

# Throw Away that Standard and Listen: Your Two Ears Work Better

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The acoustics of a concert hall is often described with the help of ISO3382-1:2009 parameters. However, several recent studies suggest that ISO3382-1 cannot explain the details of subjective perception nor preferences of the listeners. The current parameters, averaged over listener positions, and the use of only mid frequencies are definitely inadequate. We have recently measured over 15 concert halls around Europe with a novel measurement system – the loudspeaker orchestra. It consists of 34 calibrated loudspeakers on stage to simulate an orchestra, the most common sound source in concert halls. For objective analysis and spatial sound reproduction, we measure spatial impulse responses from each loudspeaker at accurately defined receiver positions. This enables accurate comparison of the properties of spatial impulse responses between halls. Furthermore, we have developed methods to convolve anechoic symphony orchestra recordings with the measured spatial impulse responses for multichannel loudspeaker listening. Both subjective comparison of halls and objective analysis with time-frequency and spatiotemporal properties of impulse responses have helped us to link architectural features and subjective perceptions. This article gives example of these links and shows the importance of early reflections for engaging sound.

## 1. INTRODUCTION

The acoustics of concert halls and rooms have been investigated for over 100 years. Since the pioneering work of Sabine<sup>1</sup>, scientists have strived to understand why some concert halls sound better than others and what perceptual attributes contribute to the general opinion of extraordinary acoustics. In order to understand human response to the complex sound field in an enclosed space, research on room acoustics has been done with both objective and subjective methods<sup>2</sup>.

Subjective comparison of concert halls is not an easy task, because preferred acoustics depends on a large number of elements. The music, the conductor, and the performance of the orchestra greatly affect the listening experience, and the contribution of the auditorium itself is hard to isolate with subjective surveys. Traditionally, concert hall evaluation research has been implemented with questionnaires<sup>3,4,5,6,7,8,9</sup>, or by comparing recordings or simulations<sup>10,11,12,13,14,15,16</sup>, with

attributes that are usually defined by the researchers. The studies made in-situ while listening to a real orchestra have revealed that important perceptual features are *loudness*, *reverberance*, and *intimacy*. Laboratory studies have confirmed these discriminating factors, but the possibility for instant comparison inherent in the test conditions helped subjects to also hear differences in *clarity*, *openness*, *spaciousness*, and *timbre*. However, spatial sound rendering in the laboratory, while suitable for comparative judgments, has not been at the level of authentic reproduction of the original sound environment, thus the spatial sound quality of these investigations have room for improvement. Moreover, despite numerous earlier studies, concert hall acoustics and human perception of sound in such spaces are not yet understood in all aspects.

A few years ago, the ambivalent interpretation of interviews done in-situ in concert halls and the methodological problems of traditional listening tests in

laboratories made us rethink the whole subjective evaluation process. We borrowed a sensory evaluation methodology from the food and wine industry<sup>17</sup>; wine tasting shares similar problems with acoustics, such as multidimensional perceptual attributes and matters of personal taste. The sensory evaluation process requires that listeners are able to compare concert halls in the blink of an eye. Therefore, to capture the sound of the same symphony orchestra in every hall we invented a novel concept to simulate a symphony orchestra in real halls: a loudspeaker orchestra<sup>18</sup>. The loudspeakers reproduce anechoic symphony orchestra recordings<sup>19</sup>, and recordings at different seats are made with multi-microphone techniques. In our recent studies, the multi-channel spatial sound rendering has been realized with Directional Audio Coding<sup>20,21</sup> and with Spatial Impulse Response Rendering<sup>22,23</sup>. Recently we have developed a novel method, the Spatial Decomposition Method, to perform even more authentic spatial sound reproduction in the laboratory<sup>24</sup>. With multichannel 3D sound rendering techniques, concert halls can be accurately compared enabling the use of sensory evaluation methods to extract the multidimensional perceptual differences between concert halls<sup>25,26</sup>. Moreover, the preference ratings have been tentatively linked to the sensory profiles to explain the perceptual features behind preferred acoustics.

## **2. OBJECTIVE MEASUREMENTS OF CONCERT HALLS**

As the subjective comparison of concert halls is difficult and often biased by matters of taste, researchers have tried to invent objective ways to measure some features of the acoustics. This work has led to the definition of acoustic parameters described in the international standard ISO3382-

1:2009<sup>27</sup>, illustrated in Figure 1. The standard requires that room impulse responses should be measured with an omnidirectional loudspeaker from few source positions on the stage to 6-10 receiver positions in the audience area. The capturing microphone should have omni or figure-of-eight directivity. The parameters are computed from the sound energy decays at different frequency bands.

The ISO3382-1:2009 standard has been criticized from many angles<sup>28,29</sup>. For example, the algorithms to compute the parameters are imprecise, the applied frequency range is inadequate, and a single omnidirectional source does not correspond to a real orchestra, which, in reality has dozens of sources with varying directivity characteristics. Moreover, averaging results over several receiver positions hides information as the parameters vary at different seats quite a lot. However, it is generally accepted that some of the standard parameters correlate quite well with subjective perceptions, e.g. Strength (G) with loudness and early decay time (EDT) with reverberance. In contrast, other perceptually relevant factors, e.g., intimacy, have no corresponding objective parameters, and values for parameters that correlate with subjective preference judgements are very cumbersome to define.

In order to overcome the inherent simplifications in standard ISO parameters, we have recently taken a novel approach to measure and analyze concert hall acoustics, illustrated in Figure 2. The spatial impulse responses are measured with all loudspeakers of the same loudspeaker orchestra used to simulate symphony orchestra for subjective studies. The directivities of the loudspeakers are not omnidirectional and they differ from the directivities of real instruments. However, we have tried to minimize the possible errors by choosing appropriate loudspeakers<sup>18</sup>. The spatial impulse responses for objective analysis are

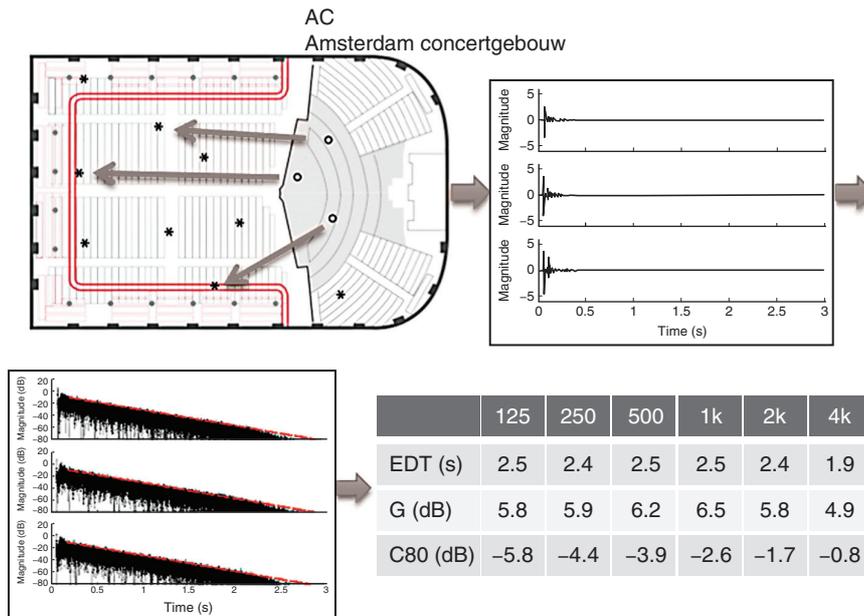


Figure 1. Impulse response measurements from a few source positions to 6-10 receiver positions are the basis for the objective measurements in a concert hall. The room acoustical parameters (ISO3382-1:2009), such as early decay time (EDT) or clarity (C80) are presented as spatial averages of values derived from the decay of the sound pressure level.

captured with a microphone array, currently with six omnidirectional microphones. Such an array enable analysis of the spatial distribution of sound energy. With such information, new time-frequency and spatiotemporal visualization techniques allow examination of sound energy levels in many dimensions: time, frequency, and space (azimuth and elevation). Visualizations<sup>30</sup> link the development of the spatial sound field over time to the plan and section drawings of the measured concert halls (Figure 2).

Figure 2 is an example analysis of the spatial impulse responses of Concertgebouw, Amsterdam when the receiver position is 19 meters from the closest loudspeakers on stage. The time-frequency plot on the top right shows how the frequency response (average of all 25 source channels) evolves in time. The black thick line shows that after 30 ms there is quite deep dip between 100 and 200 Hz, the well known seat dip caused by diffracted and delayed copy of the direct sound<sup>31,32</sup>. However, at 70 ms after the direct sound the frequency

response is already quite flat and after that sound energy grows gradually. After 200 ms (last grey line, the red line is the final response) the energy still grows at all frequencies indicating nice and audible reverberation. When looking at the spatial distribution of the sound energy (again averaged over all source channels), it can be seen on the bottom left that the first 30 ms forms a triangular shape with clearly separated direct sounds. Thus, two reflections from side walls indicate fast lateral reflections giving strength to the direct sound and nice frontal sound image with good auditory source width. Again, the sound energy grows gradually in all directions suggesting good and smooth envelopment. The final response (red curve) is round and stays few dBs below dashed circle, which indicates energy of sources in free field at 10 meters (normalization that is used in ISO parameter Strength,  $G$ ). The middle figure on the bottom row shows sound energy distribution on section. It can be seen that no strong ceiling reflection is present. In addition, the thick 30 ms

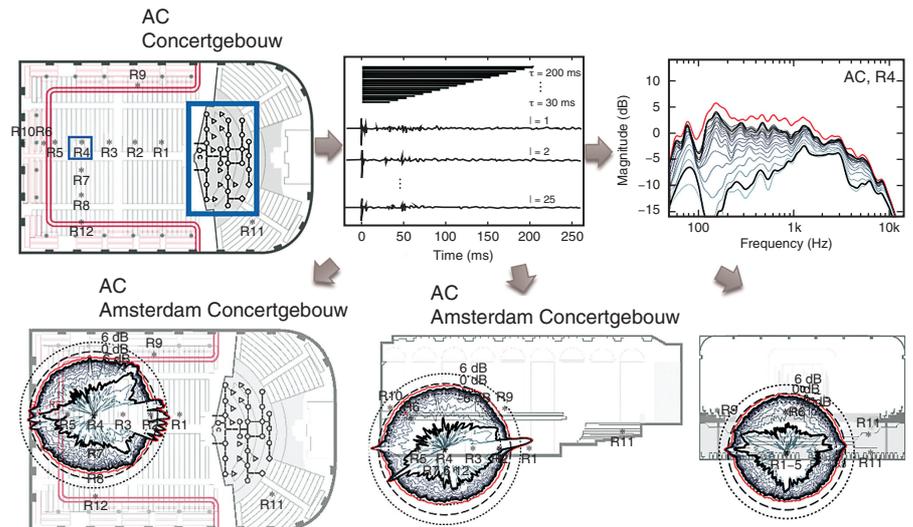


Figure 2. Our approach is to use 34 loudspeakers, which form 25 source channels, and capture spatial impulse responses with a microphone array in one receiver position at a time. The objective analysis is done individually for each response and averages of time-frequency and time-space analyses are plotted to visualize how sound field evolves in temporal, frequency, and spatial domains<sup>30</sup>.

curve shows quite a lot of energy reaching the microphones below, see also the rightmost plot showing sound energy in transverse plane. This early energy below causes the seat dip effect. In transverse plane the thick 30 ms curve shows also that there are indeed four lateral early reflections, two from side walls and two under balcony reflections. Finally, the spatial distribution of reverberation is uniform and the final level is quite high.

### 3. CONCERT HALLS MEASURED WITH THE LOUDSPEAKER ORCHESTRA

So far we have measured 19 concert halls with our loudspeaker orchestra. Nine of them are in Finland and 10 central European halls were measured in November 2012<sup>33,34</sup>. All data have not been analyzed yet and so far we have studied only the Finnish halls with listening tests using sensory evaluation methods<sup>25,26</sup>. These studies have already revealed a lot of novel information on the discriminating subjective attributes that can be used to describe aural differences between halls and how different people compare the halls<sup>35</sup>. In

addition, the results made us study detailed properties of reflections and we found that early reflections from diffusors might lower the sound quality<sup>36</sup> and lateral reflections are preferred as they are perceived louder than median plane reflections due to the shape of the human head<sup>37</sup>. However, much more work is still needed to find all links between architecture of concert halls and the perceived sound and room acoustics quality.

Although we have not yet studied the famous European concert halls with formal listening tests, some example cases are presented here. A few interesting seats are analyzed with the novel spatiotemporal visualization technique<sup>30</sup> (see Figure 2).

#### 3.1. EXAMPLES OF THE DIFFERENT SOUNDING SEATS AROUND EUROPE

Figure 2 already showed the sound distribution in one of the best seats in Europe. Very similar sound energy distribution can be found, e.g., in Musikverein, Vienna and Stadthalle, Wuppertal, see Figure 3. All these visualizations show strong enough direct sounds, clearly visible lateral

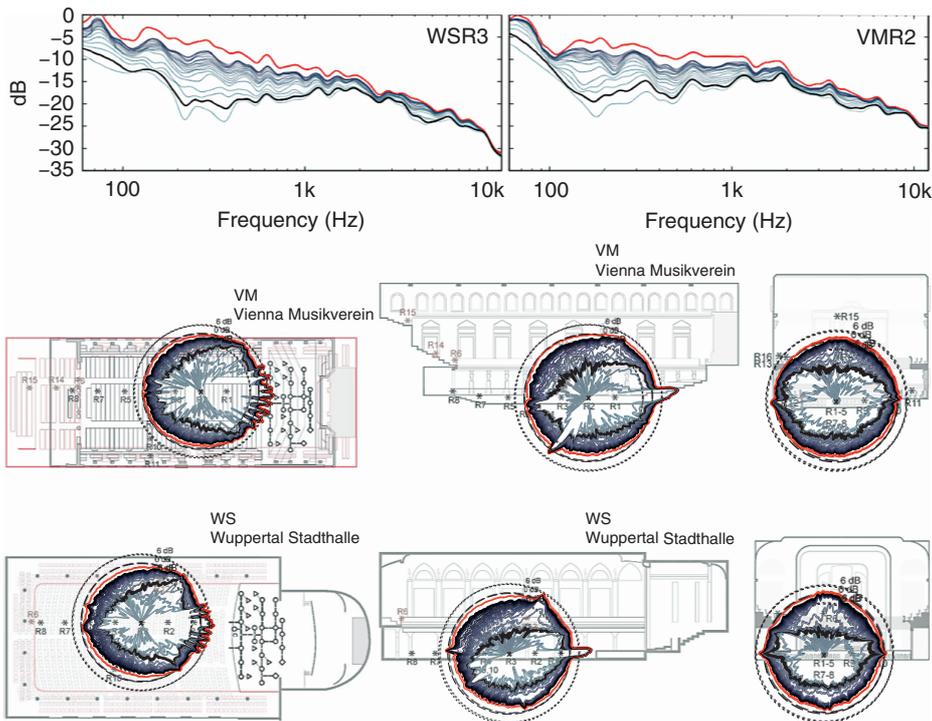


Figure 3. Spatial distribution of sound energy in Vienna Musikverein at the distance of 11 meters and Wuppertal Stadthalle at 15 meters from the loudspeaker orchestra.

early reflections, hardly any ceiling reflections, very good envelopment and enough sound power. The visualizations of changes in frequency responses tell about the frequency balance and timbre of sound, and indeed all these three seats (in Figs. 2-3) have slightly different sound color. However, all of them have enough/strong bass and a lot of high frequencies resulting in warm sound with good envelopment and openness.

It is not a surprise that the best seat examples are from shoe-box halls. Those halls also have a flat floor on the audience area enabling nice enveloping reverberation. If the audience area is strongly inclined the seats behind block the enveloping reverberation. This is quite well seen in the directional analyses shown in Figure 4. Moreover, due to the lack of the side reflections the thick 30 ms curve is oval and the final energy (red curve) is not round. In Berlin Philharmonie there are quite late side reflections that might be perceived as echoes. The section plots show nicely the ceiling reflections typical to these

geometries. In Cologne Philharmonie the far back wall of the hall reflects energy that reaches the listening position very late, making the perceived sound image even more monophonic.

The final examples are from two vineyard type halls, seats on the side or behind the orchestra, see Figure 5. Such seats have obvious balance problems between instrument sections and loss of high frequencies due to the directivity of instruments<sup>38</sup>. The lack of early lateral reflections is clearly seen and the envelopment is mild. Moreover, even though the seats are quite close to the stage the overall sound power is weak. The section plots show strong and quite late ceiling reflections that might result, together with attenuated high frequencies, in a distant sound image.

#### 4. FINAL REMARKS

The purpose of art, including acoustic music presented in a concert hall, is to bring joy to everyday life and tell stories. The composers try to convey their ideas, feelings, imagination,

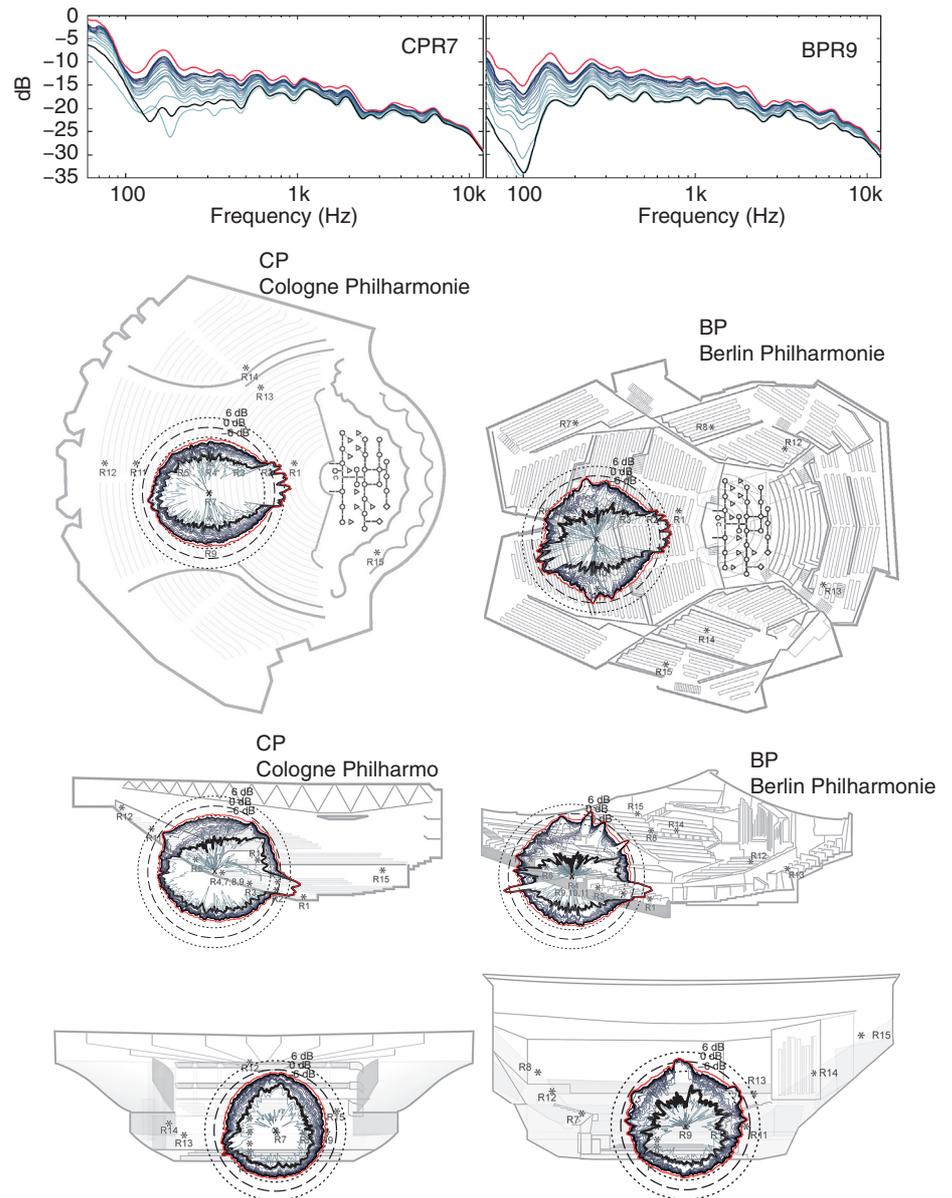


Figure 4. Spatial distribution of sound energy in Cologne Philharmonie and Berlin Philharmonie.

emotions, etc. with the help of musicians, to the listeners. Therefore, the concert hall has to support musicians in their work and it needs to carry the music from the stage to the audience with full spectrum and dynamics. The concert hall as a medium for sound propagation is a linear system, while the dynamics of music and human binaural hearing are non-linear in many ways<sup>39</sup>. The objective means to measure acoustics are based on impulse responses and parameters derived from them, which is physically correct as the hall is a linear system. However, the interpretation of those parameters

should be revised to take into account the non-linearities of music dynamics and human hearing. For example, just noticeable differences of objective parameters should be frequency dependent to understand better the acoustics of concert halls.

Most people seems to prefer the acoustics that renders the sound of an orchestra intimate and close, with good clarity and openness and the most importantly the sound has to be loud enough and envelop the listener. To render open sound with large dynamics the concert hall has to create quite strong early lateral reflections with full

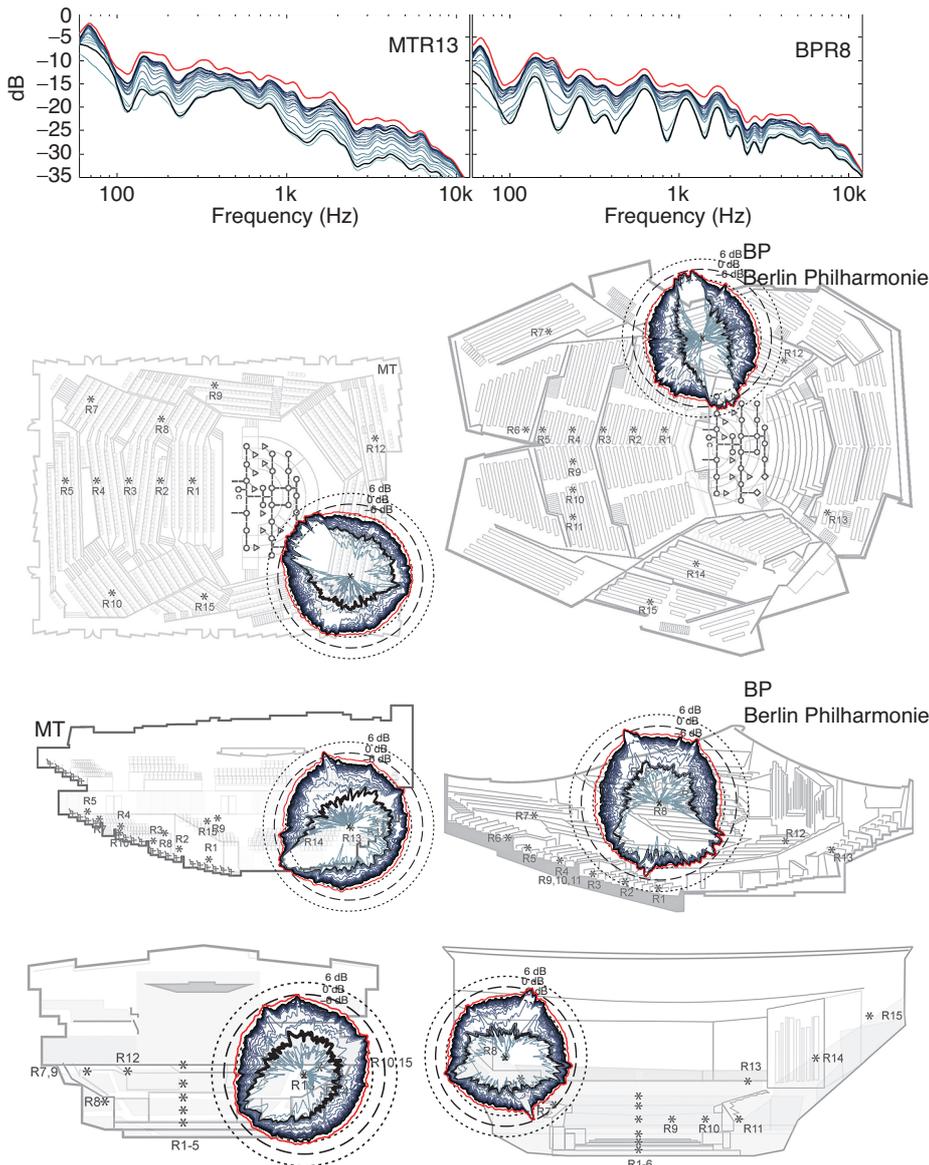


Figure 5. Spatial distribution of sound energy close to the orchestra on the side audience sections in Helsinki Music Center and Berlin Philharmonie.

bandwidth<sup>37,40</sup>, hopefully from surfaces that do not modify the phases of different frequency components<sup>36</sup>. The ingredients of engaging sound are large dynamics, proximity, envelopment, flat and rich frequency response and finally slightly emphasized bass to give warmth to the sound.

## ACKNOWLEDGMENTS

I like to thank the whole Virtual Acoustics team for the hard work that has led to the results presented here. The research leading to these results has received funding from the Academy of Finland, project nos. [257099] and the

European Research Council under the European Community's Seventh Framework Programme (FP7/2007-2013)/ERC grant agreement no. [203636].

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### MARKET IN NOISE RIGHTS

Airports should be able to buy the right to expand and emit more noise by paying compensation to local residents, a think-tank has proposed. The UK's Institute of Economic Affairs (IEA) said government involvement in the debate over aviation capacity is both unnecessary and undesirable and so airports need to be given the ability to cut deals with local residents independently. Rather than getting involved in decisions about where to expand capacity, politicians should give airports a means to reach agreements with residents affected by their decisions. A compensation mechanism would allow agreements that benefit both airports and those who live in their surrounds, the think-tank said. Also, the IEA said "tax havens" could be created around airports which pay a large proportion of local levies, allowing residents to pay lower taxes.

### COMPLAINTS DATA ISN'T ALWAYS WHAT IT SEEMS

More than half of the 3,405 noise complaints filed in January by Chicago residents near O'Hare International Airport came from just five households. And 1,363 airplane-noise complaints came from a single address in northwest suburban Itasca - an average of 44 per day for the entire month. Meanwhile, a Norridge household filed 419 complaints, and 261 came from a single address in Wood Dale.

### 3% OF UK WINDFARMS PRODUCE LF NOISE

Only about 3% of windfarms in the UK are likely to produce a low-frequency sound that can be heard up to a kilometre away. The thumping "whoomph"-like sound, produced when the blades on a turbine partially stall because of changes in wind speed and direction, is about as loud as the noise from a single carriageway road, according to a review of evidence on the effect. Opponents of windfarms often cite noise concerns along with aesthetic complaints, but the problem is shown to be infrequent and can be easily fixed with software changes, said trade body RenewableUK, which commissioned the report. The noise - known as other amplitude modulation - is different to the normal "whooshing" sound that can be heard close to turbines as they cut through the air. The review looked at previous reports, including a 2007 University of Salford paper that found of the 133 wind turbine sites around the UK at the time, four were definitely creating the sound, and eight were possibly connected to it but could not be proved conclusively. "It can be read that a similar percentage could apply now," said a RenewableUK spokesman, suggesting at least 15 of the current 521 wind turbine sites are affected by the problem. The report, by the Temple Group environmental consultancy, also said that the problem is easily solved by changes to the software running the turbine, which rectifies the stalling problem. Local authorities that receive complaints about such noise can force turbine operators to rectify the issue.

### ARE NOISE COMPLAINTS RACISM?

Tampa (Fla) police fielded more than 6,000 noise complaints last year. About 850 of them concerned booming car stereos that disrupt sleep and shatter the quiet in neighborhoods. The city acted last year to curb the complaints after the state Legislature balked at passing a statewide measure. Some legislators were concerned the crackdown on loud car stereos amounted to racial profiling. Police in Tampa said many of their complaints came from neighborhoods with large minority populations.