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Spatial impression: measurement and perception of concert hall acoustics and reproduced sound

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ABSTRACT

The fields of concert hall acoustics and sound reproduction are traditionally studied separately, with little interaction between them. However, it is apparent that a great deal can be gained from combining the two disciplines, as long as the differences are considered. Firstly, the perceived spatial impression afforded by the two acoustical situations is reviewed, and the similarities and differences are highlighted. Secondly, the optimum method for applying concert hall measurements to sound reproduction is assessed. Finally, the potential success of applying the developments made in measurements of sound reproduction systems to concert hall acoustics is considered.

KEYWORDS : spatial impression, sound reproduction, auditorium acoustics

INTRODUCTION

As noted by Soulodre at a recent conference [1], despite the similarities between auditorium acoustics and sound reproduction, collaboration and interaction between the two fields of research has been rare. On the one hand there are the concert hall acousticians, who are traditionally trained in acoustics and read publications on acoustics and architecture, whilst on the other there are the audio engineers, who are traditionally trained in electroacoustics and electronics and read publications on signal processing and sound reproduction. However, the two fields of research do have common aspects, and by making use of the results of both fields a greater understanding of audio can be gained.

Similarities between auditorium acoustics and reproduced sound

The most direct comparison between auditorium acoustics and sound reproduction can be made when the reproduction system is attempting to recreate the auditory cues of a concert hall in the reproduction room. This may be considered as the recording and reproduction paradigm of ‘you are there’, where the intention of the reproduction is to deceive the auditory senses of the listener in the reproduction room, so that the perception is the same as if he or she was listening to a live musical source in the concert hall. The ultimate aim of this approach may be to fully recreate the physical sound field that would be around the listener in the concert hall. If this is achieved, both the perceived effect and the objective measurements that relate to this will be identical, meaning that the two paradigms are directly comparable. Unfortunately, the most commonly available sound recording and reproduction methods are not yet able to accurately recreate the physical sound field of a concert hall in the listening room, which means that the perception and the physical result may be somewhat different. However, there are similarities, as will be discussed later.

Another link between the fields of auditorium acoustics and sound reproduction can be found in the manner in which subjective experiments that investigate auditorium acoustics are conducted. Due to the difficulty of constructing concert halls with easily variable acoustical properties and the limited range of variations that are possible, the majority of studies into the spatial impression of auditorium acoustics have been conducted using reproduced sound (e.g. [2, 3, 4, 5]). There appears to be sufficient similarity between the two paradigms to allow experimental results gained using one mode to be applied to the other, therefore it is possible that research that is not deliberately intended for this translation may also be used.

Differences between auditorium acoustics and reproduced sound

Despite the similarities between the two fields of research outlined above, there are also a number of fundamental ways in which concert hall acoustics and reproduced sound may differ. A key reason is that the acoustical characteristics of a natural sound source in an acoustical environment, such as a concert hall, are inevitably limited by both the physical attributes of the components (the sound sources and acoustical environment), and the influence of tradition and expectation.

For instance, the acoustical environment can be made from a wide range of materials and be one of a wide range of shapes and sizes. Each of these physical parameters has an effect on the resulting sound field and therefore on the subjective attributes such as loudness, intimacy, clarity, tone, timbre and spatial impression. However, in spite of the apparently limitless options that are available from this range of physical parameters, the reality of the acoustical environment and acoustical propagation mean that only a limited range of reflection patterns are possible, with the properties of the earlier reflections largely dictating the properties of the reverberation. In addition, the traditions and expectations of concert hall design mean that the acoustician has limited scope in the design parameters that will be accepted.

In a similar manner, the sound sources within the acoustical environment could have a potentially unlimited range of physical parameters. However, it is likely that the sound source will be a traditional musical instrument which, whilst there are a large number of varieties, can be classified into a relatively small number of categories in terms of their acoustical properties (e.g. strings, brass, reed-based wind, percussion, etc.).

Contrary to the physical reality of concert hall acoustics, sound reproduction affords much greater flexibility in the sounds that are created, due to the ability to synthesise sound sources and acoustical environments that are not physically possible. Examples of this include sound sources that are based on physical modelling but which resonate in more than three dimensions, sound sources whose properties vary greatly over time, and sound sources that can be spread to sound as if they are emanating from all around the listener. In a similar manner, acoustical environments can be synthesised whose properties are not physically possible, including characteristics that vary over time, early reflection patterns with extreme characteristics and later reverberation that is unrelated to the pattern of the earlier reflections.

The greater flexibility afforded by sound reproduction means that more controlled investigations can be made into the perceived effect of sound and the relationship between perception and objective measurements. However, the best method to apply these results to concert hall acoustics must also be considered. This paper examines the effect that these similarities and differences between the two paradigms have on the perception and measurement of spatial impression[1], and it is discussed how the results of research undertaken in each discipline may be applied to the other.

PERCEPTION OF SPATIAL IMPRESSION IN CONCERT HALL ACOUSTICS AND REPRODUCED SOUND

The final judge of the quality of a concert hall or a sound reproduction system is always a human listener, therefore it is logical to start by considering the perceptual aspects of spatial impression. This includes ascertaining the subjective attributes that make up spatial impression in order to compare concert hall acoustics and sound reproduction and to attempt to define the perceived spatial impression as accurately as possible.

It must be noted that the task of describing the spatial impression of acoustical environments is difficult, as it is a task which is not commonly undertaken [6]. In other words, in natural listening our attention is usually

[1] For the purposes of this paper, the term ‘spatial impression’ is defined as the overall term that refers to the perception of attributes of the audio which can be described using the first three dimensions; those of height, width and distance, including those arising from sound sources and from the acoustical environments in which the sources are located.

focused on the sound sources rather than the acoustical environment. For example, from an evolution standpoint humans are more interested in what type of predator is nearby and where it is, as opposed to whether the surrounding environment is a cave or a forest, as this could be determined more easily through the use of other senses.

There are also other challenges in the perceptual study of the spatial attributes of acoustical environments. Firstly, it is likely that certain other types of attributes (such as variations in timbre) will be more noticeable than spatial attributes. This may cause the variations in spatial impression to be partially obscured, and will make it more difficult for the listeners to accurately identify and describe the variations in spatial impression. This problem can be reduced by selecting or artificially generating sounds that have larger variations in spatial impression; however, this is difficult to undertake for concert hall acoustics due to the limitations of the physical properties of concert halls, as discussed above. Secondly, in order to accurately identify and describe variations between two stimuli with the greatest sensitivity and accuracy, it is generally considered that it is necessary to allow the listener to instantly switch between the stimuli as required [7]. However, this is impractical to achieve when comparing concert halls unless an artificial reproduction is used, and this can introduce its own problems and inaccuracies.

Perception of spatial impression in concert hall acoustics

As previously mentioned, the elicitation of the spatial attributes of sound from listeners is a difficult task, and this task is made more challenging by the unique problems involved in comparing the perceived auditory attributes of one concert hall with those of another. In spite of this, a number of studies have been conducted to elicit the individual subjective attributes that make up the overall auditory perception of a concert hall (such as those summarised in [8]). From these, a large number of attributes has been determined, though in each study only one or two terms may be interpreted as relating to spatial impression. For instance, the research of Barron resulted in seven attributes, of which only one may be interpreted as relating to spatial impression (described by the term ‘envelopment’) [9]. In spite of the small number of spatial impression attributes that have been elicited, spatial impression has been found to be an important factor in determining the perceived quality or preferability of a concert hall [10].

One of the problems that has arisen in the research into spatial impression in concert halls is the lack of a standard vocabulary or set of attributes. Firstly, this has led to the use of a large number of terms, including spatial impression, spaciousness, envelopment, apparent source width, source broadening, listener envelopment, and diffusivity. Secondly, these terms have been used to refer to different perceived attributes by different authors; for example the term envelopment sometimes refers to the *source* being surround by sound, and sometimes refers to the *listener* being surround by sound. This has added confusion to earlier research, which makes it difficult to make comparisons between studies. In addition, it has even caused confusion within experiments, as noted by Barron who wrote that his ‘envelopment’ rating scale was used differently by different listeners [9].

More recently, two main spatial attributes have become commonly used: ‘apparent source width’ (ASW) and ‘listener envelopment’ (LEV). These have been defined by Morimoto as:

ASW – “the width of a sound image fused temporally and spatially with the direct sound image”.

LEV – “the degree of fullness of sound images around the listener, excluding the precedent sound image composing ASW” [11].

It may be interpreted from these definitions that ASW relates to the properties of the perceived source, and LEV relates to the properties of the perceived reverberation. These two spatial attributes now appear to be widely accepted as the two components that make up spatial impression in concert hall acoustics, though it is apparent that detailed research has not been conducted to determine whether any additional attributes can be elicited from listeners.

Perception of spatial impression in reproduced sound

Recently, the perception of spatial impression in sound reproduction has been studied in detail by Berg and Rumsey, using a range of musical stimuli with a range of reproduction methods. In the initial experiment a large number of terms were elicited that consisted predominantly of spatial attributes due to the nature of the stimuli, but which also included non-spatial attributes [12]. Further experiments were conducted to refine and verify the terms, which led to the following results (adapted from [13]):

- Source-related terms: source width, source envelopment, source distance, source ease of localisation, ensemble width.
- Room-related terms: room width, room envelopment, room size, level of reverberation.
- General terms: naturalness, preference, presence.

Based on previous research, Rumsey developed a set of spatial attributes that was intended to be used to describe the perceived spatial impression of reproduced sound [14]. He used what he termed a ‘scene-based approach’, which involves describing the spatial impression of the auditory scene on a number of levels. Firstly, the spatial impression of each individual source is described (including the position, width, depth, distance and envelopment). Secondly, the spatial impression of each ensemble or group of sources is described (again including the position, width, depth, distance and envelopment). Thirdly, the spatial impression of the acoustical environment is described (including the depth, width, envelopment and presence). Finally, the spatial impression of the entire scene is described (including depth, width and any overall terms such as naturalness). A graphical example of a number of these attributes is shown in Figure 1. Whether all of these attributes are used depends on the stimulus and the required task, but this approach can be used as the basis for a large number of studies.

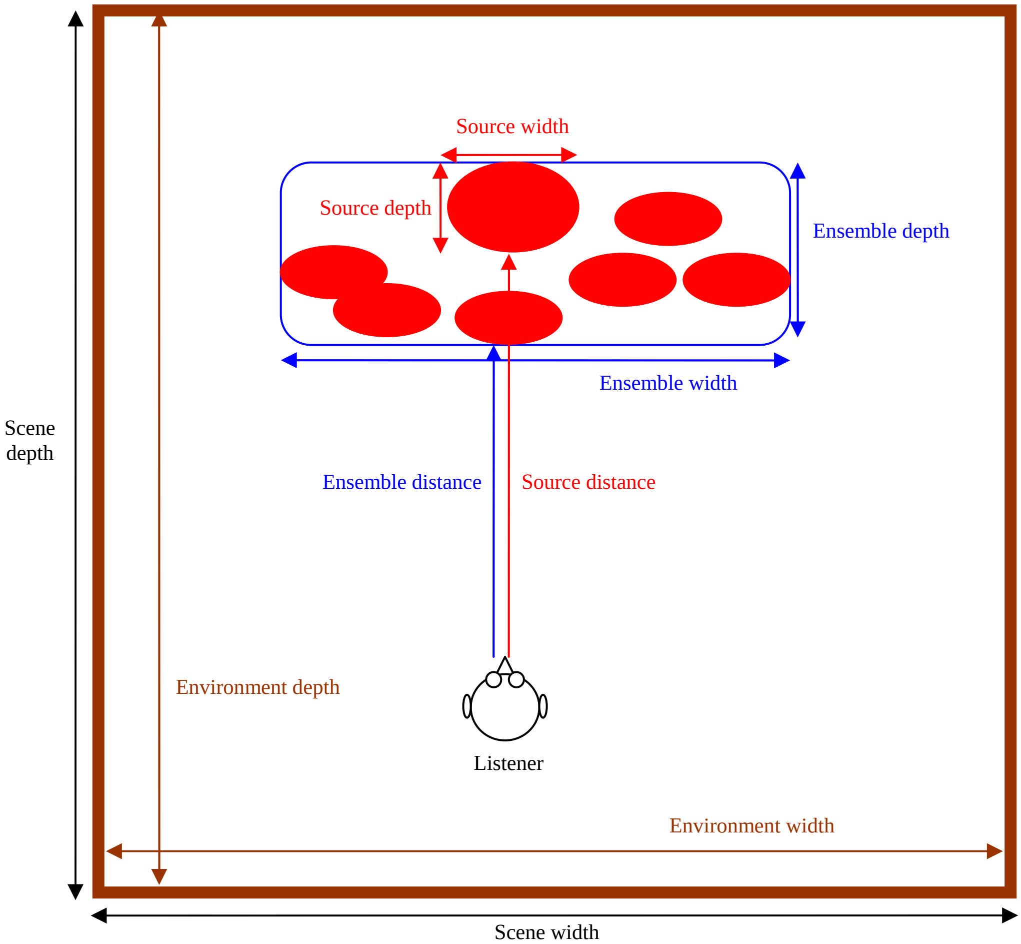

Figure 1: Graphical interpretation of some of the spatial attributes defined by Rumsey using the scene-based approach.

Discussion

The most obvious difference between the spatial attributes that have been derived for concert hall acoustics and those that have been derived for sound reproduction is the number of individual terms. For concert hall acoustics, the consensus appears to be that two terms are sufficient, whereas with sound reproduction it appears that more terms are required. There are two possible reasons for this. Firstly, the greater flexibility of sound reproduction means that it is likely that more factors can be changed compared to concert hall acoustics. Based on this it is logical that more terms are required to separately identify and describe the range of spatial attributes in sound reproduction. For instance, the sound from a source may be perceived to envelop the listener in sound reproduction, but this is unlikely to occur with a traditional musical instrument in a concert hall. This will require terms related to envelopment to additionally specify the appropriate scene component. Secondly, it appears that more detailed research to elicit spatial subjective attributes has been undertaken in the field of sound reproduction. This is partly due to the fact that it is simpler to undertake such experiments in sound reproduction compared to concert hall acoustics, and partly due to the fact that the differing requirements of the two disciplines means that the research has focused on different areas.

The consensus that fewer spatial attributes may be needed to describe the spatial impression of concert hall acoustics raises a question: are two terms sufficient, or can use be made of the more detailed research undertaken using sound reproduction? For instance, the term 'apparent source width' (ASW) is somewhat vague. It is not clear whether this refers to a single source, a section of instruments, or the apparent width of the entire orchestra. Perhaps the use of the scene-based paradigm described by Rumsey and summarised above can be used to clarify exactly what is meant. The term 'listener envelopment' (LEV) is also somewhat vague, as from the term itself it is not clear that this relates solely to the perceived reverberation, and it may include a number of factors including the reverberation level in addition to a spatial component, as indicated by the research of Bradley and Soulodre [15]. Again, perhaps the use of the scene-based paradigm together with other terms can be used to specify the meaning more precisely.

MEASUREMENT OF SPATIAL IMPRESSION IN CONCERT HALL ACOUSTICS AND REPRODUCED SOUND

The previous section reviewed some of the work that has been undertaken in concert hall acoustics and sound reproduction regarding the perceived spatial impression, and discussed the potential benefits of combining this research. It is logical to attempt to undertake a similar review for objective measurements in concert hall acoustics and sound reproduction, as similar benefits may be derived from combining these two research disciplines.

Objective acoustical measurements may be divided into two categories; those which quantify physical parameters without regard of the subjective effect of those parameters, and those which are intended to accurately reflect a specific perceived attribute. As this paper is concerned with the perceived spatial impression, measurements of the latter type are considered in most detail, though some reference is also made to measurements of the former type.

In terms of the relationship between the objective measurement and the perceived effect, Morimoto defined three classes based on the situations in which the measurement reasonably matched the subjective attribute [16]. These were as follows:

1. Measures which correlate with the subjective perception for all source signals and all sound fields.
2. Measures which correlate with the subjective perception for only some source signals and all sound fields.
3. Measures which correlate with the subjective perception for all source signals but only some sound fields.

An ideal measurement would be of the first type, closely correlating with the subjective perception in all situations. However, either of the latter types of measurement could be useful, as long as the limitations of the measurement are clearly explained and understood.

Application of concert hall measurements to reproduced sound

The majority of the initial research into objective measurements that relate to spatial impression was undertaken in the field of concert hall acoustics. For this reason, it is logical to start by considering how these may be applied to reproduced sound. If the aim of the sound recording and reproduction is to recreate the physical sound field of the concert hall in the reproduction room and this is done successfully, then it is reasonable to expect that any acoustical measurements of the sound fields in each room that are made would give identical results. In this case, any of the concert hall measurements can be directly applied to the reproduction, though the measurement will quantify the properties of the original acoustical environment, as the reproduction is a direct replication of this.

However, based on the most common loudspeaker-based sound reproduction systems, it is unlikely that the physical sound field of a concert hall can be accurately reproduced in the reproduction room. For instance, the reflections from the reproduction environment will superimpose themselves on the recorded signal, and this will affect the sound field at the listening position. Also, a very large number of loudspeakers is likely to be required to be able to accurately recreate the direct sound and all the reflections that would be present in a concert hall [17].

In the case of an inaccurate reproduction of the sound field of the concert hall, a useful measurement can be made that compares the reproduced sound field with the original sound field, as was done by Furlong [18]. A measure of the accuracy of the reproduction can be obtained by comparing the results of a wide range of acoustical measurements between the reproduction room and the concert hall. If a quantification of the physical difference between the situations is required, then almost any relevant acoustical metric can be employed. However, in some circumstances it is more useful to be able to predict the perceived difference between the original and reproduced sound fields.

For instance, a reproduced sound field may have a large number of physical differences compared to the original sound field, however if the salient perceptual cues have been recreated effectively, then the subjective perception in the listening space could still be similar to the original. In this situation, an acoustical measurement developed for use in concert halls may still be applied to the reproduced sound field, even though this is not an exact replication of the original sound field. As long as the measurement relates to the salient physical cue that creates a certain subjective effect, then the relationship between the subjective effect and the objective measurement should be independent of the method by which the cue is created.

This approach can be used to evaluate the likely success of the two most common concert hall measurement methods that relate to spatial impression, namely those based on lateral energy (such as LF and LG) [2, 15] and those based on the interaural cross-correlation coefficient (IACC) [10, 19]. The former relates mainly to the physical properties of the concert hall (i.e. the azimuth of the reflections) and the latter relates more closely to the human hearing system (in that it is a binaural signal that is analysed). An example of the difference between these measurement techniques in sound reproduction is virtual surround sound, where the physical sound sources are usually positioned in front of the listener, yet psychoacoustic cues can be simulated to give the subjective effect that a sound is arriving from a direction in which there is no source [20]. In this case, a subjective perception may be created which is consistent with lateral reflections, though the lateral energy measurements are likely to register that the acoustic energy arrives from the loudspeakers that are positioned in front of the listener, with little energy arriving from the side. Therefore, in this situation, the relationship between the lateral energy metric and perceived spatial impression may break down due to the artificial simulation of the necessary psychoacoustic cues. On the other hand, as the psychoacoustic cues that are simulated are based on creating the salient characteristics of the signals at the ears of the listener, it is more likely that measurements based on a binaural signal, such as an IACC, will still work in this situation. This is not to say that lateral energy measurements do not work for sound reproduction; for example Soulodre and colleagues have found that there is a strong correlation between these and listener envelopment for certain stimuli [21]. However, the authors suggest that the lateral energy measurements should be treated as an approximate technique that indicates the methods that can be used to alter aspects of the spatial impression, rather than an accurate predictor of the perceived spatial impression for a wide range of source signals and sound fields.

Development and implementation of absolute measurement techniques

So far, only comparative methods have been considered for applying the objective measurements to reproduced sound. Whilst these may be useful in some cases, they are limited by the availability of recordings of sources in concert halls, the availability of measured results of the original acoustical environment, and the properties of the recorded signals. It would also be useful to measure sounds that do not have a natural original acoustical environment, such as pop recordings made with multiple microphones and artificial reverberation or simulated acoustical environments. In order to achieve this, an absolute measurement model that accurately reflects the perceived spatial attribute for all source signals and sound fields needs to be developed, along with a suitable application method.

For the purposes of this paper, an absolute measurement technique is defined as one that relates accurately to a specific subjective effect, and that outputs the results in a consistent manner on an intuitive scale. An example of this is a measurement of source width that gives a result in terms of a subtended angle and that is highly correlated with the subjective judgement for all source signals and production methods (i.e. natural or reproduction).

A number of researchers have investigated techniques to improve absolute objective measurements that relate to spatial impression, including Morimoto and colleagues [11] and the current authors [22]. For example, the aim of the current authors is to develop a measurement that can predict the perceived source width and environment width of a sound in a manner that meets the first level of Morimoto's classification scheme outlined above. A number of advances have been made in this research, however further work is needed before the goal is achieved.

It is also useful to consider the optimum method for applying this type of measurement. It could be used to give a more accurate prediction of the spatial impression of the reproduction of an original acoustical environment as discussed above, though in this case it does not have to be a comparative analysis. However, the results of an absolute analysis in this manner will only have limited use, as the measurement result will include the parameters of the original source signal and acoustical environment, the microphone technique, the mixing and storage technique, any additional processing, the rendering and reproduction technique, and the properties of the reproduction acoustical environment.

In addition, the optimum value of the measurement needs to be defined, and this is likely to be dependent on the task and the signal used in the experiment. In other words, it needs to be considered whether a greater value in the measured result relates to an improvement in the sound field. It is likely that this is dependent to a certain extent on the signal; for instance an optimum value for a metric related to apparent source width may be lower for an oboe than a piano. For this reason, the relationship between the measured result and overall quality or preference still needs to be determined, most likely by the experimenter, as the result is likely to be situation dependent.

A more precise method for analysing the properties of the reproduction system would be to measure specifically developed test signals. For instance, a representative signal could be created that attempts to vary the measured result over as wide a range as possible (e.g. a signal where the interchannel cross-correlation coefficient varies from -1 to +1). This could then be reproduced over the reproduction system under test, and the measured result would give an indication of the relationship between the input signal and the resulting sound field for that system. It is not yet clear what the optimum result of this type of analysis should be, and further research is needed to quantify this; however one objective could be to make the reproduction system as flexible as possible in terms of the sound fields that can be created, and this can be quantified by examining the range of measured results that are possible.

Application of absolute measurement techniques to concert hall acoustics

It is also useful to consider how these absolute measurement techniques could be applied to concert hall acoustics. As they are intended to work for all source signals and all sound fields, then they should be directly applicable to all acoustical situations that a listener can experience, meaning that they should work in concert halls. However, these types of measurement may require alternative application methods compared to the existing measurement techniques. For instance, conventional concert hall measurements are usually undertaken by analysing the properties of a measured impulse response. As the absolute measurement techniques are designed to accurately reflect the perceived effect of each source signal, then it may be more appropriate to measure representative source signals, as discussed in [22]. In addition, for sound reproduction the idea that measurements could be made to determine the range of spatial impression that the system could create was discussed. It is possible that this technique could be also applied to concert hall acoustics, though research is needed to investigate how this can be achieved. Finally, the previous section discussed the relationship between the measured result and preference or quality, and it was concluded that this is likely to be dependent on the specific source signal, situation and task. It remains to be seen whether this is also the case for concert hall acoustics.

CONCLUSION

The aim of this paper was to bring together the research into the perception and measurement of spatial impression in concert hall acoustics and sound reproduction in order to determine what benefits can be achieved by combining these two fields.

Firstly, the similarities and differences between concert hall acoustics and sound reproduction were explored, with the conclusion that sound reproduction allows greater flexibility in the sound fields that can be created.

Secondly, the research into the perceived spatial attributes of concert hall acoustics and sound reproduction were compared. It was found that in concert hall acoustics two spatial attributes are commonly used, whereas a much larger range of terms have been determined in sound reproduction due to the greater flexibility of this as well as more detailed research in this area. It was suggested that the scene-based paradigm for describing the perceived spatial impression in sound reproduction should be applied to concert hall acoustics in order to describe the perceived spatial impression more accurately.

Thirdly, the research into the objective measurements that relate to spatial impression in concert hall acoustics and sound reproduction was examined. It was found that the majority of this work has been undertaken in the field of concert hall acoustics, and it was considered how the resulting measurement techniques can be applied to sound reproduction. It was found that there are situations in which the measurements can be applied directly, and that measurements based on binaural signals are likely to be most successful in a wide range of situations. It was suggested that absolute measurement techniques would be most useful, and methods for applying these to sound reproduction and concert hall acoustics were considered.

This paper has shown that it is advantageous to combine the results of research in concert hall acoustics and sound reproduction, as there are strong similarities between the two fields. In each case it was found that the initial work was undertaken in concert hall acoustics, that this work could be adapted for sound reproduction, and that advances made in sound reproduction could be applied back to concert hall acoustics. However, the differences also need to be considered and taken into account when transferring the results.

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