this case, appears equally favourable could be due to other properties in the two halls with these low ST_{early} values.) Anyway the purpose of ST was never to be used for overall assessment of stage acoustic quality, i.e. a high correlation between ST and *OAI* was never assumed or expected. Its purpose is as simple as its definition: to measure the amount of early/late reflected energy in a consistent way. This is important some times: e.g. in attempts to quantify the effect of measures like reflectors installed for the improvement of early reflection properties in specific hall. At least it has made sense in many practical cases: the old Danish Radio Concert Hall, Göteborg Concert Hall, the Norwegian Broadcasting Hall in Oslo and in the Queens Hall in Copenhagen to mention a few of our own experiences.

A few of the parameters suggested by other authors should be mentioned. Some of these parameters simply calculate energy ratios in ways slightly different from the

ST parameters. As the time limits in the ST parameters have not been validated, there are good reasons to try such modifications. O'Keefe [33] tried different source receiver distances, Chiang [23] measured ED80 Early to Direct ratio like $ST_{Early/Late}$ but with integtration interval 5–80 ms and Late to Direct ratio with interval 80 ms - ∞. Ueno [22] simply changed the source –receiver distance to 30 cm, but this was basically motivated by practical circumstances in her laboratory simulation system. The earlier mentioned parameter suggested by Luxembourg; LQ_{7-40} [27] is different in evaluating the balance between very early and later reflections, but without relating these to the direct sound.

It should be mentioned parameters employing very narrow time intervals like LQ_{7-40} or G_{7-50} are not measurable at low frequencies!

Dammerud suggested Early-Mid Decay Time (EMDT) being EDT calculated between 20 and 130 ms. He also measured Strength, G, with many different time intervals for early and late reflections but he found that only G_l and C_{80} gave consistent results when measured without the orchestra on stage. Dammerud measured all parameters except ST with the microphone being placed at least 4m away from the source.

JJD also mentions that parameters based on omnidirectional impulse responses are insufficient, mainly because direction of matters due to the almost fixed layout of the different instruments of the symphony orchestra on stages and the problems associated with achieving a proper balance between them at the musicians' ears. Doing his work under the supervision of Mike Barron in Bath, England, he naturally suggests Lateral Energy Fraction to be used as a first approach to a directional measure!

4.3 STAGE DESIGN

Regarding firm recommendations for the acoustic design of halls and stages for symphony orchestras, research has not yet given clear answers; but Dammeruds suggestion to look at H/W ratio is supported by other work and is in line with design practice during the last couple of decades. High and narrow halls allow the furthest strings on each side of the stage to be closer together and reduce reflection delays from the side walls. If "narrow" implies that the stage is deep as well, it will still be possible to keep sufficient distances between brass/percussion and wood wind/strings to avoid too high levels, and a high ceiling will allow for reverberance to "bloom" for better support and better evaluation of balance between groups.

The preference for a higher H/W ratio is also supported by results from recent renovation projects of stages in Göteborg and Gävle in Sweden. In Göteborg, reducing the size and modifying the shape of over head reflectors made early reflections from above weaker and might have improved the musicians' contact with the hall reverberation as well. The same effect was achieved in Gävle where the orchestra judged in favor of reducing the number of ceiling reflectors.

High H/W ratios has also been found to be preferred in simulations with soloists [34], and already Meyer [17] mentioned high ceilings to be favoured by conductors.

Dammerud explains orchestras' preference for high H/W by this causing less masking of the string sounds by the louder brass (as also do Andersson [24]). Dammerud also suggest side wall reflectors with down ward tilted upper parts to improve cross stage communication. This has actually been our practice since we first suggested it for the the renovation of the old Danish Radio Hall in 1988. Other halls with this feature are The Norwegian Broadcasting Hall in Oslo and the Queens Hall in Copenhagen shown in

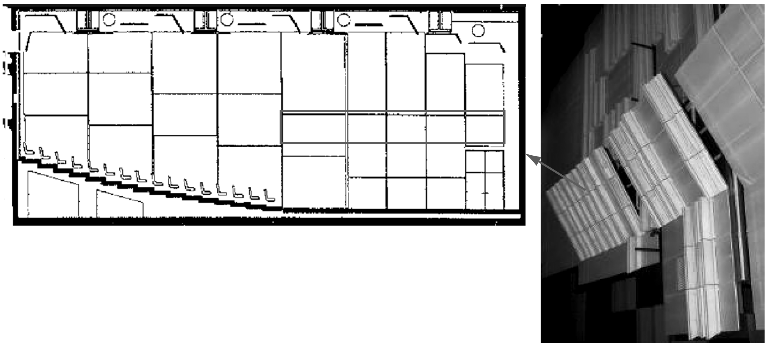


Figure 9. *Variable, tilted side wall reflectors in the Queens Hall in the Royal Library in Copenhagen.*

Figure 9, to mention a few.

Dammerud mention that strings in particular like curved risers. Such risers, first introduced in the Berlin Philharmonie in 1962, have been increasingly popular in recent years and will obviously reduce the attenuation of the string sounds propagating across the stage. It is likely that this reduction (plus the effect of tilted side wall reflectors) is sufficient to substitute early reflections from above in the communication among the string groups. Overhead reflectors were found to be important in old DR hall, but apparently they are not in the new DR hall, where after one and a half years the same orchestra – now sitting on curved risers - is happy with the ensemble in spite of the over head canopy being placed very high (14 m). It may be added that in this hall the reverberant sound level is quite moderate.

On the other hand it is well documented that early reflections influence *ensemble* and late reflections influence *support* and *reverberance*. A practical solution in many halls is to install a movable canopy or an array of smaller reflectors above the stage, which can be adjusted during tuning of the hall with the (resident) orchestra - or perhaps even on a day to day basis depending on the repertoire.

Another question is whether too much reverberation (lack of Clarity or modulation transfer) is a problem on concert hall stages. Several investigations indicate that this could be the case. We have also found this to be a problem particularly in small rehearsal halls with volume less than say 6000 m^3 and reverberation time above 1.6–1.8s. In the new concert hall in Aarhus with variable acoustics and volume about 15,000 m^3, reverberation is reported to be slightly problematic when T is set high above 2 s.

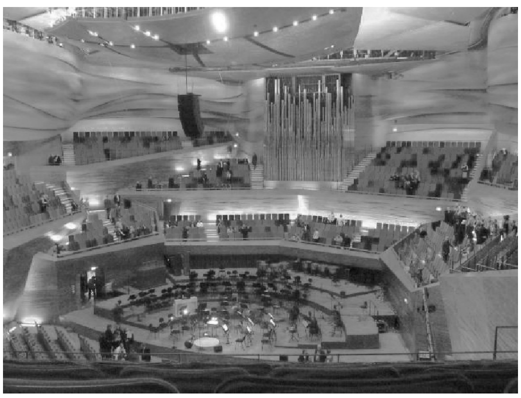


Figure 10. *Curved risers and high canopy in the new Danish Radio Concert Hall in Copenhagen.*

5. SOUND LEVELS IN ORCHESTRAS

A few remarks should be added regarding musicians' exposure to high sound levels, which has been regulated by law within the European Union since 2008. Since then, we have had the opportunity to measure exposure levels and calculated noise doses on musicians in two orchestras in Denmark [35]. The rule is that the exposure levels must not exceed 85dB L_{Aeq} over an 8 hour work day. Our results showed exposure levels between 87 and 99 dB for members of the Aarhus Symphony Orchestra between 82–91 dB for members of the Royal Opera Orchestra. These values were measured according to ISO 9612, which means that the contributions from the various "tasks" of musicians, which we defined as individual practice, rehearsals and concerts, were added together. For many wind and percussion instruments, the contribution from individual practicing was often higher than from rehearsals or concerts. Another surprising result was that those playing the loudest instruments – and being exposed to the highest levels - were not the ones complaining the most. The most annoyed are the players of the weaker wood wind and string instruments who have to sit close to the loud instruments – which they can not control!

The big question is: what can we do about it without killing the music? Some obvious measures are:

- Provide adequate space on stage to avoid close proximity to loud instruments
- Install sound absorbing screens where close instruments are still too loud
- Do NOT install absorption on reflecting surfaces close to the orchestra (except near very loud instruments), as this will reduce ensemble and likely make each musician play even louder!
- Modify the playing style towards finer nuances in stead of more loudness.
- Choose conductors who support this strategy!

The key message is: do not treat the problem like a normal noise case in which installation of absorption is the natural choice. If the needed early reflections are removed, the effect will most likely be the opposite: the musicians will intuitively play louder!

6. CONCLUSIONS

Research in the field of stage acoustic is still lacking sufficient, experimental verification regarding which properties of the sound fields and architectural features of halls govern the subjective experiences of orchestra musicians.

Among objective measures suggested, only $ST_{Early/Late/Total}$ has been used by several acousticians. Some records exist of this measure being meaningful (and even supported the existence of an optimal range for ST_{Early}); but other investigations have indicated no correlation with subjective judgements.

There are indications of a the level of reverberation to be of importance; but we have neither a good parameter for its measurement or a defined optimal range.

Most experiments in laboratories have been unrealistic by the sound of the full orchestra not being represented in the sound field; but laboratory experiments still have a role, as only in a controlled environment can one zoom in on aspects such as refining the time limits for energy integration in suggested objective parameters. In particular, a set up like the one used by Ueno can be of great value in the future.

Most field experiments have involved too few halls for significant results to appear. Progress is also limited by the fact that musicians have difficulties in distinguishing between different subjective aspects in their judgements. Therefore, we do not have any convincing objective parameters for measurements neither of *Overall*

Acoustic Impression nor of more specific aspects.

A minimum requirements for the results from a field experiment to be of general value must be that the number of stimuli (halls) is larger than the degrees of freedom required to represent the possible variables, and with those being many (one can easily list at least ten independant variables in concert hall and stage design) it is necessary to have data from many more than 10 halls in order for significant results to emerge. (This was also our strategy in looking for the relationships between architectural design variables on the objective acoustic parameters. After a decade our database contained more than 50 halls [36].)

Therefore, researchers and consultants must unite in an effort to collect sufficient data on musicians' evaluation of halls as well as on objective parameter values and architectural descriptions from these halls. This can only be done if we agree on a minimum set of questions to be included in every new subjective survey of halls and on a minimum set of objective date to be measured and collected as well. The first task is to select a group of volunteers who will set up a framework for such efforts, initiate some fund raising, develop questionnaires, select objective parameters, define measurement procedures, take care of communication, collection and distribution of data and organize analysis of results.

The prospects are good. Many papers on this topic have been published in recent years and it is my hope that we can continue working along these lines.

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KIDS TWO DECIBELS TOO NOISY

Hong Kong's Lantau International School is situated in Pui O, a popular beach resort filled with holiday villas. Its 70 students - seven to 11 years old - are being told by the Environmental Protection Department to hush up, because their voices at play exceed the 60 decibels allowed in rural areas. According to EPD, they're too rambunctious by two decibels during class breaks. The school has sought a judicial review of the order and is still awaiting the outcome.

NOISE TOPS LIST OF NEIGHBOUR COMPLAINTS

In the UK, at least five million people are currently annoyed with their neighbour, and over 10 million have had a neighbour problem in the last year - but a quarter fail to take any action, finds new research from Which? Legal Service. The consumer champion found that noise tops the list of neighbour complaints, with around three in five people annoyed by loud voices or arguing, blaring music and TVs. A quarter of those affected are irritated by door slamming, a similar percentage have been disturbed by their neighbours' noisy pets, and one in five by regular parties. Five per cent have been privy to hearing their neighbours having sex. Noisy neighbours disturb four in ten people's sleep, while others complain that the noise makes them irritable, angry or stressed. One in five sufferers have seen their work or health affected. Despite this, a quarter of people who are frustrated with their neighbours have made no attempts to rectify the problem fact, ten per cent chose to take revenge by becoming nuisance neighbours themselves. A third spoke calmly to their neighbours about the issue, while one in five contacted their Local Authority. 17 per cent of people were forced to call the police.