



Room acoustical quality of concert halls: perceptual factors and acoustic criteria – return from experience

Eckhard Kahle
ekahle@kahle.be
Kahle Acoustics
188 avenue Molière
1050 Brussels
Belgium

ABSTRACT

Several acousticians have attempted to define a complete set of factors describing room acoustic quality, based on laboratory and/or real hall listening tests. After finishing a PhD thesis on room acoustic quality, the author has worked on new constructions of performance spaces, renovations as well as optimizations of existing spaces and the question can now be asked whether the widely used set of objective criteria and perceptual factors proves sufficient to describe the problems and challenges encountered.

When working on high-quality acoustic spaces, the commonly used set of acoustic criteria is insufficient to describe all aspects and problems. Further descriptors are required with respect to both acoustic measurements and perceptual factors. Proposals for additional acoustic criteria and their link to the architecture of a space will be given, aiming to better describe the signature of a room with respect to both source presence and room presence.

The concept of “stream segregation” into source presence and room presence is confirmed, but for both the “source” and “room” parts not only the magnitude (strength) needs to be considered but equally more detailed aspects like “lateralness” and direction of arrival, i.e. what could be called the “spatial center of gravity”. For example, changing the spatial center of gravity of the reverberation has very strong perceptual consequences. Another aspect that often tends to be neglected is the question of orchestral balance (for audience members but equally for musicians on stage) that can strongly be influenced by acoustic design decisions.

1 INTRODUCTION – ROOM ACOUSTIC QUALITY AS A MULTI-DIMENSIONAL SPACE

The fact that room acoustic quality is not a one-dimensional concept and that there are several independent factors governing our perception of room acoustics and room acoustic quality has been known for a long time.

Already Wallace Clement Sabine in one of his seminal papers^{1,2} talks about “three aspects that are required so that hearing may be good in any auditorium” and later defines these three aspects as: (1) Loudness, (2) Distortion of Complex Sounds: Interference and Resonance and (3) Confusion: Reverberation, Echo and Extraneous Sounds. It is interesting to note that “reverberation” only appears in the description of the third aspect in Sabine’s list. But as only the aspect of reverberation was defined by a formula (and a correlation established between the

perceptual factor and a measurable parameter), the other aspects were unduly neglected in the years after Sabine's death.

Beranek^{3,4,5}, in his multiple publications, re-established and increased the notion of multiple aspects of room acoustics quality, delving both into description of perceptual factors and measurable criteria as well as the correlations between the two. His books and the opening of the Philharmonic Hall in New York lead to a strongly increased activity in room acoustics research and the correlations between objective criteria and perceptual factors, see as well Barron^{6,7}.

Several of the initial studies (for example of the Göttingen^{8,9} and Berlin^{10,11} groups) yielded between three and four independent factors, but it is believed that this is due to the experimental setup, as all subjects in a perceptual test have a tendency to concentrate on the three or four (or generally the minimum number) most salient features for the differentiation task.

Only meta-studies, combining the information from several individual studies or laboratory experiments (or allowing individual subjects different organizations of the perceptual space, as in Lokki¹²), can increase the number of revealed dimensions and therefore approach the full number of dimensions of the perceptual space. The largest number of perceptual factors, leading to a multidimensional space of 11 dimensions, was found in a series of laboratory experiments at IRCAM in Paris that used multiple listening tests, keeping criteria constant in later tests that had been found relevant in the earlier tests^{13,14}. The model was verified with a series of listening tests (and measurements) in real concert halls and opera houses, leading to a somewhat reduced, but still large number of at least 8 perceptual factors¹⁵.

The studies at Ircam revealed early energy and late energy (termed "source presence" and "room presence") as perceptual factors, rather than total energy (loudness) and the ratio of early to late energy. This finding can be linked to the concept of stream segregation, as described for example by Griesinger^{16,17}, Schuitman & De Vries¹⁸ or Dau¹⁹.

For the multi-dimensional space of room acoustic quality, accepting the notion of stream segregation is equivalent to a change in base, or a rotation of the main axes of the space. Rather than thinking in terms of G and C80 (so loudness and "clarity" – where we know that C80 is not a very good descriptor for clarity), it means thinking in terms of G_{early} (or all energy that is integrated with the direct sound into the source stream) and G_{late} (all energy that is integrated into the room presence stream). But a change of base – and the naming of the major axes – can facilitate the understanding of the details involved. The notions of "source presence" and "room presence" should first be considered in terms of loudness: the loudness of the source is one perceptual factor, the loudness of the room another perceptual factor. As the term "loudness of the source" is generally considered to be an attribute of the source and not of the room response, the terms "source presence" and correspondingly "room presence" are preferred as names for the perceptual factors linked to room acoustic quality. Loudness of the room (the perceptual attribute linked to the objective notion of amplification of the room) is the sum of two perceptual evaluations and not an individual perceptual factor. Secondly, given that loudness is evaluated independently for the early part of the room response and the late part of the room response, it is suggested that other aspects like spatial response and frequency balance should equally be evaluated (and measured) separately for the early and late part of the room response.

In addition to objective criteria and perceptual factors, it is interesting for the discussion and the development of further ideas to include the concept of “architectural criteria”. There are multiple studies in the room acoustic literature about correspondences (and correlations) between perceptual factors and objective room acoustic criteria. Much less documented are the relationships between architecture and room acoustic quality. Room acoustics – and therefore room acoustic quality – only occurs within built spaces, therefore there will be correlations between the built environment and the perception of room acoustic quality. This is sometimes important when optimized acoustic criteria do not exist (for example Dammerud^{20,21}), and helpful for acoustic consultants during the early design phases and during interaction with architects. It is believed that current knowledge in fact allows expressing at least most aspects of room acoustic quality in terms of architectural criteria.

Another interesting aspect of architectural criteria is their more direct link to physical space. Recent studies on blind people (for example by Halmrast²² or Katz²³) have clearly shown the ability of blind people to use sound for the extraction of important information about the physical space they (and we) live in, from distance to objects to dimensions and volume of spaces we are in. Doidge²⁴ found that blind people had an enlarged area of their brains to carry out these functions, showing that brains can develop differently according to the person’s personal needs and efforts. But if blind people can use sound to extract information or evaluate dimensions, they are using the same physical features of the human hearing system that non-blind people use – they have just learned to better use information that is available to all listeners.

In terms of evolution, all of our senses are optimized to give us information about the world we live in and the objects we are interfering with. The author feels very strongly that this holds for our hearing – and therefore as well for our perception of room acoustical quality: what we want is a maximization of useful information, and optimized acoustics can therefore be interpreted as acoustics that maximizes useful information.

Skalevik^{25,26} finds that with a limited number of objective criteria (in fact, some acoustic criteria and some architectural criteria) one can explain a significant part of the variance in the subjective judgment of rooms. Using “TVr-theory” (TVr for reverberation time T, Volume V and distance r) in his examples about half of subjective variance is explained, and using 5 objective criteria from ISO 3382 about 60% of the variance is explained. This rather reduced number of criteria – and therefore dimensions – seems rather surprising in explaining a significant part of subjective variance. The non-explained part of the variance, is it statistical noise, or secondary information? Or, on the contrary, is the non-explained part of the variance the difference between an acceptable concert hall and an excellent concert hall? There are reasons to believe that while TVr theory, or a reduced number of objective criteria from ISO 3382, will reveal the most salient features in the *comparison* between rooms, they do not describe what makes some rooms special, the difference between acceptable acoustic conditions and conditions that are excellent.

If we accept the notion of room acoustical quality being a multi-dimensional space, then the dimensionality (i.e. the number of dimensions) of this space needs to be identical irrespective of whether we describe this space in terms of room acoustic perception, objective acoustic criteria or in terms of architectural criteria. This does not require that there is a one-to-one relation between a perceptual factor, an objective criterion and an architectural parameter, as they do not need to be collinear. But the number of dimensions needs to be identical in any complete description and the interesting consequence is that if we find a new dimension in one of the three descriptions, this dimension must exist in the other descriptions.

2 CASE STUDIES

Case studies will be discussed in the following section of this paper, as much as possible focusing on experiences and experiments within a given room, so without changing (or without drastically changing) the “standard parameters” like reverberation time, C80 or G. The purpose is to show that when working with real rooms, standard parameters are not sufficient to tackle all situations. We believe that additional parameters need to be taken into account in order to describe the finer details of room acoustic quality, both for audience members and musicians on stage.

2.1 Salle Poirel, Nancy

The Nancy Symphony Orchestra is playing in the *Salle Poirel*, a moderately-sized hall from the late 19th Century. The hall, seating about 900, has a small stage house, and as part of a renovation in 1999 a quite closed, wooden orchestra shell was added. Astonishingly for most acousticians, the reactions from the musicians and even more from audience members and experienced listeners were very negative and the orchestra stopped using the concert shell after a few concerts. The main complaint was not that the reverberation time with the concert shell was too long (reverberation time with shell was still below 2 seconds) and that loudness levels on stage were sometimes excessive, but that the sound from the shell was muddy, compressed, lacking clarity and creating localization problems – all of the sound, both early sound and reverberation, was coming from the same location, from the stage.



Salle Poirel, Nancy: without orchestra shell (left photo), the black rear wall is acoustically absorbing, and with orchestra shell (right photo). The orchestra preferred to play in the configuration without orchestra shell as the tight shell created more negative than positive effects before absorption was added.

Kahle Acoustics worked with the Nancy Symphony Orchestra during the 2010/11 season both concerning the orchestra pit and the concert hall. Several trials were carried out, some consisting of adding reflectors in the configuration without the orchestra shell (without shell musicians had difficulties hearing each other) and some consisting of adding significant amount of absorption inside the orchestra shell. The latter finally gave the best results, placing most of the absorption on the rear wall (for improved balance), but leaving a reflective strip at ear height for the musicians in the last row. While placing absorption at ear (and instrument) height reduced the loudness levels, it reduced on-stage communication as the beneficial reflection helped the musicians in hearing other musicians placed further upstage.

2.2 Casa da Musicá Porto

The Concert Hall at Casa da Musicá in Porto has always had good acoustics, especially for medium-sized ensembles, but it turned out that the hall's Symphony Orchestra had in fact never been fully happy with the room's acoustics. Musicians complained about difficulties of hearing on stage, the sound in the hall was somewhat frontal and often compressed during big orchestral *tuttis* and serious balance problems were observed. Kahle Acoustics was asked to evaluate the acoustical quality of the room and to make remedial proposals – even changing the room, if required. The following image shows a photo of the room as set when we arrived, prior to any changes.



Concert Hall at Casa da Musicá Porto, configuration as found at the beginning of the acoustic tests.

It turned out that no real “remedial measures” were required in terms of the building – what was required was to reset the room and the variable acoustics features of the room.

The most striking observation when arriving was that, on stage, the loudness was already excessive when the orchestra musicians (and not even all of them) were warming up. In addition to being overly loud, the sound on stage actually masked all of the room response of the hall, no sound or return of sound from the hall could be heard.

An acoustic test was prepared, occurring during a series of normal orchestral rehearsals, with two main changes:

- several acoustic curtains were prepared that could be thrown over the glass balustrade of the choir balcony, placing absorption at the back of the stage;
- several canopy settings were tried, raising the canopy and tilting the canopy in order to increase projection of sound from the stage into the audience area (and therefore reducing sound levels on stage).

Musicians instantly reacted positively to absorption being placed behind the brass and percussion instruments, stating that loudness levels are reduced and that hearing of string players was significantly improved. In the beginning, no curtains were placed behind the tympani at the center of the stage, as the balance with the tympani was found to be good. We were approached by a flute player who noted that the sound on stage was still somewhat confused; he invited us on stage next to him – where his observation could very rapidly be confirmed. Once again the situation was significantly improved when placing a curtain behind the center of the stage, basically covering 100% of the rear wall of the stage with absorption, between the stage and choir balcony. The absorption has in the meantime been placed behind the acoustically transparent, perforated metal cladding, and some absorption was even integrated into the side walls of the stage next to the brass and percussion players in an invisible manner.



Concert Hall Casa da Música during the acoustic tests: rear wall absorption, raised and tilted canopy.

Raising – and especially tilting – the canopy created another striking effect, this time mainly in the audience area, totally transforming the sound. With the canopy tilted, the sound became significantly more “generous”. All participants agreed that the sound was much better, really a different acoustics and in fact “a different hall”.

Comments included “much more generous, now the music gets to us rather than staying on stage”, “more open, airy, much less compressed”, “better intelligibility and definition”, “better projection and openness”. Furthermore, the subjective distance to the musicians was significantly reduced. Another interesting observation was that the conductor could suddenly be understood anywhere in the hall – while he used to never be intelligible.

How can a change in inclination of a canopy have such a striking effect? Is it only the effect of a slightly increased early energy due to the increased projection? We believe that this is not the case, and that the most significant change is another one: separating source and room spatially.

Improving and facilitating stream segregation improves clarity and definition; shifting reverberation away from the stage stops the sound being compressed and creates space around the sound sources and improves openness. And the reduced subjective distance may in part be due to stronger reflections, but more likely due to the fact that the “room has moved backwards” – so if the room has moved backwards, relatively the listener is closer to the sound sources.

The Concert Hall at Casa da Musicá in Porto allowed us to perform another test that is highly significant in this context: the hall is traversing the entire building in the long section; both the wall behind the choir balcony and the wall behind the audience are full-height sinusoidal glass walls. Both glass walls can be covered with a decorative and a separate, acoustically absorptive, curtain – but it turns out that the decorative curtain is not tight enough to block out Portuguese sunlight, therefore the decorative and the acoustic curtains are normally used together. One wall faces East and the other wall faces West – therefore the curtain in front of the choir wall was used in the morning (dress rehearsal) and the curtain in front of the rear wall was used for concerts (mainly in the evening but sometimes in the late afternoon). Indeed, both curtains have approximately the same surface area – and most ISO parameters will be unchanged or at least similar with either curtain in use. But the acoustic quality of the room is dramatically changed when using one or the other curtain, with a very clear preference by the author (and now hall management and musicians as well) for the curtain behind the choir balcony. Not only is balance improved, the feedback and room response to the musicians is improved as well. But the most significant difference is the spatial separation between source presence and room presence: with the curtain at the back of the audience, both source presence and room presence are located on or above stage (so very close to each other), with sometimes unpleasant interference effects and decreased clarity, and the room (or the back of the room) behind the listener is totally absent and dead. With the curtain behind the choir balcony, source presence is on stage and clarity is much improved, while the room behind the listener is “active” and awake. There is a highly beneficial spatial difference between source presence and room presence – or shall we say between the “center of gravity” or the source presence and the “center of gravity” of the room presence.

2.3 Concert Hall, KKL Luzern

The Concert Hall in Lucerne, Switzerland, is a rectangular shoebox hall, with a U-shaped reverberation chamber behind the organ and to the sides of the upper side balconies. Variable acoustics absorption, in the form of vertically moving banners, is installed in several locations

inside the reverberation chamber. The acoustic absorption is used to limit the reverberation time difference between the inner and the outer room to a musically optimal value, as a function of the opening of the reverberation chamber doors.

What is interesting in the context of this paper is that there is a significant perceptual difference between placing absorption in the side parts of the chambers (next to the side balconies, in front of the stage edge) or in the rear part of the chamber (behind the organ or in the side corners, in any case far behind the stage edge). Absence of absorption in the side parts of the chambers is preferred, making the reverberant sound more lateral (as expressed by LEV and LLG, late lateral G, see²⁷). In addition, presence of absorption in the rear part of the chamber is preferred, as this shifts the center of gravity of reverberation and room presence from being located *behind the stage edge* to being *in front of the stage edge*, so from being behind the center of gravity of the source presence to being in front of the center of gravity of the source presence.

2.4 Casino Barrière, Toulouse

Casino Barrière Toulouse is a 1200-seat multi-purpose theatre with a relatively dry acoustics but considerable volume as it is mainly used for amplified events. During the renovation of the Opera (Théâtre du Capitole) in Toulouse, an opera performance was staged in this room as well as in another theatre, and for the occasion an artificial reverberation system based on the MCR-principle was rented. The advantage of an MCR system with digital control is that the levels of individual loudspeakers can be set independently, creating “negative absorption” and reflections in different areas of the room. It was found that the system sounded best when the loudspeakers mounted on the rear wall of the room were set significantly louder than other loudspeakers, basically “waking up” the room as much as possible acoustically, including the back wall of the room.

Furthermore – and probably equally relevant in the context of this paper – the singers and musicians highly appreciated the audible room response and actually asked us to further increase the loudness of the room response. Similar musician reactions were collected both at Casa da Musicá and during the acoustical setting of the canopy at the Stavanger Concert Hall: tilting the reflectors above the stage enhances the room response back to the musicians, given the musicians stronger feedback and allowing them to more clearly hear the late reverberant room response, confirming similar findings by Dammerud²⁰.

2.5 Auditori, Barcelona

Kahle Acoustics was asked to help the Orquestra Simfònica de Barcelona to help with problems of on-stage hearing. The orchestra had already noted that the acoustics for the musicians was significantly improved when a projection screen (perforated and therefore sound absorbing) was placed behind and above the orchestra. The same effect was created using an absorbing curtain either in the organ loft (no organ is placed there yet) or next to the organ loft. It turned out that further absorption needed to be placed closer to the musicians, at the transition between stage and choir balcony. When this additional absorption was placed behind the brass and percussion, the woodwind players indicated that they could now hear the strings in front of them to a sufficient degree.

Another problem for several of the musicians of the orchestra is the absence of sufficient room response or too weak room response. Indeed, most of the balcony fronts as well as the rear wall of the room are angled in such a way as to avoid echoes back to the stage, the room being used for amplified events as well. While this absence of room response may be beneficial

against a slap-back from the hall for amplified events, this situation is detrimental for symphony orchestra musicians! It should be noted that the consequence is not only that absorbing rear walls should be avoided, but equally that diffuse treatment of the rear wall as well as balcony fronts needs to be kept moderate or even should be avoided if the main use of the hall is for symphonic music.

Arau, the acoustic designer of the room, has communicated on his interaction with the orchestra, concluding that fulfilling the ST1 criterion is not sufficient to create fully acceptable stage conditions²⁸.

From the observations made in Auditori Barcelona as well as several of the other case studies, it seems clear that the ST1 criterion needs to be re-evaluated. As a minimum, ST1 should be measured for several locations on stage and the variation of ST1 is at least as critical as the mean value. In addition, ST1 should ideally be *stronger* for string positions and *less strong* for brass and percussion positions – which is often difficult to achieve and actually contrary to standard acoustic design beliefs. Acoustic absorption needs to be placed at the rear of concert stages, in order to avoid that ST1 for brass and percussion is significantly stronger than ST1 for woodwinds and strings. Otherwise, brass instruments cannot hear strings, and for woodwinds the sound energy of the brass (plus rear wall reflection) can at times severely mask the string sound making communication more complicated. Furthermore, on stage and even with continuous music, an audible return from the room is required for musicians, as equally found by Dammerud²⁰.

2.6 Melbourne Recital Hall and Kilden Concert Hall, Kristiansand – acoustic diffusion

During ICA 2010 a visit to the Melbourne Recital Hall was organized. Playing and speaking in the empty hall, it was observed that the highly diffusing finishes in the hall tend to reduce integration of reflections into the early sound and therefore reduce source presence. This observation was later confirmed by Lokki²⁹ through laboratory experiments. It is interesting to relate these findings to results obtained by Warzybok et al.³⁰ indicating that the length of the time window for integration of an early reflection of speech is dependent on whether masking noise is diffuse or localized.

Another observation on diffusion was done during a listening test in the concert hall of Kilden, Kristiansand. In this hall, the prism-shaped, large-scale diffusion elements on all walls and the diffusive treatment of the ceiling make an evaluation of the room size and the distance to room boundaries considerably more difficult than in halls with less diffusion treatment, leading to reduced room presence. Is a fully diffuse room response really preferred acoustically?

2.7 Laboratory listening tests – double slope decays and late sound clusters

In a laboratory experiment on Parametric Reverberation of a Concert Hall³¹, using listening tests through 8-channel loudspeaker reproduction, effects of double slope decays and variable levels and timing of clusters of late reflections were studied. Results were not entirely conclusive and will not be discussed here in detail, but shifting energy (clusters of reflections) within the time interval between 100ms and 200ms after the direct sound had strong effects, changing the *physicality* of the space. This means that reflections arriving later than 100ms can provide strong cues on the physical parameters and dimensions of a space – changing our perception of space and therefore changing our listening experience.

If shifting energy within a time interval later than 80ms after the arrival of direct sound can have strong effects, how is this measured and represented in terms of acoustic criteria? One of the conclusions of the study was that “the objective measures of ISO 3382 do not explain the audible differences between the samples.”

2.8 Choir rehearsal room Toulouse

The Théâtre du Capitole (opera) in Toulouse had to move out of their choir rehearsal room, and a derelict cinema was transformed into a choir rehearsal room. During the first rehearsals, reactions of the singers were extremely negative and Kahle Acoustics was called in for a study and improvement proposals. While the room is clearly on the small side for a rehearsal room for a professional choir, first inspection and measurements, as well as first listening impressions from a window on the first floor looking into the upper part of the volume of the room, showed no immediate problems or insurmountable difficulties. It was only when testing the room after the choir had left that the main problem was identified: the lower side walls of the shoe-box shaped room are vertically inclined, “leaning forward” with an angle of about 5°, leading to a significant amplification of the sound level in the lower part of the room and a “bathroom effect”. The inclination of the walls “holds” the energy in the lower part of the room and the sound of the upper volume is entirely masked for singers in the lower part of the room. Placing acoustic absorption in front of the side walls (about 50% of the surface of the lower walls) improved the situation but was still not sufficient to suppress all negative effects of the tilted side walls.

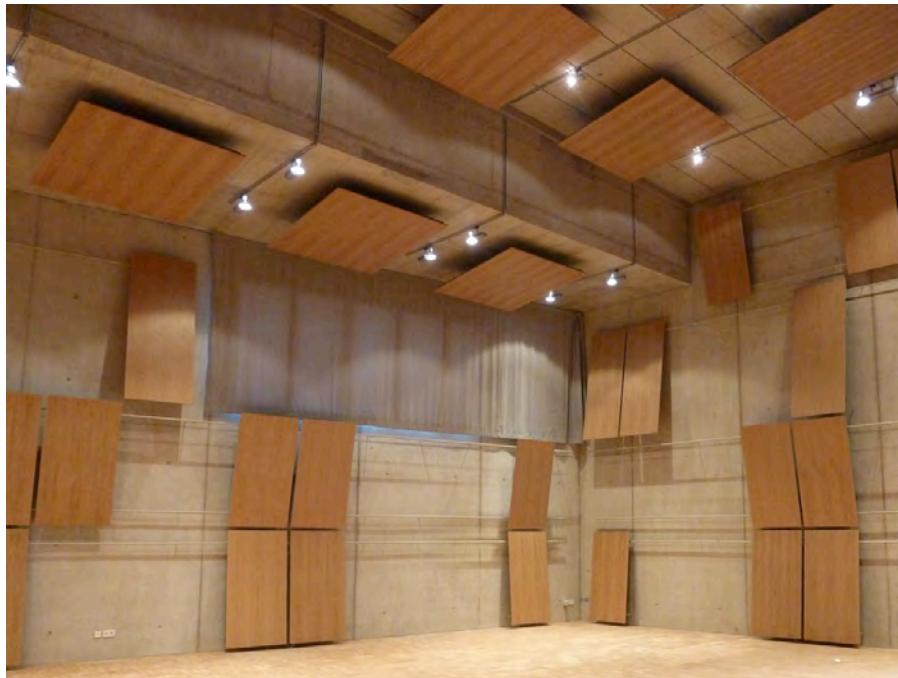


Vertically inclined side wall, leaning forward, choir rehearsal room Toulouse.

How are the effects of non-vertical walls correlated with acoustic criteria? A detailed analysis of the objective acoustic measurements of the space showed no evident correlations with typical room acoustics criteria (for example those of ISO 3382), with one striking exception: it was found that, for all receiver locations in the lower part of the room both the early energy and the late energy were significantly above the values predicted by Barron’s Revised Theory. Could it be that a room is considered to be “exceedingly loud” and “oppressive” by singers not for a certain value of G (as well as G_{early} and G_{late}) but for the fact that the room is louder than Revised Theory (and therefore human experience) is predicting it to be? Are we evaluating rooms “in comparison to expectation” and not based on absolute, objective, values? The experience of the Toulouse choir rehearsal room may corroborate and complement similar results found by Barron³² when investigating loudness judgments as a function of distance to the stage, as well as results from Hyde³³.

2.9 Freiburg rehearsal room

The study of the Toulouse rehearsal room occurred during the interior design period for a rehearsal room in Freiburg, Germany. The rehearsal room, with a floor surface of about 200m² but including a “technical balcony” that enlarges the upper part of the room to a ceiling surface of about 250m², is used by the Freiburger Barockorchester and the Ensemble Recherche, a contemporary music ensemble. The project was built on an extremely tight budget, and it was clear that there was no money to clad all the walls with acoustic finishes. The concept, from the onset of the project, therefore had been to mainly use exposed concrete but then add “free-floating” wooden reflectors. It was finally decided to hang wooden panels on metal bars in four lines. All panels are vertically inclined: the panels in the lowest line (in the plane of the sound sources) are leaning backwards (therefore sending the sound to the upper part of the room), the panels in the second line are leaning forward (acting like inclined choir balcony fronts insuring good communication between opposite sides of the stage), the panels in the third line are once again leaning back and the panels in the upper-most line are leaning forward.



Rehearsal Room Freiburger Barockorchester with vertically inclined reflector panels.

The perceptual results and musician reactions are very clear. First of all, the room sounds “bigger than it is”, which is most likely correlated with the fact that the sound levels for receivers located about 1m above the floor are reduced by the vertically inclined panels that are leaning back and therefore are sending sound to the upper part of the room. Secondly, the room is used (and preferred by musicians) with a reverberation time that is significantly higher than would be expected for the size and use of the room. The reverberation time of the empty room is close to 1.5 seconds, mid-frequencies.

Since the opening of the Freiburg rehearsal room, two acoustic tests have taken place: optimizing the placement of musicians within the room, and adding acoustic absorption and reflector panels. The first test was in preparation for a recording of Mozart piano concertos. For one of the concertos the accompanying orchestra consisted of strings and some woodwind players only, while for another concerto the orchestra included brass and percussion – and for

this concerto the orchestra was arranged all around the piano. When there is a clear direction of the orchestra (strings only) musicians preferred to have some absorbing curtains *behind* the orchestra. With the orchestra surrounding the piano, no curtains were acceptable – always the musicians playing into the curtains objected. The result is clear: musicians accept (or prefer) absorption behind the orchestra; they prefer to minimize absorption in front of them as this diminishes their feedback and the room response.

The second test was with different orchestra sizes. For the largest orchestra size (about 40 musicians), the best result was found when moving the musicians as far away from the walls as possible and adding some acoustic curtains at the back of the orchestra, behind the musicians and especially close to the loudest instruments. But for smaller ensemble sizes, the on-stage communication was found to be difficult. This is quite logical – but somewhat contrary to what happens on a stage of fixed size: the bigger the orchestra, the less help and support they need. But the smaller the orchestra, the more they would need help from the room, yet they are located further away from the boundary surfaces of the stage. Finally, best results were obtained by placing reflecting panels behind the strings (left and right side of stage), in between the musicians and the side walls of the room. The effect was especially strong for the double basses, placing reflectors behind double basses significantly increased both definition and bass sound in general. For the test, beer-garden tables were used, which means that the panels were vertically inclined, leaning back, see image hereafter. A comparison was done between the situation with the tables leaning back and the tables being upright, perfectly vertical. The preference both from musicians and listeners was for the tables “leaning back”. Interestingly both musicians and listeners used the same word for their judgment: that the sound is “more open” when the tables are leaning back. “Openness” (identified by Lokki¹² as a perceptual factor) or “space around the sound sources” or the sound being “airy” are terms quite regularly used in the recording and HiFi world, but to our knowledge not regularly used in the acoustic literature. The term was not used in the Ircam questionnaire either – the author now finds this term extremely relevant when listening to and evaluating rooms, but it is clearly non-trivial to link this term to a measurable acoustic criterion.



Final setting of the rehearsal room during acoustic test with the Freiburger Barockorchester. Risers were preferred for woodwinds and brass even in the rehearsal condition. Note the vertically inclined beer-garden tables close to the strings and note the absorption behind the orchestra. No absorption was acceptable in front of the orchestra.

3 CONCLUSION AND OUTLOOK

The case studies discussed in this paper have clearly shown that standard acoustic parameters, especially those included in ISO 3382, are not sufficient to grasp the finer details of the sound field and identify all objectionable defects. When working on high-quality performing arts spaces and when optimizing the acoustic result for audiences and musicians, additional aspects not properly described by readily available acoustic criteria need to be considered. Can suggestions be given as to what additional criteria need to be investigated or defined? Or do we need to look for totally new parameters, outside of the scope of acoustic criteria as currently defined?

The concept of stream segregation into one stream linked to source presence and a separate stream linked to room presence is found to be extremely useful. Source presence and room presence are initially defined as the loudness of the early response and the loudness of the late response of the room. A first generalization and improvement of the measures could and should be to measure all acoustic parameters (loudness, but equally frequency balance as well as spatial aspects) separately for the early and late parts of the impulse response. For example, our listening experiences indicate that bass response should correlate much better with the early part of the room response rather than the late room response. Furthermore, the case studies confirm that laterality of room presence (late lateral G, as identified by Bradley²⁷) is more important subjectively than laterality of source presence (there are cases where the latter can be too much) – while in the literature (and for computer simulation programs) values for LEF and IACC are almost exclusively reported for the early room response.

Further research should concentrate on identifying exactly which reflections are integrated into source presence, depending on direction of arrival, phase coherence relationships as well as strength and number of individual reflections. It should be clear that the standard concept of a “transition time” set at 80ms (or 50ms for speech) is certainly not a sufficient parameter for measuring the magnitude of source presence. The same holds for the late response: which reflections (or which type of reflections, depending on time and direction or arrival, strength and phase relationships) are integrated into room presence? And, are all contributions to source presence or room presence equal in their effects? For example, we know that the same amount of late energy, spread over a longer time (longer reverberation time, same late energy) has less detrimental effects on clarity and speech intelligibility. Is the same true the other way around, that different parts of source presence have different effects on the perception of room presence? In any case, it should be clear that there is feedback between the different streams: room presence will affect the perception of source presence, and vice versa.

The case studies discussed in this paper indicate that it is preferred for *room presence* to be spatially separate from *source presence*, so as to decrease the interference between source presence and room presence. The same may well be true temporally: that a clear temporal separation between source presence and room presence is preferred.

In the design of new spaces, a fine balance must be struck between the strength of the source presence and the remaining energy for the development of room presence and reverberation. This is discussed in more detail in a companion paper that is part of the ISRA conference, by Jurkiewicz et al.³⁴ On the other hand, sufficient source presence by strong early reflections is required in concert halls in order to support long reverberation times of 2s or more and their benefits.

Working with orchestras and orchestra musicians reveals further interesting aspects. First of all, the question of orchestral balance is extremely important in real concert halls. Orchestra balance should be considered as an independent perceptual factor and further research into the relationships between orchestral balance and room acoustic criteria would be highly welcome.

The criterion ST1 criterion needs to be re-evaluated and improved. As a minimum, ST1 should be measured for several locations on stage and the variation of ST1 is at least as critical as the mean value. ST1 should ideally be *stronger* for string positions and *less strong* for brass and percussion positions – which is often difficult to achieve and actually contrary to standard acoustic design beliefs. Acoustic absorption needs to be placed at the rear of concert stages, otherwise brass instruments cannot hear strings, and for woodwinds the sound energy of the brass (plus rear wall reflection) will severely mask the string sound.

For orchestra musicians, very objective needs can be identified, and the needs can be linked to the physicality of the space. On stage, the concept of competing reflections vs. compensating reflections as introduced by Dammerud²⁰ is very helpful, and the problem is often one of “too much” rather than one of “not enough”. In addition, musicians need an audible response from the hall, allowing them to identify the rear wall and be reassured that their sound fills the hall to the last row. Musicians equally need to hear the reverberation of the hall on stage, so that they can judge tonal and orchestral balance as heard by the audience.

For audience members, are there similar “objective needs” or objective reasons for subjective preference? There are several indications that this is indeed the case, and once again this can be linked to the physicality of the space and the concert experience: first of all, we want to hear the sources, so hear and understand the message and have a physical connection to the sources (and players). Secondly, we want to get information about our surrounding, so the room we are in. Stream segregation explains this, and case studies indicate acoustic conditions that facilitate stream segregation are subjectively preferred. Talking about physicality, or physical representation of space, as audience members we “listen” to areas of rooms: which parts of the room are more or less “active” acoustically? Something that is actually quite difficult to measure with acoustic criteria. Microphones are omnidirectional or identify direction of incidence of sound, where the human hearing seems to identify areas of acoustic activity and/or compare real acoustic response with expectations. Another interesting area for further research therefore seems to be the question of “locally excessive sound levels”, whether this is on stage (for musicians), around the stage (perceived from the audience area) or in other parts of a room. How do we identify and measure this phenomenon: do we need to place microphones even in areas where there are no listeners? And how do we solve problems of locally excessive sound levels? Diffusion is not necessarily a solution to a problem of locally excessive sound levels, contrary to what one may think. Acoustic diffusion, especially when acting according to Lambert’s law, will have a tendency to keep sound close to the stage, in fact increasing the loudness difference between receivers close to the stage and receivers far away from the stage. While diffusion is helpful in avoiding unwanted reflections that can be perceived as echoes, the above case studies have equally shown that diffusion suppresses useful information at the same time as suppressing unwanted defects. Furthermore, diffusion will diminish any “signature” of a room and therefore reduce the room’s personality. One of the most fascinating experiences in a room with good acoustics is when, during an orchestral *crescendo*, the room gradually wakes up, revealing one part of the volume after another. For this to happen, the different parts of the room need to be acoustically defined and discernible. It is the author’s belief that diffusion should be used with caution, ideally just enough to suppress unwanted defects.

Finally, an additional thought on “stream segregation”: is there a link between room acoustic stream segregation (between the source stream and the room stream) and stream segregation as used in the auditory world: the capacity to separate individual orchestral instruments? Room acoustic quality can influence stream segregation in that it makes it more or less easy to focus on individual instruments – and is the number of individual instruments one can identify, or focus on, a part of room acoustic quality?

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