Can Reproduced Sound be Evaluated using Measures Designed for Concert Halls?

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ABSTRACT

For several decades, spatial perception has been a key focus for researchers working in the field of concert hall acoustics. As a result, this work has led the way for many important developments in both objective and subjective measurement methods that are in widespread use today. This paper examines how measures used in concert hall design can be used in the study of spatial audio.

1. INTRODUCTION

The history of formal subjective testing in the field of concert hall acoustics now spans more than a century. The first steps can be attributed to Sabine who conducted his pioneering work on reverberation time using nothing more than a stopwatch and his ears. The post-war surge in new concert hall construction ensured that numerous new studies would be undertaken around the world to better understand the many aspects of architectural acoustics. This effort included not only subjective testing, but also the development of invaluable acoustical measurement methods and advanced signal processing techniques. The result was a dramatic improvement in our understanding of the various subjective parameters that combine to determine whether the acoustics of a concert hall are good or bad, as well as several objective measures for predicting these parameters.

Much of the subjective work done in the field of concert hall acoustics was done at a time when digital computing and signal processing were in their infancy. As such, the researcher was quite limited in the type and complexity of tests that he could conduct. As the technology advanced so did the subjective testing methods, to the point where subjects can now easily switch instantly between multichannel stimuli having 32 or more channels. The current state of computing power, multichannel sound cards, and signal processing capabilities means that future advances in this field are now limited primarily by the researcher's own imagination.

These newfound subjective testing abilities have contributed to some important developments in our understanding of the perception of spatial aspects of sound fields. For example, it is now well accepted that spatial impression is actually composed of at least two components; apparent source width (ASW) and listener envelopment (LEV). The author's own research has focused on the perception of LEV, for which two objective measures have been derived.

In this paper we begin by considering the context in which subjective research has been done in the field of concert hall acoustics. We then examine some of the subjective research that has been done in the field of concert hall acoustics. Objective measures that have resulted from this work are defined and their applicability to the evaluation of reproduced sound is considered. In particular, we discuss the use of concert hall measures for evaluating the spatial aspects of reproduced sound.

2. CONTEXT OF CONCERT HALL STUDIES

Before examining the subjective research work that has been done in the field of concert hall acoustics over the past century, it is important to understand the context in which much of this work has been done. Historically, as compared to the field of audio engineering, the link between researcher and practitioner has perhaps been more direct in the field of concert hall acoustics. The subjective research in this area has often been conducted in conjunction with acousticians directly involved in concert hall design. These acousticians have frequently operated as acoustical consultants on various large-scale projects. As such, their subjective research has often been very driven by the need to design a new concert hall or fix a problem with an existing hall. This inevitably results in research that is more applied and which must be conducted within a limited time frame.

Alternatively, in cases where the research was not being done for a specific project, the end goal of the subjective studies was almost invariably to derive or refine objective measures that could be used in the design of future concert halls.

This situation is quite different from what is often found in audio engineering, where the end goal of a given subjective study may be to evaluate the performance of existing audio systems. For example, numerous subjective tests have been conducted over the years to evaluate and compare the performance of perceptual audio codecs [1]. A successful outcome in such a study is to demonstrate the relative subjective ranking of the codecs with statistical reliability. One may conduct similar subjective tests to evaluate the performance of other audio systems, such as loudspeakers or surround sound systems. The goal of these *subjective quality* tests is not to try to understand why a given audio system outperforms (or under-performs) the others. The need for such subjective testing is sufficient to have warranted the standardization of several formal subjective testing methodologies [see 2 and 3 as examples].

2.1. The audience for the research

As in other areas of engineering, the primary audience for audio engineers conducting subjective studies is likely to be other audio engineers. For example, codec developers are usually very thorough in examining the results of subjective tests comparing the performance of various perceptual codecs. Other audio engineers will also scrutinize the results of such subjective tests to help them choose which codec to include in the design of a new system or audio product. In this type of scenario, the researcher conducting the subjective tests is merely the messenger and, assuming that accepted test procedures have been followed, he is generally quite shielded from harsh criticism. Even in a situation where blatant errors have been made in the subjective test procedures, the criticism is very likely to remain within the audio engineering community.

The situation can be quite different for those who conduct subjective tests in order to answer specific questions in the design or renovation of a concert hall. Here, important decisions have often been based on the results of very limited study and “gut instinct”, and the ultimate audience (and critics) of this work includes not only other acoustics researchers, but also, architects, musicians, conductors, music critics, and the general public.

Few researchers conducting subjective tests in the field of audio engineering need worry about the level of public criticism that some acousticians have faced.

> “*The Royal Festival Hall is the worst major concert arena in Europe. The will to live slips away in the first half hour of rehearsal*.” Sir Simon Rattle – conductor.
>
> Philharmonic Hall is “*a great big, yellow $16,000,000 lemon*.” Harold C. Schonberg – critic for the NY Times.

(In referring to the acoustical renovations performed on Carnegie Hall.) “…*acoustics are not a science, not even an art, but a roll of the dice*.” Bernard Holland – critic for the NY Times

In other cases, the acoustician may find the assessment of his work linked to factors well outside the boundaries of acoustics.

> (In referring to the interior color scheme for Philharmonic Hall). “*How can one make beautiful music in a blue room?*”
> George Szell – conductor.

2.2. No guts, no glory

As author Paul Mitchinson notes, “Most audio scientists are fortunate enough to confront their problems in dim windowless laboratories, well away from the public eye; acousticians are not so lucky.”[4] Acousticians who work as consultants must convince the building committee of their knowledge and competence, and they must further convince this committee to entrust them with a project whose budget may well exceed $100M. It must also be realized that the acoustician must work within the confines of the architect’s vision and design. It is the acoustician’s task to make this design sound good. To achieve this, the acoustician must frequently conduct some form of subjective tests to try to predict the acoustical implications of certain architectural decisions. Through these subjective tests, the acoustician will make his best estimate of which approach will yield the best possible acoustics. In the world of architectural acoustics there have been several notable successes and failures in trying to put the results of subjective tests into practice.

Symphony Hall in Boston, which opened in 1900, is widely regarded as one of the finest concert halls in the world due to its acoustics. It also has the unique distinction of being the first auditorium in the world to have an acoustical design in accordance with mathematical formulae. Wallace Sabine, a physics professor at Harvard University was asked to act as consultant on the design of the hall. At the time he had been conducting research to acquire a scientific foundation to explain why the acoustics in some rooms are good, while they are not in others [5]. Sabine recognized that the rate at which sound (reverberation) decays in a room is critical to the quality and suitability of that room's acoustics. The rate of decay must be neither too short, nor too long.

To study this, Sabine conducted numerous subjective tests to collect data. Using organ pipes, seat cushions, a stopwatch, and his ears, Sabine measured the time it took for sounds at different frequencies to decay as a function of room volume and the amount of absorptive material in the room. Ultimately he derived an equation to objectively predict the reverberation time, which he used successfully in the design of Symphony Hall.

Leo Beranek's Music, Acoustics & Architecture, first published in 1962, provides the results of unique study of the acoustical qualities 54 concert halls around the world. Beranek interviewed musicians, conductors and music critics to obtain their subjective opinions regarding the quality of the acoustics of these halls [6]. Based on the results of this survey, he derived a *grade* (from C+ to A+) for each hall and compared these grades to a limited set of objective measures (e.g., *RT*) and architectural drawings of the halls. From this work, Beranek hypothesized that in order for a hall to achieve good acoustics, the single most important requirement is that it have a sufficiently short initial time delay gap (*ITDG*).

In 1958 Beranek put his theory into practice in his design of a new orchestra enclosure and acoustic canopy covering the front third of the Tanglewood Music Shed. Here Beranek made extensive use of overhead reflectors ("clouds") to shorten the *ITDG*. The results were universally hailed as a great success.

Bolstered by the results at Tanglewood, Beranek also relied extensively on the use of overhead reflectors in his acoustic design of the new Philharmonic Hall at Lincoln Center, which opened in 1962. The array of uniformly spaced overhead reflectors spanned nearly the entire length of the hall with the intent of keeping *ITDG* values low. Unfortunately, the acoustical results were considered to be a dismal failure, and in 1976 the interior of the hall was demolished and replaced with a completely new design The hall is now known as Avery Fisher Hall. A critical flaw was found to be in the design of the overhead reflectors, which did not reflect bass frequencies.

It is probably fair to say that the failure at Lincoln Center was the single largest motivating factor for the boom in research in the field of architectural acoustics in the second half of the 20^{th} century. In 1966, Manfred Schroeder and his colleagues from Bell Labs were asked to study the source of the acoustical problems plaguing Philharmonic Hall [7]. From their work they concluded that a lack of early lateral reflections could be an important problem. In keeping with this theory, Harold Marshall published a paper in 1967 noting the acoustical importance of the cross-section of a concert hall [8]. Based on a review of the available literature and some preliminary subjective tests conducted at the Institute of Sound and Vibration Research in Southampton, Marshall hypothesized that "lateral reflections were the most important single component of the early reflections in halls".

Marshall used this as the fundamental basis of his bold acoustical design of the Christchurch Town Hall in New Zealand, which opened in 1972 [9]. The overall shape of the hall is a faceted ellipse (a potential acoustical nightmare), and makes use of a complex reflector system designed to provide an abundance of strong early lateral reflections. The acoustical design is generally considered to be quite successful, owing largely to the sense of intimacy in the hall.

3. SUBJECTIVE TEST METHODS

A large variety of subjective test methods have been used to study concert hall acoustics over the years. The methods can be broadly divided into either field or lab based studies. The two approaches trade off the need for strict experimental controls that are possible in a laboratory setting, versus the need to accurately expose the subjects to the complete sound field as can only be obtained in the concert hall itself. Accordingly, the two approaches each have their merits and their shortcomings.

As indicated earlier, regardless of which method is used, the goal of the subjective tests is almost invariably to assist in the design of a new concert hall, fix a problem with an existing hall, or derive and refine objective measures that can be used in the design of future halls.

3.1. Field Studies

Beranek's Music, Acoustics & Architecture reports the results of a large study conducted by the author in the late 1950's [6]. Beranek interviewed musicians, conductors and music critics to obtain their subjective opinions regarding the quality of the acoustics of 54 different concert halls. In the interview the "subject" was first asked to provide general comments about the halls with which he was familiar. The subjects were then asked to rank-order the halls he knew best.

Based on the results of the interviews and his own listening, Beranek assigned each hall into one of five categories ranging from "Fair" to "Excellent". After comparing the rating for each hall with the available objective measures, Beranek produced a *rating scale for acoustical quality*, to indicate the relative importance of eight independent perceptual attributes.

Table 1: Beranek's rating scale for acoustical quality.

Attribute	**Relative Importance %**
Intimacy	40
Liveness	15
Warmth	15
Loudness of direct sound	10
Loudness of reverberant sound	6
Balance and blend	6
Diffusion	4
Ensemble	4

The relative importance of the attributes listed in Table 1 put a clear emphasis on *intimacy*, which Beranek believed to be directly correlated with the *ITDG*. It is for this reason that Beranek made extensive use of overhead reflectors in Philharmonic Hall at Lincoln Center.

There are several limitations in this study, some of which Beranek himself points out. First, the participants had not visited each of the halls and so the number of evaluations varied from hall to hall. Though not stated explicitly, it appears that each participant provided comments for about 10 halls on average. Another consideration that is not discussed is the amount of time that had passed since the participants had visited the halls.

Most of the music critics involved in the study were from the USA, many of whom were on the eastern coast. One would therefore expect there to be more evaluations of concert halls in that geographical region. Also, all but one of the five European critics were from England. Interviews of the European critics were done by mail.

Regarding the data collected from musicians and conductors, one could easily imagine that their opinions may be influenced by the relative success of their performance in a given venue. Moreover, the reputation of each hall was likely to influence the participants' opinions.

Beranek performed the task of assigning the final ratings for the halls, and since he included his own opinions in the ratings there is a reasonable chance that the ratings were somewhat (unintentionally) biased.

Another approach to field studies is to have groups of subjects attend a series of live concerts together and have them complete a questionnaire. Two large studies were conducted in the past using this approach. In the 1971 study by Hawkes and Douglas, listeners attended live concerts and completed questionnaires consisting of 16 bipolar rating scales [10].

In Barron's 1988 study, expert listeners attended live concerts in 11 British concert halls and completed a questionnaire after each concert [11]. His questionnaire was a shortened version of the one developed by Hawkes and Douglas. Barron correlated his subjective results with a set of objective quantities measured using an omnidirectional loudspeaker in the unoccupied halls. Since the presence of an audience can have a profound effect on the acoustics of the hall and since the radiation pattern of an orchestra spread across a stage must obviously be different from that of a single loudspeaker placed in the middle of that stage, one can immediately see a difficulty in trying to correlate subjective and objective data under these circumstances. The subjects listened to quite different conditions than those that were measured. This along with the influence of various non-acoustical factors, are limitations encountered with studies involving live concerts. Indeed the correlation between the subjective results and the objective measures was relatively low in Barron's study.

3.2. Laboratory Studies

The other approach to subjective testing is to simulate the sound of a concert hall as accurately as possible in a laboratory setting. Two such studies were carried out in Germany in the 1970's. In both of these studies the stimuli consisted of dummy head recordings of music made in real halls.

In the Göttingen study two directional loudspeakers were placed on stage in 25 concert halls and anechoic music was played through them and recorded via a dummy head [12]. However, the objective measures used in that study were derived from impulse responses measured using a spark source with the dummy head as the receiver. Naturally the directional characteristic of the omnidirectional spark source must be quite different from the combined directional pattern of the loudspeakers. It is known that the directionality of the source has a profound effect on the resulting acoustic measures and therefore the objective measures could not have precisely represented the sound fields that the subjects were judging. As well, the directional characteristics of the summed ear signals were not omnidirectional [13]. The playback system used two loudspeakers in an anechoic chamber with steps taken to cancel the acoustic cross-talk [14]. In the Göttingen study, subjects were asked to compare sound fields in pairs and identify the one that they preferred. The results were subjected to a factor analysis and correlated against different objective measures. A key finding of this study was the strong negative correlation between *interaural coherence* and preference. That is, listeners preferred low interaural coherence.

In the Berlin study, dummy head recordings of the Berlin Philharmonic Orchestra were made in six halls [15,16,17]. These recordings were played to subjects over headphones. There are two well-known problems associated with headphone playback of dummy head recordings: in-head localization, and front/back confusion. Both of these shortcomings imply obvious limitations in the realism of the reproduced sound fields. Also, in the Berlin study the objective measures were derived from impulse responses measured using a spark source. As with the Göttingen study, the objective measures may not have been entirely indicative of what the subjects heard. Subjects in the Berlin study were asked to rate 19 different subjective parameters of the sound fields on a six-point bipolar scale. More comprehensive comparisons of these past studies and their results can be found in [11,18].

In their 1995 study, Soulodre and Bradley attempted to overcome some of the limitations of the previous laboratory studies [19]. Sound fields were produced by convolving anechoic music with binaural impulse responses measured in actual concert halls. The impulse responses were measured using maximum length sequences played through an omnidirectional sound source (dodecahedron loudspeaker) placed at center stage of each hall.

Subjects listened to the resulting sound fields over a binaural simulator system consisting of a pair of near-field loudspeakers equipped with mechanical barriers and signal processing to reduce acoustic cross-talk. They conducted eight separate listening tests in which they asked subjects to compare the sound fields according to the same perceptual parameters used by Barron. Subjects were asked to make their judgments based on the *differences* between pairs of sound fields.

A key advantage of the method used in the Soulodre and Bradley study is that the impulse responses used to produce the subject stimuli were identical to those used to compute various objective measures. Also, by asking subjects to rate differences, any bias introduced by the playback system tended to be minimized. In this study, very good correlations were obtained between the subjective results of the corresponding objective measures.

4. NON-SPATIAL OBJECTIVE MEASURES

Numerous objective measures have been developed that are commonly used to predict various perceptual attributes in concert halls. In some respects the objective measures used in concert hall research are fairly coarse in nature. For example, objective measures are typically done on an octave band basis, rather than using a higher frequency resolution. Moreover, the measures often only span the range of octave bands from 125Hz to 4kHz. Similarly, several time-domain measures simply partition the impulse response into early and late energy with a hard boundary between the two. Despite these potential limitations, the measures tend to perform quite well at predicting subjective perception in concert halls. This is perhaps not too surprising since "more detailed" measures might indicate significant differences in nearby seats, whereas the perceived sound at nearby seats tends to be relatively uniform.

In this section we examine objective measures that are not specifically related to the spatial aspects of sound fields.

4.1. Reverberance

Sabine proposed the reverberation time *RT* as an important predictor of acoustic quality in rooms. *RT* is defined as the time it takes for sound to decay by 60 dB. It is frequently measured by applying a straight-line fit to the decay from –5 to –30 dB. Subsequent studies have shown that a listener's perception of reverberance correlates better with the early portion of the decay [20,21]. As a result, the early decay time *EDT* is generally accepted as a better measure of subjectively perceived reverberance. *EDT* is defined as the time it takes for sound to decay by 60 dB as measured from a straight-line fit to the decay from 0 to –10 dB. *EDT*, averaged across the octave bands from 125Hz to 4kHz has been found to correlate very well perceived reverberance [11,19].

4.2. Loudness

The first objective measure of loudness in halls appears to have been proposed by Yamaguchi [22]. Lehmann later proposed the same measure, calling it *strength index* [15]. Barron and Lee modified the measure by replacing the sound power level of the omnidirectional source by the level at a particular distance under free-field conditions [23]. This version of the measure, as shown in the equation below, is equivalent to the difference between the sound pressure level measured at the receiver location and the level of the same source measured at a distance of 10 m in an anechoic environment.

$$G = 10\log\frac{\int_0^\infty p^2(t)dt}{\int_0^\infty p_A^2(t)dt}(dB)$$

p(t) is the room impulse response. In [19] it was found that an *A*-weighted version of *G* gave the best correlation with subjective results.

4.3. Clarity

Most objective measures of clarity consist in some way of a ratio of the early-to-late sound. Generally speaking, greater levels of early energy are expected to increase clarity while greater levels of late energy are expected to decrease clarity. The dividing point between early and late is usually chosen as 50 ms for speech and 80 ms for music. For music the most commonly used objective measure is *C*80 as proposed by Reichardt et al [24].

$$C80 = 10\log\frac{\int_0^{0.08} p(t)dt}{\int_{0.08}^\infty p(t)dt}(dB)$$

One difficulty with this measure is that there is an abrupt boundary between the early and late sound. To alleviate this problem, the center time *TS* was proposed.

$$TS = \int_0^\infty t \cdot p^2(t)dt$$

In practice, *C*80 and *TS* are usually highly correlated in real rooms. Values of *C*80 and *TS* in the 500 Hz and 1kHz octave bands tend to give the best prediction of perceived clarity.

4.4. Bass

Beranek proposed the bass ratio as a predictor of bass perception in concert halls [6]. However, there does not appear to be any direct subjective data supporting this measure. Bass ratio is defined as the ratio of the low- to mid-frequency *RT* values.

In his study of British concert halls, Barron found bass ratio to be a very poor predictor of the subjective perception of bass balance [11]. Soulodre and Bradley obtained a similar result and found the perception of bass to correlate best with the strength of the bass frequencies [19].

5. SPATIAL OBJECTIVE MEASURES

In this section we examine objective measures related to the spatial aspects of sound fields.

5.1. Intimacy

Beranek describes intimacy as follows, "A hall that is small has visual intimacy. A hall has acoustical intimacy if music played in it sounds as though it is being played in a small hall. In the special language of the recording and broadcasting industry, an intimate hall has presence." [6]. The initial time delay gap (*ITDG*) is typically suggested as an appropriate objective measure of intimacy.

5.2. Spatial Impression

It is now well established that spatial impression (or spaciousness) consists of at least two separate components; apparent source width (ASW) and listener envelopment (LEV). ASW is defined as a broadening of the apparent width of the sound source, while LEV refers to the listener's sense of being surrounded or enveloped by sound. However, this is a relatively recent realization, and for many years there was quite a bit of confusion in this area due largely to a casual use of terminology. In the past, researchers and acousticians used often used the terms spaciousness, spatial impression, envelopment, and apparent source width interchangeably.

5.2.1. Apparent Source Width

Most of the early subjective studies into spatial impression were actually examining ASW. That is, the experimenters would vary different acoustical parameters and ask the subjects to rate the apparent width of the signal. Most studies found that ASW was related to the early lateral reflections in the sound field. Barron systematically studied the effects of the strength, delay time, and angle of arrival of a reflection on the perception of ASW [25]. His results demonstrated that stronger early lateral reflections resulted in a wider source image (greater ASW).

Barron and Marshall related spatial impression to the relative level of the early arriving lateral sound energy [26]. Although they called the perceived effect "spatial impression", their subjects were judging the apparent broadening of the source. They proposed the lateral energy fraction *LF* as an objective measure of this effect. It is now common to make a distinction between *LF* values for the early energy versus the late energy. LF_0^{80} is the fraction of the sound energy arriving from the side or lateral directions within 80ms after the direct sound.

$$LF_0^{80} = \frac{\int_0^{80} p^2(t)\cdot\cos^2(\alpha)dt}{\int_0^{80} p^2(t)dt},$$

where p(t) is the room impulse response and α is the angle between the direction of arrival of a reflection and the line through the ears of a listener facing the source. The measure indicates that early reflections arriving from more lateral angles (i.e. closer to 90°) will provide higher values of *LF* and thus greater ASW. In practice, *LF* measurements are typically done using a figure-of-eight microphone with the null pointed toward the source.

In his study, Keet found judgments of ASW to relate to short-time cross correlations obtained using a stereo pair of cardioid microphones and a test signal radiated into an auditorium from a single loudspeaker [27]. This finding formed the basis for much research into the relation between ASW and the inter-aural cross correlation, *IACC*.

$$IACC(\tau) = \frac{\int_{t_1}^{t_2} p_L(t)\, p_R(t+\tau)dt}{\left(\int_{t_1}^{t_2} p_L^2(t)dt \int_{t_1}^{t_2} p_R^2(t)dt\right)^{1/2}}$$

p_L and p_R are the instantaneous sound pressures measured at the ears of a dummy head. Morimoto and his colleagues at Kobe University have conducted extensive research into the relation between the *IACC* of the early energy and ASW [eg, 28,29].

Interestingly the architectural acoustics community has seen a quite lively debate over whether *IACC*-based measures or *LF*-based measures are more suitable predictors of ASW. In the author's opinion, an appealing aspect of the *LF* measure is its simplicity, and the ease with which one can predict the likely effects of a change in the early reflections. Conversely, the effects of an individual reflection on *IACC* are not as intuitive. However, there is some appeal in using a dummy head to measure properties.

5.2.2. Listener Envelopment

As stated earlier there was much confusion about the usage of terms such as apparent source width and envelopment, with the terms being used interchangeably. Therefore, results of earlier subjective studies indicated that early lateral reflections provided both apparent broadening of the source width and envelopment. However, Soulodre and Bradley demonstrated that, while early lateral reflections do provide a broadening of the source width, it is the late lateral energy that produces envelopment [30]. They found LEV to be determined primarily by the amount of late-lateral energy (arriving beyond 80ms after the arrival of the direct sound) in the sound field and proposed the following objective measure to predict LEV [31].

$$LG_{80}^{\infty} = 10\log\left\{\int_{.08}^{\infty} p_F^2(t)dt \Big/ \int_0^{\infty} p_A^2(t)dt\right\}, dB$$

where $p_F(t)$ is the instantaneous lateral sound pressure as measured using the figure-of-eight microphone and $p_A(t)$ is the response of the same source at a distance of 10m in a free-field. They obtained the highest correlation with their subjective results when they used the value of LG_{80}^{∞} averaged over the octave bands from 125Hz to 1000Hz.

6. USING CONCERT HALL MEASURES

The title of this paper asks the question of whether or not measures intended for evaluating concert hall acoustics can be used to evaluate reproduced sound. Soulodre *et al* have conducted several subjective studies to determine whether or not objective measures of LEV are suitable for evaluating the perceived LEV in multichannel surround systems [32,33,34]. In these studies, subjective tests were conducted using a standard configuration 5.1 channel surround system in an ITU-R BS.1116 [2] compliant listening room.

Listeners rated the level of LEV in a given sound field as various acoustical parameters including *RT* and *C*80 were systematically varied. The results clearly demonstrated that subjects were able to easily distinguish variations in each of the acoustical parameters, thus suggesting that these measures should be applicable to reproduced sound. Moreover, they found that the LG_{80}^{∞} measure proposed in [31] worked very well at predicting the perception of LEV in the reproduced multichannel sound fields.

Soulodre *et al* recognized that there could be certain shortcomings in the subjective tests that led to the derivation of the LG_{80}^{∞} measure. In concert hall research the dividing point between early and late energy has traditionally been set to 80 ms. That is, any energy arriving within the first 80 ms after the direct sound is considered to be “early energy”, while all energy arriving after 80 ms is considered to be “late energy”. This is reflected in acoustic measures such as *C*80, which is a relative measure of the early-arriving energy versus the late-arriving energy in a sound field. As such, objective measures of LEV such as LG_{80}^{∞} have used 80 ms as the point where the late energy begins. However, the transition point between early and late energy had not been investigated in studies of LEV even though there was evidence that this may not be the optimal transition point for measuring LEV.

Soulodre *et al* conducted new subjective tests to further study the boundary between early and late energy across frequency. Based on their results, and motivated by the fact that the forward masking abilities of the human auditory system decrease with increasing frequency, they proposed the following integration limits as boundaries between early and late energy.

Table2: Perceptually motivated integration limits.

Octave band	Integration limit
125 Hz	160 ms
250	160
500	160
1000	75
2000	55
4000	45
8000	45

They also recognized that LG_{80}^{∞} is actually composed of two components. One component is related to the level of the late-arriving sound energy, while the other component is related to the spatial distribution of the late-arriving sound energy. They studied the relative influence of these two components and found that the level component’s influence is half that of the spatial component. This was used to develop a new (lateral energy fraction based) objective measure of LEV defined as,

$$GS_{perc} = 0.5 \cdot G_{perc} + S_{perc}, \text{dB}$$

where

$$G_{perc} = 10 \log \left\{ \frac{\int_{perc}^{\infty} p_o^2(t)\ dt}{\int_{0}^{\infty} p_A^2(t)\ dt} \right\}, \text{dB}$$

is the *strength* measure, and

$$S_{perc} \equiv 10 \log \left\{ LF_{perc} \right\}.$$

The *perc* subscript indicates that the perceptually motivated integration limits of Table 2 are to be used. G_{perc} represents the level component and S_{perc} represents the spatial distribution component. GS_{perc} is taken as the average of the values across the octave bands from 125 Hz to 8000 Hz. It can be seen that whereas LG_{80}^{∞} uses only the octaves from 125 Hz to 1000Hz, GS_{perc} uses information up to 8000Hz.

Soulodre speculated that the spatial distribution component of GS_{perc} could also be defined using a measure based on *IACC* [35]. In typical sound fields, *IACC* is not uniform across frequency. Specifically, at lower frequencies *IACC* is always close to one, and so the octave bands cannot be averaged directly. To overcome this shortcoming, Soulodre normalized the *IACC* values across frequency using the squared-magnitude coherence for two omni-directional receivers spaced *d* meters apart in a diffuse sound field. The squared-magnitude coherence provided a lower limit for the expected value of *IACC* in a diffuse-field and thus allowed *IACC* to be normalized on an octave band basis. Soulodre proposed the following *IACC* based objective measure of LEV.

$$GS_{perc} = 0.5G_{perc} + 10\log\left\{\frac{1}{\overline{IACC}_{perc}}\right\}, \ dB$$

Again, the *perc* subscript indicates that the perceptually motivated integration limits of Table 2 are to be used. $\overline{IACC}_{perc}$ represents the $IACC_{perc}$ values normalized across frequency. The performance of both the *LF*-based and *IACC*-based versions of GS_{perc} were evaluated against subjective results and the two versions of GS_{perc} were found to be roughly equivalent. Both versions were found to correlate very well with subjective results, and both significantly outperformed LG_{80}^{∞}.

In the course of conducting their various subjective tests into the perception of reproduced sound, Soulodre *et al* were able to successfully make use of several objective measures designed for concert halls. However, it should be recognized that they were creating the reproduced sound fields by processing anechoic music through custom reverberators. Many of the acoustic measures designed for concert halls require access to the impulse response of the sound field. Therefore, these objective measures could not be used to directly analyze an existing recording.

It should also be recognized that when playing an audio recording one is actually listening to the acoustical characteristics of the room in which the recording was made, combined with the acoustical characteristics of the reproduction system (loudspeakers and room). Specifically, the impulse response of the recording environment is convolved with the impulse response of the playback system, and it is not generally possible to de-convolve the two. Though perhaps not intuitively obvious, the playback system limits the possible range of each of the acoustical parameters (e.g., *RT*, *C*80, *ITDG*, etc.) that can be reproduced. In the author's opinion, the perceptual impact of this is not fully understood or appreciated. The impact is likely to be more important in environments such as small rooms and automobile cabins.

6.1. The multi-stimulus test method

One might ask whether subjective test methods developed for research into concert hall acoustics can also be applied to the assessment of reproduced sound. Not only is this possible, it has been done. It is interesting to note that the multi-stimulus subjective testing methodology was developed in the course of the author's research into the perception of spatial aspects of concert halls. The multi-stimulus approach is the basis of the so-called ITU-R MUSHRA test method that is now commonly used for a wide variety of subjective evaluations, and is now the method most commonly used for evaluating audio codecs [3,36].

6.2. A final (cautionary) note

Those interested in reproduced sound often refer to the work of Ando. Ando was an early supporter of the use of *IACC* as an objective measure for concert halls. Specifically he sought to use *IACC* as a means of predicting subjective preference of sound fields [37]. Ando examined the effect of a single echo on subjective preference. His work was done in an anechoic chamber using only two loudspeakers: one for the direct sound and one for the echo. He concluded that 55° is the preferred angle for a reflection since it provided the lowest *IACC* value (even though this was not the angle that produced the highest subjective preference in his study).

Many in the audio community refer to this conclusion and as a result, some have concluded that multichannel surround systems should have a loudspeaker located at this angle in order to have optimum performance. The author disagrees with conclusion for several reasons.

While Ando's work certainly represents a useful step toward our current understanding of the effects of early lateral reflections and their relation to *IACC*, the work cannot be considered to be complete. A single reflection in an anechoic environment is not a realistic approximation to the complexities of sound fields in concert halls. It is not reasonable to expect one's preference for a given reflection angle under anechoic conditions to be the same as when one is exposed to a more complex and realistic sound field. This has been borne out by the discovery that changes to the early reflections in a sound field become more difficult to perceive as the level of the late energy is increased. That is, in more realistic sound fields (those which include reverberation) the spatial effects of early reflections (ASW) become difficult to hear [30]. As a result, it would seem more reasonable to select the loudspeaker placement based on the need and ability to localize sources in the sound field.

In the author's opinion, those interested in reproduced sound have perhaps placed too much emphasis on Ando's results.

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