Investigations of Musicians' Room Acoustic Conditions in Concert Halls. Part I: Methods and Laboratory Experiments

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Investigations of Musicians' Room Acoustic Conditions in Concert Halls.
I: Methods and Laboratory Experiments

Summary

This paper is the first of two dealing with the relationships between the subjective room acoustic needs of performers of classical music and the objective properties of the sound field on orchestra platforms. In the present paper a set of a priori subjective parameters are listed, which have been derived from extensive interviews with musicians from the classical music field. After a discussion of advantages and limitations of sound field simulations in the laboratory versus field experiments in real halls, a number of laboratory experiments are reviewed, in which especially the SUPPORT and ease of ensemble aspects are investigated. (Results from field experiments are dealt with in the second paper [1].) It is found, that SUPPORT is related to the amount of reflected energy relative to the energy emitted, and a parameter ST ("Support") is defined for measurement of this quality. However, the pronounced masking effect of the direct sound implies that in some halls the level of early reflections is below audibility. Concerning ensemble it is found that an efficient transmission of direct sound and of early reflections is important for the possibility of two players to hear each other. This efficiency, with respect to level as well as speed, can be measured by the parameter EEL ("Early Ensemble Level"). A certain amount of reverberation is found to be favourable from a solo sound quality viewpoint, but may reduce the ease of ensemble playing.

Untersuchungen der raumakustischen Bedingungen für Musiker in Konzertsälen.
I: Methoden und Laboratoriumsexperimente

Zusammenfassung

Diese Arbeit ist die erste von zweien, die sich mit den Beziehungen zwischen den subjektiven raumakustischen Bedürfnissen der Künstler bei klassischer Musik und den objektiven Schallfeldeigenschaften auf Orchesterpodien beschäftigen. In der vorliegenden Arbeit wird ein Satz von subjektiven a priori-Parametern aufgezählt, die von ausführlichen Interviews mit Musikern aus dem Bereich der klassischen Musik abgeleitet wurden. Nach einer Diskussion der Vorteile und Beschränkungen von Schallfeldsimulationen im Laboratorium im Vergleich zu Experimenten in realen Sälen, wird über einige Laboratoriumsversuche berichtet, in denen speziell die „Unterstützung" (SUPPORT) und die Leichtigkeit des Zusammenspiels untersucht werden. (Ergebnisse von Experimenten vor Ort werden in der zweiten Arbeit [1] behandelt.) Es stellt sich heraus, daß die „Unterstützung" mit der reflektierten Energie, bezogen auf die ausgestrahlte Energie, zusammenhängt, und es wird ein Parameter ST („Support") für die Messung dieser Eigenschaft definiert. Allerdings bedingt die ausgeprägte Verdeckungswirkung des Direktschalls, daß in manchen Sälen der Pegel der frühen Reflexionen unter der Hörbarkeitsschwelle liegt. Hinsichtlich des Zusammenspiels stellte sich heraus, daß eine wirksame Übertragung des Direktschalls und der frühen Reflexionen für das gegenseitige Hören zweier Spieler wichtig ist. Die Effektivität dieser Übertragung sowohl hinsichtlich des Pegels als auch der Schnelligkeit kann durch den Parameter EEL („Early Ensemble Level") gemessen werden. Es zeigt sich, daß ein bestimmter Anteil von Nachhall für die Qualität des Solospiels günstig ist, aber der Leichtigkeit des Zusammenspiels abträglich sein kann.

Recherches sur les conditions d'environnement acoustique des musiciens dans leurs salles de concert.
I: méthodes d'études et expériences de laboratoire

Sommaire

On traite, en deux articles, du problème des relations entre l'ambiance acoustique subjective, dont ont besoin les musiciens d'un orchestre exécutant une œuvre de musique classique, et les propriétés objectives du champ acoustique qui règne au niveau de la plate-forme d'orchestre. Dans ce premier article, on a commencé par établir une liste de paramètres subjectifs, sélectionnés a priori à partir d'une série d'entretients avec des musiciens spécialistes de musique classique. Puis on discute des avantages et des inconvénients des essais de simulation du champ acoustique au laboratoire comparativement aux expériences en salles réelles, qui seront examinées en détail dans le second article. Ensuite on passe en revue une série d'expériences en laboratoire où ont été étudiés avec un soin spécial les deux aspects suivants du problème: le SOUTIEN et l'aisance du jeu d'ensemble. On a trouvé que l'aspect «soutien» est lié à la proportion d'énergie réfléchie par rapport à l'énergie acoustique totale émise. On a donc défini un paramètre ST («support» en anglais) pour mesurer cette qualité. Cependant le son direct exerce un important effet de masquage qui implique le fait que dans certaines salles le niveau des réflexions précoces

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pourra tomber en dessous du seuil d'audibilité. En ce qui concerne le jeu d'ensemble, il faudra assurer une transmission efficace du son direct et du son précocement réfléchi afin que deux exécutants puissent s'entendre réciproquement. Une telle efficacité, en niveau comme en instantanéité, pourra se mesurer au moyen du paramètre EEL («Early Ensemble Level»). On remarque aussi qu'un certain montant de réverbération favorisera la qualité acoustique du jeu en solo mais pourra diminuer la facilité à jouer avec ensemble.

1. Introduction

The room acoustic properties of orchestra platforms comprise a very important element of the working conditions of musicians. The room can be regarded as an extension of their instruments, through which they perceive the sound and quality of their own and co-players' performance. Musicians adjust level, tempo, phrasing, timbre and intonation – i.e. their means of musical expression – according to what they hear. Therefore the acoustics on the platform have a great impact on their possibility of passing on the musical message to an audience (attenders of the performance or home listeners) as well as on their inspiration and satisfaction as performers. To this it should be added that musicians quite often complain about the acoustic conditions, – even in halls which are liked by the audience.

Despite these facts major research efforts in this field were not started until about ten years ago. The first results from subjective experiments on musicians' room acoustic conditions were published in 1978 [2, 3]. By then, the most important aspects of listeners' room acoustic perception had been quite well described and made measurable by objective parameters, which are now widely agreed upon.

The success of the previous research on listener conditions in the sixties and seventies (highlighted by major efforts from Göttingen [4] and Berlin [5]) was to a great extent due to the development and use of advanced experimental techniques: electroacoustic simulation or dummy head recordings for presentation of sound fields, and multidimensional statistical methods for analysis of responses. Consequently it was natural to start the investigations of performers' conditions by using the same experimental techniques and the same way of structuring the questions to be answered:

1) Which subjective aspects are present in musicians' judgments on room acoustic conditions?
2) Which properties of the impulse response (objective parameters) determine each of these subjective aspects?
3) Which elements of the design govern the behaviour of each of the objective parameters – and in turn the subjective parameters?

Answers to the second question should – hopefully – lead to the definition of measurable, objective parameters correlating with subjective judgments.

Answers to the third question should lead to guidelines for the design of spaces with proper acoustic conditions for musicians. Alternatively, proposed designs can be evaluated and developed after calculation/measurement of the objective parameters in computer/scale models.

In 1979 research along this line was started at the Acoustics Laboratory at the Technical University of Denmark. What follows is a review of our experiences since then concerning out attempts to answer the first two of the three questions above.

2. Subjective aspects

Due to the scarcity of previous work dealing with musicians we found it necessary to start by obtaining an overview of their room acoustic needs, i.e. to establish an a priori vocabulary for all relevant subjective aspects. This was done by carrying out an interview survey among professional musicians [6]. 32 performers of classical music (conductors, pianists, singers, and players of various orchestral instruments) were asked to describe the elements of their room acoustics concern, and to rank the relative importance of these elements in different playing situations. From their answers, the set of candidates for subjective aspects explained below was formed.

In addition to these, musicians will, of course, be sensitive to pure acoustical faults such as background noise and echoes.

In the following, the subjective aspect names have been written in capital letters in order to distinguish them from their potential objective parameter counterparts.

REVERBERANCE is mainly perceived during breaks or shift of tone played, since it sustains the tones just played. It binds adjacent notes together, can blur details in the performance and may give a sense of response from the hall.

SUPPORT is the property which makes the musician feel that he can hear himself and that it is not necessary to force the instrument to develop the tone. It can be felt even during the onset of tones and is therefore believed to be related to properties different from REVERBERANCE.

TIMBRE means the influence of the room on the tone colour of the instrument and on the balance in level in different registers. In ensembles, TIMBRE may also influence the musicians' impression of tonal balance between the various instruments.

DYNAMICS describes the dynamic range obtainable in the room, and the degree to which the room obeys the dynamic intentions of the player.

HEARING EACH OTHER is the property required for a group of musicians to play in ensemble, i.e. with rhythmic precision, in tune, and balanced in level, timbre and expression. In large ensembles it is important to have contact both among members of each group of instruments and between the different groups. The situation is satisfactory only when a delicate balance exists between hearing oneself and hearing others.

TIME DELAY is a consequence of the speed of sound being limited. It can become quite disturbing when orchestra members have to sit far apart. It may cause rhythmic precision and tempo to deteriorate [1].

Judged from the interviewees' statements concerning the relative importance of these aspects in different situations of playing, the first four may be grouped as the "soloist" concern, and the latter two, associated with ease of ensemble, as the "ensemble" concern.

Searching the literature added no further aspects to this list [2]. This list is therefore believed to cover the main factors of musicians' room acoustics concern.

Having defined this a priori subjective vocabulary, the next step is to try to find out which properties of the sound field govern the perceived changes of each aspect. In our attempts in this direction we started by focussing on SUPPORT and on the two ensemble parameters, which are aspects not already known from research on listener conditions.

3. Experimental approaches

3.1. Real acoustic environments versus simulations

Searching for the relationships between the subjective aspects and the sound field properties involves – apart from sensible conceptual models – a great deal of experimental effort.

The primary requirement for carrying out relevant experiments is that room acoustic sound fields – of proper realism and with the possibility of changing variables of potential importance – can be presented to musicians while playing. For this purpose, two principally different methods have been used until now. Barron [3], Marshall [8], and Harkness [9] have used natural acoustic environments, in which they made structural modifications, while Marshall et al. [2], Marshall and Meyer [10], Krokstad et al. [11], Berntson [12], Nakayama [13], and Naylor [7] have created synthetic sound fields by means of electroacoustic arrangements in anechoic rooms. A combination of these methods have been employed by Nakamura [14], who made electroacoustic modifications in a rehearsal hall.

In simulated sound fields the variables can be changed with great precision within wide ranges, but the sound quality or fidelity is limited. One unambiguous advantage of simulation is the possibility of very rapid changes between different situations, which makes comparison judgements much easier and more reliable in view of the short human acoustic memory.

When structural modifications are made in a real room, or a number of different rooms are employed, no fidelity problem exists, but the number and range of variations are nearly always limited. Besides, the acoustic judgements in a real room may be disturbed by visual impressions e.g. indication of the variable settings, whereas the simulation arrangement is visually neutral, but unnatural.

As can be seen, the two methods each possess important advantages as well as serious limitations, which, however, complement each other well. Thus we have found it essential to apply both methods in order to test the general validity of the results, although in cases where the results of different methods contradict, one must be prepared to be left with more questions than answers. In the second paper [1], this problem will be seen to be an important issue when discussing the results of the field experiments.

3.2. Problems associated with the interpretation of the results

It is always difficult to interpret results of experiments concerning acoustic "quality" because of the ambiguity in the vocabulary used to describe the various aspects of the acoustic experience. Musicians will often express themselves in much more colourful terms than those used in section 2, and it is not likely that all aspects will be judged separately. Therefore, there is no real guarantee of the aspect(s) of interest to the exper-

[1] According to Naylor [7], another reason why the timing information propagates with a systematic delay within the orchestra is reaction time and a tendency among musicians to play "safely", since an entry too early is more likely to be noticed than one too late.

[2] In previous studies, it is not always clear which subjective aspects the subjects (or the authors) have been concerned about. Possible reasons for this are discussed in section 3.2.

imenter being the basis for the judgement, unless all variables of possible influence are known and can be fully controlled. As described in the following, this will hardly ever be the case.

3.2.1. Inherent risks in simulation experiments

Electroacoustic simulation offers only a simplified description of real room acoustic conditions. In most experiments reported in the literature only a very limited number of early reflections have been simulated, which means that the temporal and spatial distribution of early sound is very poor. According to our experience, this simplification always causes "sound" or timbre to be unnatural, and the degree of unnaturalness often changes with the variable settings [3]. Combined with the above mentioned problem of unveiling the basis for the subjects' responses, this implies that the results produced by simulation experiments should be interpreted very carefully – however high their statistical significance appears. Consequently, it is wrong to believe that the acoustics of an orchestra platform of a given geometry can be represented by delays and loudspeakers adjusted to simulate the four or five strongest first order reflections (which represent less than half of the total, reflected early energy [15, section 2]. Nevertheless, the need for design guidelines among architects and consultants has apparently been so urgent that even the earliest results on preferred delays of single reflections [2] were soon transformed into recommended distances to reflecting surfaces on orchestra platforms, e.g. [16] and [17]. If this was a feasible approach we would claim to have proved that symphony orchestras prefer an overhead reflector placed no more than 3 meters above floor level [15, section 6.6]. The particular delay of one reflection may have a crucial influence in a simulated sound field with only few other components present, but it is very unlikely that it will have the same importance under real conditions with more reflections (and perhaps sources) present. Besides, the "preferred delay" is known to be a function of the reflection level [13] and [15, section 5], which may have been chosen arbitrarily by the experimenter.

In cases where only a few early reflections are available, it is probably a more relevant approach to distribute these within one or a few time intervals of a certain length (e.g. corresponding to the supposed time constant in hearing: 50 ··· 100 ms) during the start of the impulse response, and then relate the results to preferable levels of energy within these intervals. Therefore our approach has been to look for energy-related objective parameters to describe the subjective changes. The relationship between these parameters and the platform design will clearly be less obvious than in the case of the mere delay preferences; but it is just a matter of further investigation to find them. Of course, this approach in simulation experiments is only valid if unwanted subjective effects caused by the arrangement, such as colouration and echoes, do not disturb the judgement of the variables tested; but this is less likely to occur with a number of "naturally" distributed early reflections than with a single reflection, which is moved along the time axis. In any case, the fidelity problem also implies that simulations are better suited to the investigation of functional aspects than of aspects related to sound quality.

3.2.2. Inherent risks of experiments in real halls

When making experiments in real halls, the problem of interpreting the results is related to the fact that normally not only one, but many variables are changed, when structural modifications are added or when one moves to the next hall. In other words, it is not possible to control each objective variable separately between the presentation of two stimuli. Thus it may be nearly impossible in a field experiment to sort out which subjective aspects have been governing the musicians' judgement as well as to identify the objective variations that are responsible for the perceived changes. Even the use of multidimensional statistical methods can only improve this situation to a limited degree.

4. Laboratory experiments

Further details of most of the experiments described in this section and other ways of analyzing their results can be found in [15].

4.1. Soloist experiments

Among the soloist aspects we wanted primarily to investigate the Support concept as mentioned previously. As early as 1931 Knudsen [18] described this quality and related it to early reflections from surfaces close to the platform. However, it is an open question as to whether these early reflections are audible or are masked by the direct sound which has a dominant level at the musician's own ears.

[3] There are at least two reasons why fidelity is such a big problem in simulation experiments with musicians: 1) Normally musicians are very skilled judges of sound quality, and 2) the subjects always have the original to compare with, namely the direct sound from the instrument.

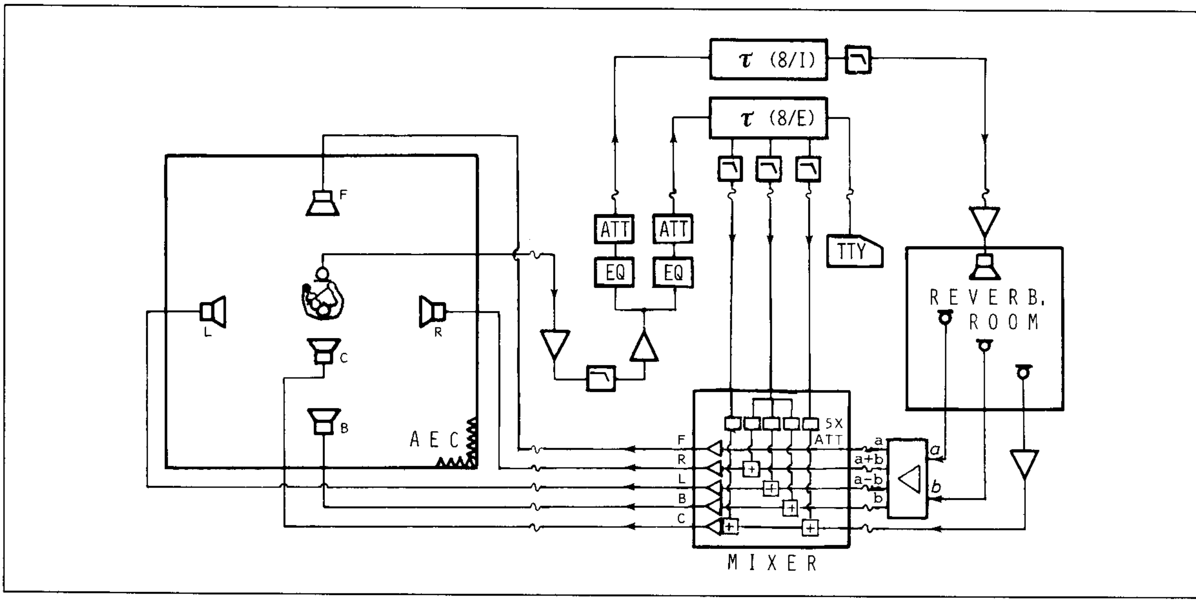


Fig. 1. Diagram of simulation arrangement for experiments with soloists.

4.1.1. Thresholds of perception of early reflections

Various authors have expressed opinions about the audibility of early reflections of the sound from one's own instruments. Harkness [19] and Benade [20] believe in their usefulness, whereas Marshall [21] does not. Krokstad [11] and Nakayama [13] have performed experiments indicating that early reflections have a positive effect; but it is not clear whether the levels used were comparable with those occurring in real halls. Therefore, a laboratory experiment was carried out to determine the threshold of audibility for a single early reflection of the sound from a musician's own instrument. This threshold was then compared to early reflection levels measured in real halls to give some idea on the importance of early reflections for the room acoustic impression of a soloist.

The threshold can be expected to depend on many factors such as delay, spectrum and the direction of incidence of the reflection, the directivity of the instrument, the motif played and the presence of other sounds. This experiment was restricted to deal with the threshold at six delays, for one direction of incidence: from above, and for three different instruments. The motif used was very brief – consisting of only one deep, long note followed by two short higher notes. The subjects were placed in the arrangement shown in Fig. 1, in which the ceiling reflection was emitted through a loudspeaker three meters above the subject's head, while diffuse reverberant sound delayed 110 ms and with a moderate level (– 18 dB relative to the direct sound level at 1 m distance) was emitted through all five loudspeakers. At each delay the threshold of audibility was determined as the level corresponding to a 50% probability of detection after Two Alternative Forced Choice tests at different reflection levels.

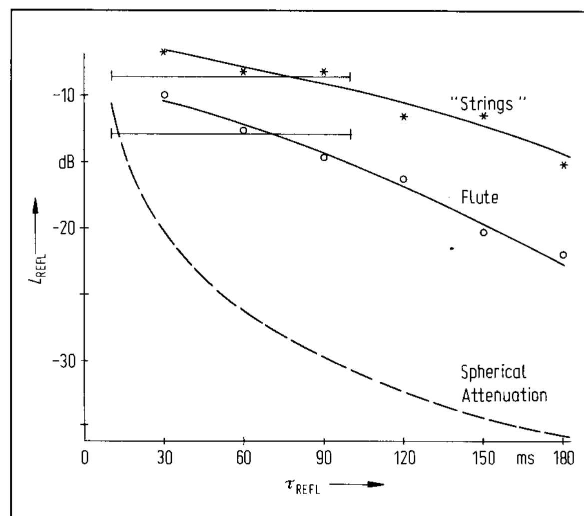


Fig. 2. Thresholds of perception of the early reflection energy of "own sound" for strings and flute players. Solid, soft curves: threshold for perception of a single reflection as a function of delay. Solid vertical lines: thresholds for a group of six reflections between 20 and 100 ms (after [22]). Dashed curve: level of a single, spherically attenuated reflection from a plane, hard surface. The ordinate is level in dB relative to the level of the direct sound 1 m from the source.

In Fig. 2 the averaged results obtained for three violin players and three cello players (not being significantly different and therefore combined into one curve denoted "strings") and for three flute players are shown. It appears that it is easier for flute players than for string players to perceive the influence of the reflection, and – as expected – for all players it becomes easier as the delay of the reflection is increased.

More recently, this experiment was repeated for a "lump" of early reflections within the 20 to 100 ms interval instead of the single reflection [22]. In this new experiment, the early reflection energy before 100 ms was formed by one group of six reflections, whose levels were varied together. The delays of the six reflections were fixed and evenly (but not equidistantly) spread over the 80 ms interval, and they were emitted from different directions. The thresholds for strings and flute players respectively are shown as the horizontal lines in Fig. 2 and they are seen to be very close to the thresholds for the single reflections. Moreover, they were found to vary less than 1 dB as the level of the later sound was changed between −17 and −21 dB relative to the direct sound.

The dotted curve in Fig. 2 represents the relationship between level and delay for a single reflection from a large, plane, reflecting surface. As can be seen, such a reflection alone will not be audible, and the question now arises, whether enough early reflections are present in real halls for the energy in this part of the impulse response to have any influence at all. This point can be illuminated to some extent by Fig. 3, in which the total level of early reflection energy within the interval 20 to 100 ms (equal to ST1 as defined in section 6) for two positions on each of three orchestra platforms has been compared to the lowest values within the same time interval of the two threshold curves from Fig. 2. In cases where the total early reflection energy does not reach this – the most opimistic – threshold for a single reflection, there is

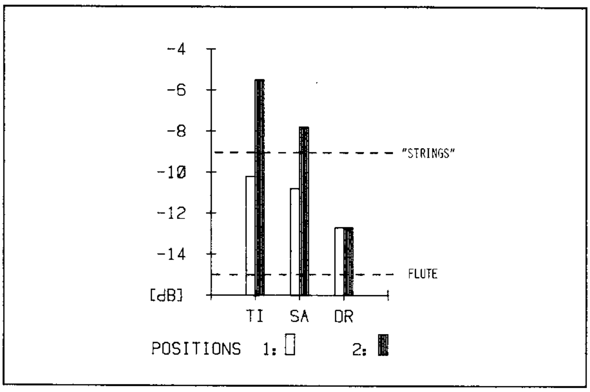


Fig. 3. Comparison of single reflection thresholds at 100 ms from Fig. 2 (dashed lines) and levels of early reflection energy (vertical bars) between 20 and 100 ms as measured with an omnidirectional source on three orchestra platforms. The position "1" was placed about 2 m from the front edge of the platform, whereas "2" was placed about two thirds of the way towards the rear wall. The dB scale is calibrated as in Fig. 2.

hardly any reason to believe in this energy having any audible effect in itself, although it will represent about half of the total reflected energy.

It is worth mentioning that among performers the "TI"-hall (Tivoli Concert Hall, Copenhagen) has the reputation of providing SUPPORT excellently, while string players (especially) miss this quality in "DR" (Danish Radio Studio One, Copenhagen). Both halls are further described in [23], [24] and [25], and are also included in the field experiments in [1].

In large orchestras it is most likely that, regardless of the ST1 value, many of the musicians do not experience Support at all because of masking by sounds from others. This may be true for string players in particular, who – in addition to having a high threshold for the perception of reflections of their own sound – have weak instruments, and many around them playing the same part. (On the other hand, the impression of the sound from the rest of the group may be a useful substitute for Support in some cases.)

4.1.2. The usefulness of early reflections

Further experiments were carried out, which confirmed that high, realistic levels of early reflection energy of sound from a musician's own instrument are judged favourably and therefore must be audible. Instead of single musicians, flute-violin-cello trios were now placed in the arrangement and played together. In paired comparison tests, the subjects judged different sound fields with respect to preference regarding the sound of their own instrument. (HEARING EACH OTHER judgements were also asked for; but these results were weaker and merely vague replicates of the soloistic judgements.)

In one experiment, four sound fields were judged, which represented variations in the level of reverberation (after 100 ms) as well as realistic variations of early reflection energy represented by three reflections between 20 and 75 ms. The motif played was Joh. Seb. Bach Trio Sonata BWV 1039, second movement, bars 1–33. The sound field variables and corresponding preference results for twelve subjects in terms of scaling along dimension 1 in the "MDPREF" solution appear in Fig. 4. The two sound fields Nos. 1 and 3 with high – and apparently audible – early reflection levels are clearly preferred to Nos. 2 and 4, with low levels. Although it has not been proved explicitly, the hypothesis still prevails that the associated change in subjective impression was related to SUPPORT.

In many of the laboratory experiments, we found that the MDPREF analysis was capable of separating the influence of "unwanted" subjective aspects on the judgements from the aspects of interest. The scalings of the stimuli along dimension 1, the consensus dimen-

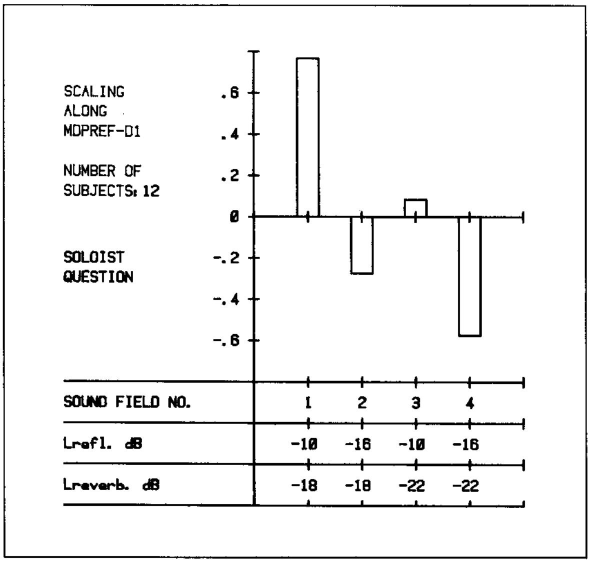


Fig. 4. Subjective preference scores from a trio experiment for four sound fields with varying levels of early reflection and reverberation energy. The subjects were supposed to base their judgements on the quality of the sound from their own instrument.

sion, often gave a much clearer picture of the source of variation than did mere subject averaging. This is probably because variance associated with aspects on which the subjects do not agree (assumed to be the unwanted ones in experiments on functionalistic aspects) is often used to form the higher dimensions. For those sceptical of this approach it can be mentioned, that in the experiment here, the differences between the stimuli was significant at a 1% level according to a traditional analysis of variance, and the sound field variables accounted for 25% of the total variance in the responses. A description of MDPREF and similar methods may be found in [30].

Fig. 4 also shows that the high reverberation level is preferred to the low one. This result is in line with the common notion that musicians are fond of reverberation, but it may also be interpreted as energy beyond 100 ms contributing to SUPPORT. It is also possible that SUPPORT is simply related to the total energy of reflected sound, of which at least 90% has arrived within the first 200 ··· 300 ms. The correlation between the subjective scores in Fig. 4 and the total level of reflected sound (early reflections + reverberation) is also as high as 0.92; but with only four stimuli, this experiment is too crude to render that result statistically significant. However, the field results reported in [1, section 3.1] point in the same direction.

It should be mentioned, that the difference in level of the total sound field (direct + reflected sound) between a situation with the level of reflected sound being − 10 dB below the direct, compared to a situation with no reflected sound is less than 0.5 dB. Therefore it is difficult to believe that SUPPORT is related simply to the total level.

4.2 Ensemble experiments

Contrary to the doubts about the usefulness of early reflections for the impression of the sound of one's own instrument, everybody seems to agree on their importance for the musicians' ability of HEARING EACH OTHER, e.g. [2, 3, 7, 8, 10, 20]. However, it is important not to regard the acoustic communication within the orchestra as being a question of early reflections alone. This can be illustrated by the two experiments described in the following. The availability of two separate anechoic rooms enabled us to simulate long distances between two players in a symphony orchestra. The arrangement, in which direct sound, a ceiling reflection, and reverberation could be generated is illustrated in Fig. 5. The mixing of the signals from the two musicians resulted in a considerable reduction of the equipment needed. The mixing implied that two early reflections of each player's own sound were also present, and varied along with the direct sound and ceiling reflection from the coplayer. However, for the relevant range of variation of these, the two reflections of their own sound should be inaudible according to Fig. 2, and this was also found to be the case in the actual arrangement[4]. Consequently, apart from a natural, common variation of reverberation, there was no risk of the judgements being disturbed by irrelevant solo aspects.

In both experiments, five violin/cello and five violin/flute duos participated. The subjects made pair comparison judgements of preference with respect to ease of ensemble after playing their respective parts in Mozart's Symphony no. 40, third movement, bars 1–14.

4.2.1. Sensitivity to delay of direct sound

The TIME DELAY aspect is naturally assumed to be related to the finite speed of sound propagation. The sensitivity to this delay was investigated in an experiment in which the delay of the direct sound was varied between 7 and 80 ms relative to the time of emission, which is equivalent to a range of mutual distance from 2 to 27 metres between the two players. In order to focus on the delay effect, the level of the direct sound was held constant. The fixed level corresponded to an 8 m distance between two musicians sitting in an orchestra, and included some frequency dependant at-

[4] Naylor [7] has also reported on the lack of influence of early reflection variation on the perception of sound from one's own instrument in an ensemble situation.

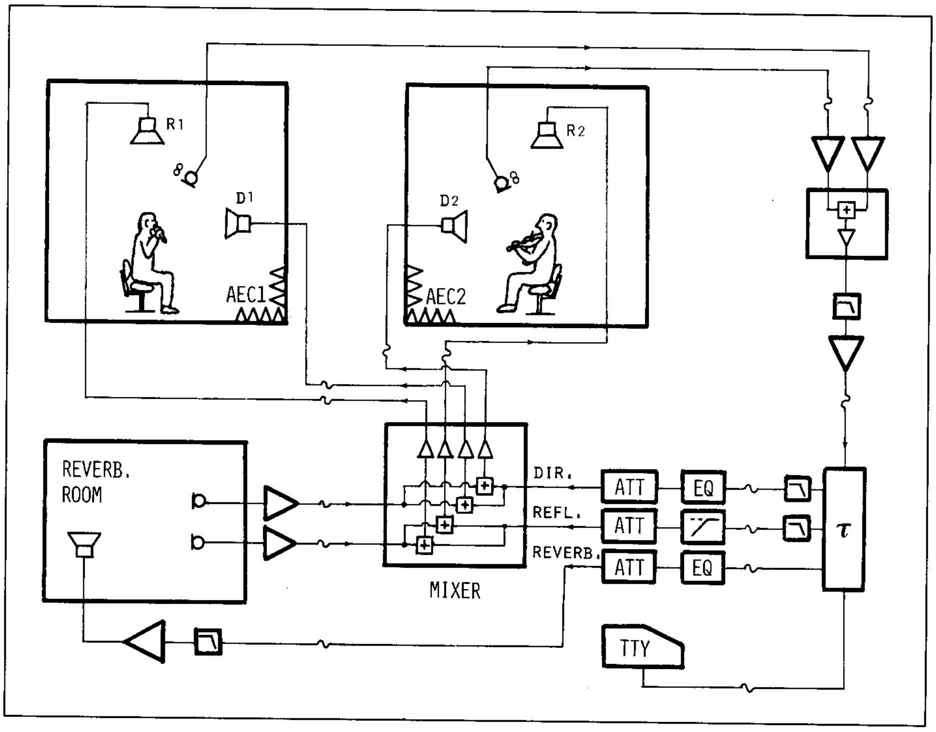


Fig. 5. Diagram of arrangement for simulation of ensemble conditions in a large orchestras.

tenuation representing others sitting in between [11]. In all presentations, delay and level of the reverberation were fixed at 75 ms after the direct sound emission, and − 20 dB relative to the direct sound level 1 metre from the source. The ceiling reflection was turned off.

The results in terms of scaling along the first dimension in the MDPREF solution appear as shown in Fig. 6 [5]. Assuming no negative effect of the 7 ms delay, the limit beyond which the delay has a negative influence is apparently placed at the intersection between the two dotted line segments. This point falls at about 20 ms, corresponding to a distance of 7 metres. Of course this limit may depend on the motif played. However, the Mozart piece played in this experiment was not particularly rhythmically demanding, and a critical distance of 7 m is still well below the dimensions of a symphony orchestra. Brass and percussion players sitting far back in the orchestra often state that they have to play ahead of the conductors baton to avoid his accusing them of being too late. The results in Fig. 6 verify that this phenomenon is not pure delusion. They are also in line with recent experiments by Naylor [26], who has found that in a train of noise pulses, one is – under the most favourable conditions – able to detect displacements of single pulses as small as 10 ms as deviations from a strict rhythm.

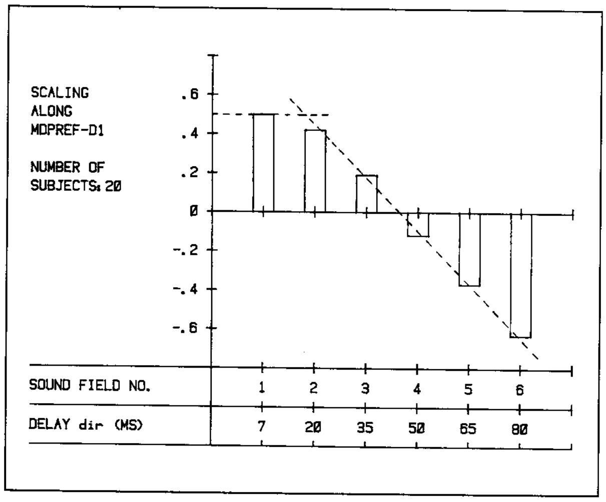
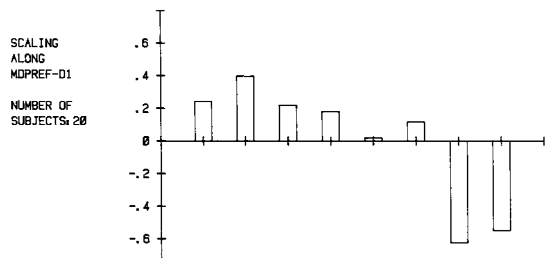


Fig. 6. Subjective scores of preference with respect to ease of ensemble for six sound fields with varying delay of direct sound propagation.

4.2.2. The importance of early sound components

The question of which components of the impulse response convey the information necessary for good ensemble playing was illuminated by another experiment, in which eight sound fields were created by varying the levels of direct sound, ceiling reflection,

[5] According to the analysis of variance, the sound field variation accounted for 30% of the variance in the subjective responses, with the differences between stimuli being significant at a 0.01% level.



SOUND FIELD NO.	1	2	3	4	5	6	7	8
Ldir-HF (dB)	-19	-19	-19	-19	-26	-26	-26	-26
Lrefl (dB)	-20	-20	-26	-26	-20	-20	-26	-26
Lreverb (dB)	-20	-24	-20	-24	-20	-24	-20	-24

Fig. 7. Subjective scores of preference with respect to ease of ensemble for eight sound fields with varying levels of direct sound, one early reflection and reverberation. The levels of each component are listed below the scores relative to the direct sound level 1 m from the source.

and reverberation in two steps each. The delay of the three components relative to the time of emission were 23, 43, and 83 ms, respectively, and the levels relative to the direct sound at one metre distance from the source were as listed in Fig. 7, which also show the subjective MDPREF-D1 scalings obtained for the eight situations [6].

When these scalings were correlated with the objective variables, it turned out that the key factor was the joint level of direct sound and early reflections relative to the level emitted (which is equivalent to "EEL" as defined later, in section 6). The relationship is significant at a 1% level. The two sound fields with extremely low scores are those with low levels of both direct sound and early reflection. Even with these two excluded from the analysis, the correlation is still significant at a 5% level. In other words, the vital factor is seen to be the efficiency of early energy transmission between the players.

A secondary tendency is also worth mentioning. In Fig. 7 the four sound fields with low reverberation levels are generally preferred to those with high levels. This may be due to reverberation having a masking influence. The effect is not statistically significant; but others [7, 11] have reported the same tendency [7].

[6] In this experiment, the sound field variation accounted for 44% of the variance in the subjective responses and, according to the analysis of variance, the differences between stimuli were significant at a 0.01% level.

[7] Naylor [7] also mentions one exception: in cases where very little early sound from the other player is present, some reverberant sound may be better than nothing.

5. Summary of results

Regarding the relationship between the subjective impressions and the properties of the impulse responses, the laboratory experiments described above indicated the following:

"Soloist" experiments:

- For players of certain instruments early reflection energy (between 20 and 100 ms) of their own sound may be completely masked in some halls, the threshold of perception being 10 to 20 dB higher than the level of a single reflection from a plane hard surface. Nevertheless,
- audible levels of early reflections are preferred, and the hypothesis is that the subjective effect can be described as "SUPPORT". It is not clear whether Support is only determined by the amount of early reflection energy or whether the energy of later components also contribute, but
- a certain amount of reverberation is favoured.

"Ensemble" experiments:

- The delay of the first component of sound from the coplayer(s), relative to the time of emission, should be small. An unmasked direct sound is therefore desirable. If masked, it cannot be fully compensated by strong but further delayed early reflections.
- The level of received early energy (direct sound as well as early reflections) relative to the energy emitted, is important for musicians to be able to hear each other, and
- it is likely that reverberation has a negative influence on this possibility.

6. Suggestions for objective parameters

Based on these findings, two objective room acoustic parameters, Support (ST) and Early Ensemble Level (EEL), have been defined as illustrated in Fig. 8. Both parameters are related to the calculation of fractions of energy within certain time intervals in impulse responses recorded on the orchestra platform. Omnidirectional transducers should be used for the measurements.

ST describes the ratio between the energy of the early reflections and the energy of the direct sound. This ratio is measured 1 m from the source, which is comparable to the distance from the performer's ear to his own instrument. Thus ST is intended as a measure of how much the early reflections assist the performer's own efforts – the direct sound – as heard by himself. High ST values should correspond to a strong feeling of Support. Depending on the instrument

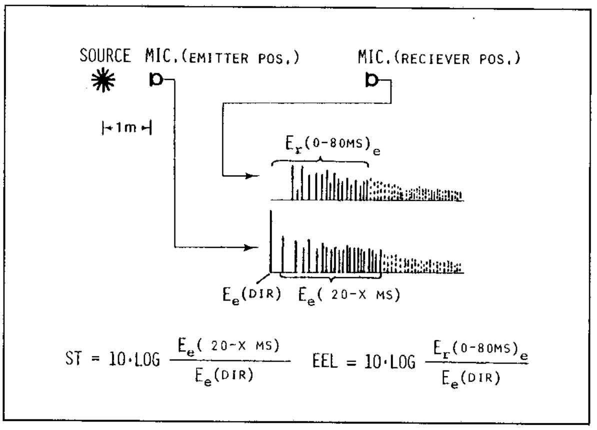


Fig. 8. The definitions of the objective parameters "Support" (ST) and "Early Ensemble Level" (EEL). Concerning the value of "X", see text.

played, an ST threshold probably exists, below which the Support quality is absent (or at least not provided by the early energy).

Due to the uncertainty concerning the contribution of later reflections, both 100 ms and 200 ms may be used as upper integration limits in the Support definition ("X" in the definition in Fig. 8). These two limits are indicated by the symbols "ST1" and "ST2" respectively in the following.

EEL is defined as the ratio between the received early energy and the energy emitted, the latter being described by the direct sound measured at 1 m distance from the source. Again, a higher EEL value should correspond to a better possibility of Hearing each other.

EEL has been made sensitive to the negative effect of the delay by the integration interval for the early energy in the numerator being counted from the time of emission. Just increasing the delay will thus also result in lower EEL values. It is not unnatural to use the time of emission as the reference, bearing in mind that one important aspect of ensemble playing is the synchronization. In other words, EEL measures the efficiency of the sound transmission within the orchestra, with respect to speed as well as to level.

For measurement of the influence of reverberation, one could at this point suggest any of the reverberance/clarity measures originating from research on audience conditions: Early Decay Time (EDT) [27], Centre Time (TS) [28], or Clarity (C) [29]. Also when measured on orchestra platforms, these parameters are always highly mutually correlated, but they are not correlated with EEL, ST1 or ST2 [25].

7. Conclusions

The laboratory experiments reviewed in this paper have illuminated certain properties of the sound field on orchestra platforms, which influence musicians' impressions of two room acoustic aspects: SUPPORT and ease of HEARING EACH OTHER. Two objective parameters: ST and EEL, have been suggested, which will be sensitive to these sound field properties. In other words, some elements have been provided for answering two of the questions listed in the introduction (section 1). However, because of the inherent limitations associated with simulation experiments discussed in section 3, we have found it essential to test the general validity of these parameters – i.e. the practical importance of the sound field variables which they measure – by carrying out further experiments in real halls. These field experiments and the overall results are described in a following paper [1].

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