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What do we know in room acoustics?

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Summary
Room acoustics has a scientific interdisciplinary concept which will be further developed in future. During the last century, several dimensions of the overall listening impression in concert halls were identified which show a good correlation with corresponding objective measurement data. It can be summarized that the three most important factors (loudness, reverberance and spatial impression) explain most of the statistical variance when comparing the acoustic conditions in auditoria. But some questions remain, particularly for stage acoustics, for dependencies within the quantities and for the overall impression. In applied room acoustics, progress can be seen concerning modeling and simulation on the one hand, and impulse response measurements on the other. Apart from the perceptual factors of room acoustics, another crucial point is the listener's sensitivity to changes in a sound field in regard to those subjective aspects. In the end, the uncertainties of simulation and measurement results must be compared with the just noticeable differences, jnd, of hearing in rooms. Thus, further cooperation of room acoustics with psychoacoustics and audio engineering is expected to stimulate more ideas and innovation in research and concert hall design.

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1. Introduction

Room acoustics is a well-established field with exciting links to architecture and music. Efficient design tools are available, and experience with solutions for various applications is the basis for daily work in acoustic consulting. After all, room acoustic design and consulting is a rather straightforward process. This statement is true when we consider elementary design rules and creation of acceptable room acoustic conditions. Acceptable acoustic conditions, however, are not always given in rooms for speech and music, simply because standards and guidelines in room acoustics are not taken into account properly.

When it comes to requirements for excellent acoustic conditions, the picture is different. In prestigious projects the acoustic conditions shall fulfill high standards. What are these standards? In ISO 3382 [1] we find definitions and guidelines for measurement and interpretation of room acoustic quantities. In famous textbooks, the most well-known by Beranek [2] and Barron [3], we find a huge amount of data of concert halls and opera houses, and these data indicate target values and tolerance ranges for successful acoustic designs.

In this article, the history of room acoustics is briefly summarized, the state of the art re-visited, and open questions discussed. Those are related to cross-disciplinary research of classical room acoustics with psychoacoustics and array signal processing.

2. A brief history of room acoustics

Wallace Clement Sabine created the first scientific approach to understand the acoustics of performance spaces. His famous "collected papers" [4] form the basis for room acoustics which we are still using today. The inter-relation between reverberation and volume and absorption was clarified and explained empirically. Little later, in the 1930s, Norris [5] and Eyring [6] presented a theory with more correct factors in the equations, which today, of course, are known as Sabine's and Eyring's reverberation equation.

Thereafter, the "fine structure of reverberation" was put into the focus of interest. Lothar Cremer, in the first edition of his book [7], illustrated the sound reflections by using geometric constructions of rays and image source, a methodology which is still among the standard methods in room acoustics. He already identified the importance of reflections, their series of arrival, their density and their global late decay.

With these findings and with availability of instrumentation for impulse response measurement, acoustic consulting was put on a scientific basis. From the 1950s, consulting firms could rely on a deeper understanding of sound fields and could advise architects accordingly. But still the specific subjective effects inside reflectrograms were hidden in the dark

2.1 1950 – … Observations in investigating monaural impulse responses

The physical aspects of room acoustics were first studied in the 1950s. The subjective impressions were correlated to physical properties of room impulse responses. One of the first observations concerning the *early reflections* was made by Rolf Thiele [8] in 1952, who provided the basis for the objective descriptors of early-to-late energy integral ratio ("Deutlichkeit"). This was finally possible with availability of multi-channel equipment in anechoic rooms. Today, we consider the concept of *Early Decay Time* as well known. This finding was given by Vilhelm Jordan [9] who discovered the relationship between reverberation and subjective reverberance. Furthermore, this period was the time for studies in correlation of subjective impressions and objective parameters. Numerous publications came out of the research groups leaded by Erwin Meyer (Göttingen), Walter Reichardt (Dresden) and Lothar Cremer (Berlin). From the main results in famous publications and dissertations just some are listed here with some keywords:

University of Göttingen: E. Meyer et al.: "Simulation of room acoustics by electroacoustic systems" [10], M.R. Schröder: "Frequency curves" [11], M.R. Schroeder: "Integrated Impulse Response" [12], H. Kuttruff: "Statistics of frequency curves" [13]

Technical University Dresden: W. Schmidt, O Abdel Alim, W. Schmidt: „Clarity" [14], L. Dietsch, W. Kraak: „Echo perception" [15]

Technical University Berlin: H. Wilkens, P.Lehmann, D. Gottlob, K.F. Siebrasse: „Correlation subjective - objective" [16-19], R. Kürer: "Centre time" [20]

With this pioneering work, room acoustics was clearly taken out of the influence of black magic. In the following years the quantities defined were tested in laboratory environments, and they were applied in measurements in halls.

2.2 1970 – … Spatial impression

At the beginning of the 1970s, many modern concepts for "good" room acoustics related to performance of classical music, opera and speech theatres were proven in theory and accepted for best practice. At that time, however, many halls were designed with modern architecture and construction methods. Usage of open concrete, mostly large flat and smooth surfaces, large and wide halls, particularly fan-shaped halls were preferred. And some of these halls did have bad critics, although reverberation time, sound level and clarity were found to be in the right order of magnitude.

James West [21] stated in 1966 that acoustically good concert halls (Musikvereinssaal Vienna and Boston Symphony hall have small width to height ratio. In 1968, Harold Marshall [22] confirmed that spatial impression is created by side wall reflections which are particularly strong in narrow halls. In the early 1970s, Michael Barron [23] in Southampton (1971) and P. Damaske and Yoishi Ando [24] in Göttingen (1972) identified the importance of lateral refections as being underestimated. They pointed out the relevance of early lateral reflections for the *spatial impression*. It affects the precision of source localization and gives an impression of diffuse sound incidence. Spatial impression still today is the most difficult component of multidimensional hearing in rooms ("Hörsamkeit").

The fan-shape hall shows indeed lack of early lateral sound. A consequence was to implement side walls with segments of tilted angles or terrasses or wineyard areas, in order to split side wall reflection and to direct them to the audience at lateral angles.

After the 1970s, acousticians and architects could rely on quite stable and complete knowledge of general principles of the room shape and its effect of early and late reflections. The book by Heinrich Kuttruff [25] in the first issue from 1972 already contained the state of the art of knowledge in room acoustics. After that time, details could be studied but the general insight into room acoustics was complete.

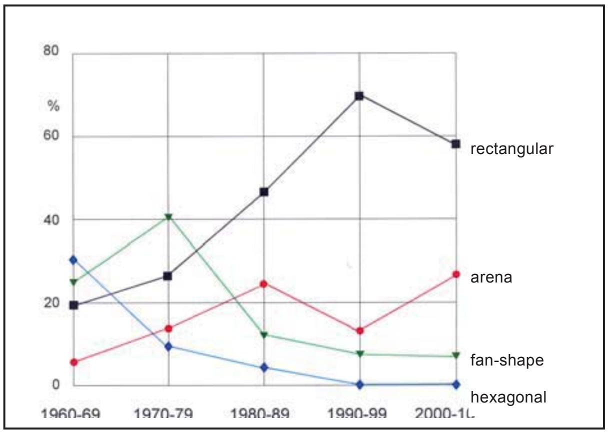

Figure 1. Percentage of room shapes chosen for concert halls built between 1960 and today (after Meyer [26]).

It is interesting that the findings in room acoustic research directly are reflected in the hall shapes built. Jürgen Meyer [26] evaluated 157 halls with seating

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capacity > 1000. He points out that the majority of room shape is rectangular, fan-shaped, hexagonal or in arena style. Thus the hall shape determines a large amount of the acoustic performance. Many details such as surface corrugations, stage, balcony and reflector design are important as well, and consideration of the directional radiation of musical instruments.

2.3 The standards years: 1990 - …

Under the convenor, Fergus Fricke, an extended issue of the international standard ISO 3382 "Measurement of the reverberation time of rooms with reference to other acoustical parameters" was developed and finally published in 1996 [1]. It not only contained guidelines for measuring reverberation time in auditoria, but as well definitions of other room acoustical parameters: Strength, G, Clarity, C_{80}, Definition, D_{50}, Centre time, ts, Lateral fraction, LF, Interaural cross correlation coefficient, IACC.

Nevertheless there have to be mentioned further milestones in room acoustics. These are related to signal processing in measurement technique, to progress in computer simulation, and to further clarification of spatial impression. In 1995, John Bradley and Gilbert Soulodre [27] investigated the subjective effect of early and late spatial reflections. They found two independent effects of spaciousness: *Apparent source width* and *Envelopment*. And they could correlate the results from subjective tests with two simple but significant objective measures: early lateral sound ratio (more or less in Barron's definition) and a new quantity, the late lateral level, G_{LL}.

2.4 Computer in room acoustics

The introduction of computers in acoustic measurements made sophisticated measurement techniques of impulse response measurements possible. This applies to real-room measurements as well as to scale models. Impulse responses could be measured with high reproducibility and, thus, comparability. In the first ISO 3382 there was already a hint to apply broadband excitation and post processing to obtain impulse responses [28].

Since 1985, computer simulations were developed and put into a state of applicability for consulting, in parallel to scale model measurements. Independently, Dirk van Maercke in Grenoble [29] (the first software listed originally developed as EPIKUL at KU Leuven), Michael Vorländer in Aachen [30], Bengt-Inge Dalenbäck in Gothenburg [31] and Graham Naylor and Jens Holger Rindel [32] in Copenhagen worked on algorithms for simulating room acoustics on the basis of architectural CAD input data. Until today, these and other programs have been used with success. Round Robin tests [33-35] showed their efficiency and as well the limits of room acoustics computer simulation. This led, among other findings, to the definiton and implementation of scattering coefficients [36] into simulation methods. Similarly to observations in real sound fields with purely specular reflections (rooms with large flat concrete walls), it was noted that artificial decays based on purely specular models sound unnaturally cold and contrasted.

3. Actual research

Room acoustics is far from being a solved problem. In spite of the standards and design tools, there is a need for research and transfer of knowledge to other engineering disciplines. Still too many meeting rooms, classrooms, auditoria, offices, train or metro stations and airports have unacceptable acoustic conditions.

As concerns actual research on subjective impression, an excellent review and outlook was given by Anders Christian Gade [37]. He states that the multi-dimensional room acoustic impression requires a much larger statistical basis of rooms, seats and test subjects than usually applied and published. Each one study cover one variable while other are tried to be kept constant. The inter-relation between clarity and loudness, or ASW and bandwidth, for instance, remains unclear, as the test conditions of different studies are not identical.

In the following some examples are described which illustrate some recent research activities.

3.1 Room acoustics and Psychoacoustics

Densil Cabrera and colleagues asked why reverberance must be based on a level decay rather than on a loudness decay [38]. Time-depending loudness includes as well spectral masking as the temporal effects of cochlear sound processing. Models from psychoacoustics are available (Fastl and Chalupper [39]) which was already adopted in a standard [40].

In fact, their loudness decay rates are well correlated with subjective reverberance. Furthermore, loudness decays can include signal properties if the decay curve is not dereived from the impulse response but from signals convolved with impulse responses. Accordingly the reverberance can be expressed in two aspects: a) the sound reverb in signal transients and its effect on the signal modulation and b) the decay after the final chord.

As concerns binaural aspects, hearing models of binaural processing are a powerful tool to evaluate localization, diffuseness and spaciousness. Based on the Jeffress model of cross-correlation [41], diverse model approaches exist (Lindemann [42], Dau [43], Breebaart [44], van Dorp Schuitman [45], among others, and those are going to be increasingly used for room acoustic research.

3.2 Room acoustic measurements

A rather new field of research is the evaluation of measurements techniques (typically application of ISO 3382) concerning the measurement uncertainty. The measurement uncertainty can then be compared with the just noticeable differences, jnd, in order to identify the significance of results. With the framework of GUM [46] it is possible to investigate the sources of errors influencing a measurement result and to specifiy the quantitative influence of each source of error on the overall uncertainty. In room acoustics, placement and directivity of dodecahedron loudspeakers were found to be crucial, as well as microphone and dummy head specifications [47, 48].

The relation between the subjective impression and in-situ diffusivity at listener positions is still an old problem which was already decribed in the 1950s by Thiele. Directivity diagrams ("hedgehog plot") illustrate the distribution of distinct specular and smooth diffuse sound incidence. But measurement of a detailed directional distribution is tedious and uncertain when it comes to specification of highly directional microphones. Alternatively, evaluation of the fine structure of impulse responses was proposed by Jeon et al. [49]. This is based on the fact that specular reflections show strong peaks in the impulse response, while diffusely scattered sound is more stretched on the time axis (this observation already led to the concept measuring scattering coefficients of surfaces in [36]). When applied to the sound field at points in the room, evaluation of the number of peaks in the impulse responses may give an insight into the amount of specular-to-diffuse reflections.

3.3 Room acoustics and Auralization

The basic algorithms of computer models were developed in the 1990s. Also at that time, the importance of scattering was recognized, thus leading to implementations of hybrid models. Their feature is that deterministic specular components in the impulse responses is calculated separately from stochastic (diffusely scattered) parts. Both parts are combined in the end. It is important to mention that the physical sound field can be separated into those two parts as well. Auralizations using such kind of hybrid models are in perceptive aspects near to recordings. To quantify the differences and to understand the reason of differences, though, is subject to research.

Besides the development of algorithms describing the physical sound propagation in room, many ideas from computer graphics were also applied to room acoustic modelling, such as space partitioning or other methods to speed-up the algorithmic kernel of ray intersection point with polygons. Due to severe differences of (narrow-band) light propagation in contrast to broadband sound propagation and differences in the ratio of room and object sizes in comparison with wavelengths, the algorithms used for creation of computer images cannot be applied in room acoustics. Nevertheless, data management and dynamic object handling developed in computer graphics makes real-time auralization possible (Acoustic Virtual Reality).

In a recently founded consortium of the Universities of Berlin, Aachen, Ilmenau, Oldenburg and the Negev, Israel, several aspects of perception in room acoustics, and furthermore recording and reproduction of spaces is investigated from various viewpoints (after Weinzierl [50]): ″The research group follows a coordinated effort to improve the complete signal chain from the numerical modelling, the data acquisition within numerical or real sound fields, the coding and transmission to the electro-acoustic reproduction by binaural technology or by sound field synthesis. A novel approach for the comparative evaluation of simulated environments will not only perceptively validate all improvements along the signal chain; it will also allow to evaluate the plausibility and/or the authenticity of virtual room acoustic environments as a whole. Moreover, it will be used to bring forth better physical measures to predict the qualities of natural acoustic environments as well.″ First results will be presented in 2012.

3.4 Array technologies in room acoustics

The development of linear, circular and spherical arrays for 3D sound field analysis inspired many investigations in room acoustics. Arrays are used for spatial decomposition and beamforming, thus for decomposition of complex sound fields into plane or spherical waves. Those waves of course stem from reflections. The advantage is that not only the temporal and spectral cues of room sound fields are captured, but their directional distribution as well. And apart from the possibility of multi-channel sound recording, this technique is very interesting for analysis of room sound fields and reflection patterns.

One of the first findings with linear arrays was that clarity, C_{80}, is very sensitive to small changes in the microphone position. If impulse responses are evaluated for adjacent array microphone just a few centimetres apart, clarity data differ more than the just noticeable difference [51]. This would indeed mean

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that the subjective impression of clarity differs significantly within an area of one concert hall seat. This does not match the listening experience at all, and accordingly the definition of the clariy index creates too a sensitive result.

The next example is application of the concept of wave field analysis, WFA, to room acoustics. This way, rooms can be compared with regard to their wave propagation patterns [52], which gives valuable insight into the spatial wave incidence and, thus, the amount of distinct specular wavefronts and diffuse components.

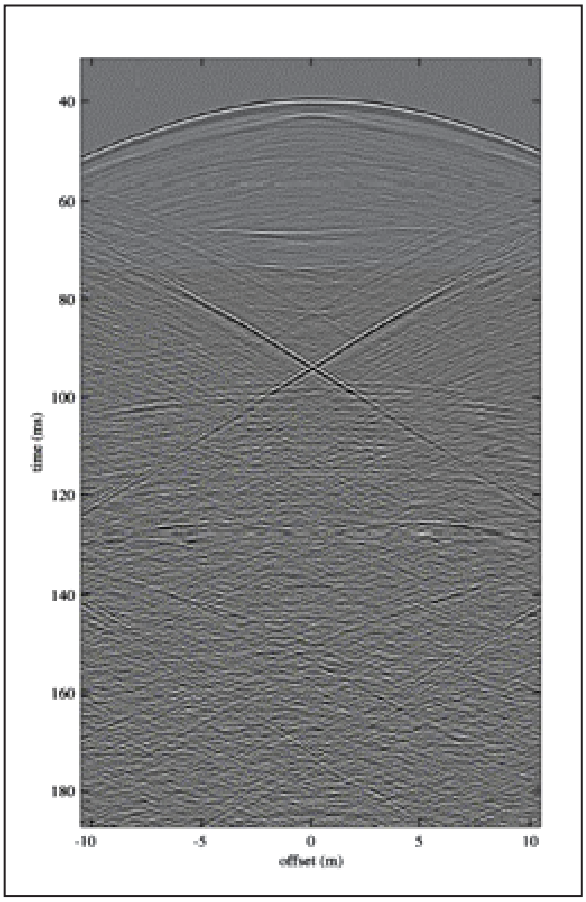

Figure 2. Wave field analysis measurement in Concergebouw Amsterdam (from [52])

4. Summary and conclusions

In room acoustics, several dimensions of the overall listening impression were identified which show a good correlation with corresponding objective measurement data. It can be summarized that the three most important factors (loudness, reverberance and spatial impression) explain most of the statistical variance when comparing the acoustic conditions in auditoria. Aspects of scattering and diffusivity and their relation to surface design are still under investigation, as well as robust descriptors of stage acoustics.

Apart from the definition of the most relevant perceptual factors, another crucial point is the listener's sensitivity to changes in a sound field in regard to those subjective aspects (just noticeable differences) and to the robustness and significance of measurement results.

Cooperation of room acoustics with psychoacoustics and audio engineering will stimulate more ideas and innovation in research and concert hall design.

Room acoustics today is far from being black magic. Instead, there is a strict scientific interdisciplinary concept which will be further developed. Methods, knowledge and guidelines from classical room acoustics will also be used for other purposes than acoustics in performance spaces, such as for train stations or airports, factory halls and offices.

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