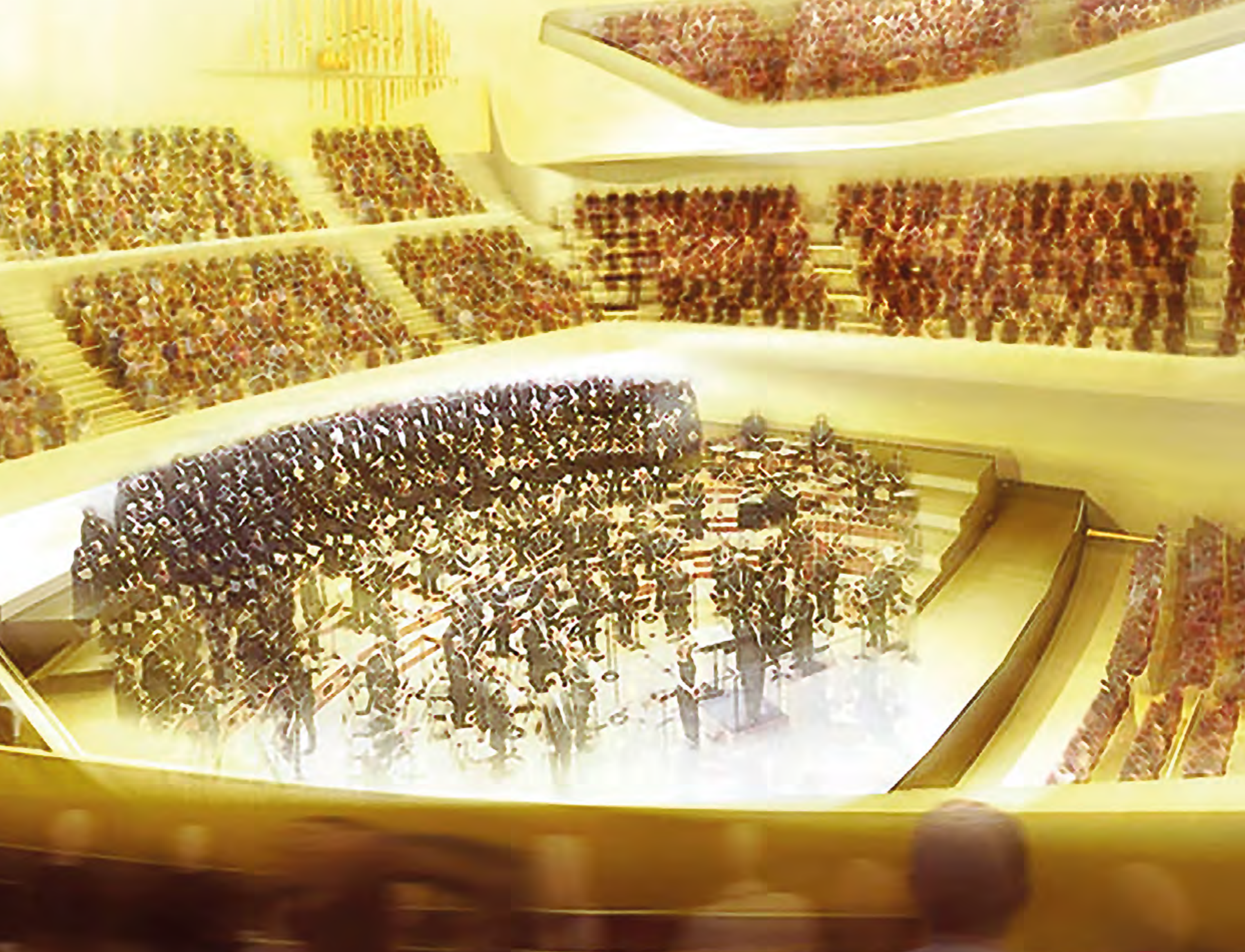
THE ACOUSTICS OF A CONCERT HALL

AS A LINEAR PROBLEM

▪ Tapio Lokki and Jukka Pätynen – DOI: 10.1051/epn/2015102
▪ Aalto University School of Science – Dept. of Computer Science – POBox 15500, FI-00076 Aalto, Finland

The main purpose of a concert hall is to convey sound from musicians to listeners and to reverberate the music for more pleasant experience in the audience area. This process is linear and can be represented with impulse responses. However, by studying measured and simulated impulse responses for decades, researchers have not been able to exhaustively explain the success and reputation of certain concert halls.



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◂P. 17: Big hall of the Philharmonie de Paris. Architect: Jean Nouvel. 3D rendering. © Philharmonie de Paris – Didier Ghislain

The acoustics of concert halls have been measured, studied, and interpreted with impulse responses for over 100 years [1]. This is a well–justified approach, as the behaviour of sound in a room is a linear system. The sound emitted by a source propagates with the speed of sound to all directions and bounces from the walls dozens of times while reaching the receiver, which is a microphone in the case of acoustic measurements. Thus, the response to an impulse (for instance a popping balloon or a start pistol) covers all possible sound propagation paths and describes the room acoustics between the chosen source and receiver positions. In addition, an impulse response measurement is relatively easy to carry out. One just needs an impulsive sound source on stage (using a loudspeaker) and one omnidirectional microphone, which captures the impulse response at a certain location. Moreover, using several source and receiver positions provides the average characteristics of the acoustics of a particular hall.

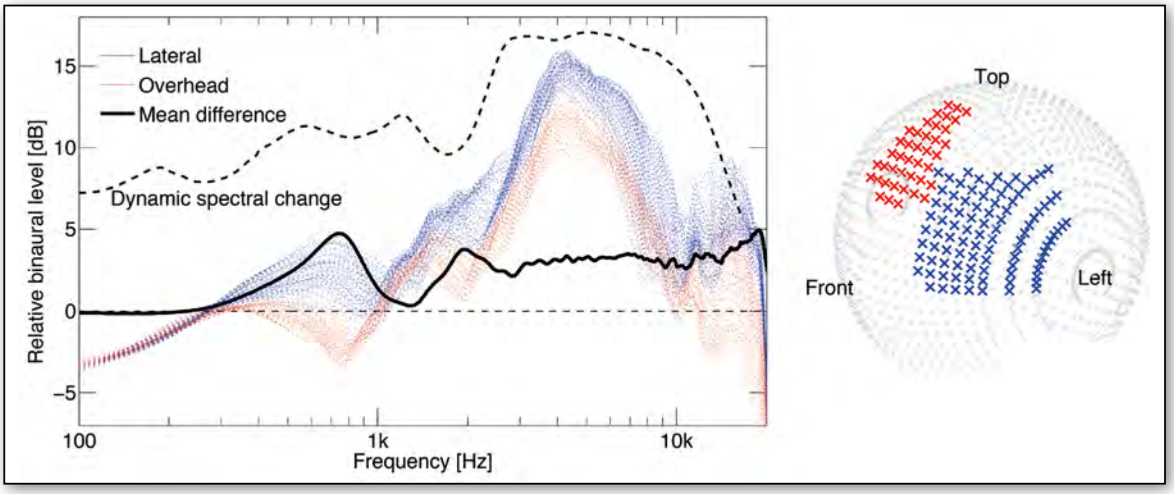
Prominent features

The concept of the impulse response offers a nice way to objectively describe the acoustics of a concert hall. To overcome the analysis of complex signals of the acoustic response, researchers have invented dozens of parameters that aim to describe the prominent features of an impulse response. The most commonly applied parameters have been included in the ISO3382-1:2009 standard. For example, this standard defines the reverberation time, *i.e.*, the time of a 60 dB linear decay of sound energy, or strength, which is the linear amplification of sound relative to sound pressure level at 10 m in the free field. The objective metrics such as these have become the de-facto standard to compare and characterize the acoustic conditions in different concert halls. Consequently, the acousticians designing concert halls try to predict these parameters using scale and computer models to guarantee the acoustical success of the new concert hall. However, experience has shown that tuning the parameters to their optimal range does not necessarily result in a successful concert hall. This has rendered concert hall acoustics somewhat mysterious for many researchers and designers.

Orchestra simulator

Our research team at Aalto University has worked since 2008 towards a better understanding of the acoustics of concert halls. We have applied psychometric methodologies borrowed from the food and wine industry to reveal which features of sound people pay attention to when listening to music in concert halls, and what kind of halls they like [2]. We have taken great care to minimize the uncontrollable variables in the music samples that we present to our subjects to compare and evaluate. For example, to keep the source constant, we have invented a symphony orchestra simulator, an array of 34 loudspeakers on stage [Fig. 1 and Ref. 2] playing anechoic (echo-free) symphony music [3]. In addition, to keep the recording system constant, room acoustics is captured via "spatial impulse responses" [4]. In other words, the measured spatial impulse responses are decoded for spatial sound reproduction system before convolution with anechoic music in order to obtain as natural sounding spatial sound reproduction as possible in laboratory conditions. When subjects then sit in our laboratory surrounded by 24 loudspeakers listening to music, they can switch recordings between different seats and concert halls allowing us to discover interesting results.

▸FIG. 1: The symphony orchestra simulator on the stage of Vienna Musikverein. © Jukka Pätynen



◄**FIG. 2:** The dashed line shows the difference in power spectrum of a symphony orchestra between *forte* and *piano* playing dynamics. The coloured curves illustrate the binaural magnitude spectrum for sound entering to the ear canal from different directions, which are indicated on the right. Finally, the thick black line is the mean difference for lateral (blue) and overhead (red) directions.

One of the most intriguing results is that some concert halls seem to expand the dynamics of music. It is clearly heard that a full orchestra crescendo from pianissimo to fortissimo is much more powerful and larger in halls which have the classical rectangular geometry, *e.g.*, the Vienna Musikverein or the Berlin Konzerthaus. But, wait a minute! This should not be possible as the acoustics of the hall is linear and measured with linear impulse responses. How can such a linear conveyor of sound compress or expand the dynamics of music? It is well known that human hearing has non-linearities, but this cannot alone explain compression and expansion of music in a concert hall.

Rigorous literature studies do not bring much light to this problem. There are some hints that such a phenomenon has been noted earlier on certain occasions. Beranek [5, p. 509] describes the effect without any explication as "listening is enhanced immeasurably by the dynamic response of the concert hall". Moreover, Marshall and Barron [6] discuss the spatial responsiveness of concert halls, *i.e.*, the widening of sound sources, by writing "a hall seems to respond to crescendi in the music [...] the effect may be perceived non-linearly." But again, no scientific explanation is provided for the apparent change in the musical dynamics.

Spectrum of the orchestra

Enhancement of dynamic expression is not evident from examination of either the hall or human (spatial) hearing alone. But these two are missing the third part of the basic source-medium-receiver communication system: music. What if we include the influence of the excitation signal, *i.e.*, the symphony orchestra, to this communication system? What has not been understood earlier in the context of concert hall acoustics research is that the spectrum of the orchestra changes strongly as a function of played dynamics. Thus, the excitation is non-linear. In a concert, we have the interaction of three simultaneous factors: non-linear excitation (musical instruments); linear sound conveyor (a concert hall); non-linear spatial hearing (human). When the interaction between these three is investigated as a complete communication system, it is hardly surprising that musical dynamics can be perceived differently in different concert halls, as the system contains two non-linear components. Let us explain the main reason for these non-linearities.

Figure 2 summarizes the non-linearities of the orchestra music and the directional spectral changes in the sound entering to the human ear due to the geometry of head and ears. When all musicians in an orchestra are playing, the average difference between piano and fortissimo dynamics is less than 10 dB at low frequencies, around 10 dB at mid frequencies, but over 15 dB above 2 kHz. For some individual instruments, such as a trumpet or a trombone, the difference at high frequencies can be over 40 dB! And these brass instruments seldom play in pianissimo passages, but they enter the ensemble in majestic fortissimos. To conclude, when an orchestra plays loud they excite much more high frequencies than mid and low frequencies. If a concert hall attenuates these high frequencies (due to relatively large absorptive surfaces, for instance), the extra energy of high frequencies in fortissimos is not delivered to the listeners' ears. Moreover, the human spatial hearing has a direction-dependent sensitivity, which works in concert with the hall geometry.

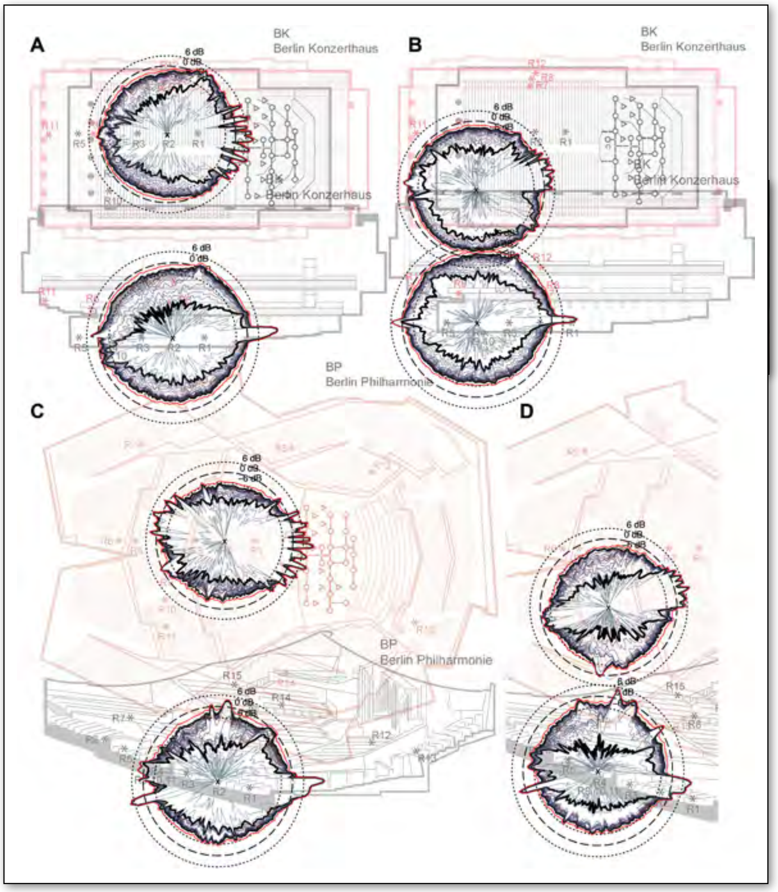
> **A full orchestra crescendo from pianissimo to fortissimo is much more powerful in halls which have the classical rectangular geometry**

Sound propagation

Now, we need to look at how sound propagates in a hall from the source to the receiver. Listeners in the audience first receive the direct sound from the stage, and then the sound reflected from the walls and the ceiling. The directions of the first reflections are important because the geometry of the human head modifies the sound entering the ear canals. When the sound arrives to the listener from the side or lateral frontal directions (blue curves in Fig. 2), the high frequencies are amplified more than for the sound reflected from the ceiling (red curves) before reaching the human head. Even though in Fig. 2 the mean difference is only a few decibels, this difference is notably in the same frequency region where the loud orchestra music has more energy than the quietly played music (dashed curve). In summary, when walls and ceiling of a concert hall attenuate high frequencies as little as possible and when the first early reflections are bounces from the sidewalls, the change of the spectrum of orchestral music makes the largest perceived crescendo [7]. Furthermore, auditory masking also plays a role here, but due to its complexity we leave it out in this context.

Figure 3 visualizes the measured spatial sound energy distribution as a function of time at two seats in the Berlin Konzerthaus (BK, rectangular hall) and in the Berlin Philharmonie (BP, audience surrounding the stage). At both seats in BK the early sound energy following the direct sound reaches the listeners from the side or front lateral directions. In addition, the ceiling reflection is not very strong, and arrives much later in time. Therefore, the early sound energy after the direct sound comes from the optimal directions for amplifying the high frequencies as much as possible (see blue curves in Fig. 2). Moreover, there are several of those lateral reflections. In contrast, in BP such early lateral reflections do not exist, but the ceiling reflections are considerably more dominant. Again, as shown in Fig. 2, those reflections emphasize less the high frequencies, which are disproportionally excited more when the orchestra plays loud. This results in weaker fortissimos and reduced dynamics to the audience. To conclude, the rectangular halls provide more reflections that support the high frequencies, which carry the power of loud playing. Thus, it is no wonder why nearly all world-renowned concert halls are rectangular with parallel sidewalls and side balconies.

The acoustics of a concert hall is a great example of research that needs multi-disciplinary understanding of music, room acoustics and human perception. Extensive research has been carried out over several decades without a comprehensive understanding of all involved components of the system. Finally, we have the technology to make rigorous studies on individual components together and this has allowed us to connect the dots and see the bigger picture clearly. Does the research in your field really understand the complete picture - could there be a non-linear component hiding somewhere, making measurements hard to interpret? ■



▼ **FIG. 3:** Spatiotemporal visualizations of sound energy on two equivalent seats in two concert halls (Berlin Konzerthaus, BK, and Berlin Philharmonie, BP). The curves indicate the forward-cumulative wide-band energy at time instants of $t = 5, 10, 20...200$ ms. The thick black curve shows the early energy accumulated from the initial direct sound up to 30 ms. The outermost red curve is the spatial energy distribution of the full room impulse response including the late reverberation tail.

About the authors

Prof. Tapio Lokki and Dr. Jukka Pätynen work at the Aalto University School of Science, Finland. Prof Lokki's multi-disciplinary Virtual Acoustics team has successfully applied sensory evaluation methods to reveal the secrets of concert hall acoustics. The team has invented novel measurement and visualization techniques for room acoustics research and developed listening test methodology to study human auditory perception. The main funding sources of the team are European Research Council and Academy of Finland.

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