

Are Virtual Sounds Real?

Michael Vorländer

Address:

Institute of Technical Acoustics
RWTH Aachen University
Kopernikusstrasse 5
52074 Aachen
Germany

Email:

mvo@akustik.rwth-aachen.de

Are virtual sounds real? Yes, they are if the computer simulation of the sound is accurate and fast.

We have enough real sounds around us. Why create virtual sounds?

Introduction

Imagine if we could listen in the future, such as music in future concert halls. Imagine if we could transport ourselves into the past, as when jazz was born in New Orleans.

A marching band in the Mardi Gras in New Orleans (LA) is a very dynamic acoustic situation that includes many moving instruments, a great deal of directional information, and many other features that create multidimensional impressions, a good mood (or annoyance), and a clear sense of this event as a vivid music festival (see bit.ly/33GBjy8). This video, which was recorded in 2017, is, in a way, an historic document, with visual and auditory information captured and stored for future replay. Although the video provides some sense of the Mardi Gras, wouldn't it be fantastic if we could be "inside" the event in a three-dimensional (3-D) immersive environment, which is quite a different experience from watching the event in the video, on TV, or as an "outside" observer?

It would also be quite amazing if we could place Louis Armstrong in one of the bands! If this works, why not change the location of the band to Bourbon Street in 1920? And then we could rather re-create this scene in full 3-D (**Figure 1, right**). With an appropriate acoustic component in virtual reality (VR), we can transform the historic scenario (see bit.ly/2X5yiVV) into an immersive 3-D experience with "real" sound instead of a silent movie with added music.

Of course, to get the immersive 3-D experience, we need more than just the recording of the total sound at the observer's (camera/microphone) position. Instead, we must start with capturing data from all of the instruments, one by one, and then

Figure 1. See and hear the difference. **Left:** watching Mardi Gras on a TV set; **right:** being literally "inside" Mardi Gras, in a virtual acoustic environment. Original photo of marching band by Prayitno, used under the Creative Commons license with attribution (CC BY 2.0).



determine their sound radiation into the environment, one by one. With this approach, we can create a new situation by extracting instruments, adding new ones, and changing the scene elements such as buildings, road surfaces, and source trajectories. This must, however, include all the dynamic and vivid atmosphere of Mardi Gras, creating a virtual Mardi Gras presented through an immersive VR device (**Figure 1, right**).

Another task that is quite different from the virtual Mardi Gras is to plan the renovation of an office space. People who will be working in the new space will want to know what it will be like. They are likely to expect an improved workplace that is more comfortable and perhaps quieter than they had before the renovation.

One way to help them envision the new workspace is to use VR to create a virtual office. This would not only include the renovated physical environment but also the sound sources (e.g., HVAC, printers, copy machines, phone calls, conversations). This VR office would thus include the room design from the architectural software as well as from the acoustic simulation. As a result, the virtual office could be seen and heard through a VR device. This virtual office can then be used for presentations by the architect and serve as the basis for discussions with the client as well as for decisions about the final design and materials. Of course, one of the most valuable features of the VR is that the user can move in the virtual office, thereby enhancing the realism of the experience.

The same technology can be used for planning the announcement system in a subway station, such as in New York City. Understanding speech announcements is not an easy task in this type of noisy space, particularly for hard-of-hearing people. A simulation in VR could not only be used for planning purposes but also for listening experiments designed to provide a better understanding of how the auditory system performs in environments with a very complex setting of moving sound sources, reverberation, and interfering speech while concentrating on the announcement from what is generally a rather poor public address system.

If you are curious to hear and see examples of applications of acoustic virtual reality (AVR), there are links to demonstrations at the end of the article.

Acoustic Virtual Reality

VR is a very powerful computer tool that is connected to 3-D devices for auditory-visual impressions. Cave automated

virtual environments (CAVEs) were invented by Cruz-Neira et al. (1992). VR started with large and expensive hardware in setups of CAVE-like environments that can best be compared to the Holodeck that was featured in the TV show *Star Trek*. The Holodeck is a room where the user can experience a virtual world, including interactions with virtual objects and/or virtual lifeforms (see bit.ly/2OcHfZe).

Although the Holodeck is likely some years in the future, we can get a somewhat similar experience with head-mounted displays (HMDs) and headphones. Using such devices, audio-visual presentation became affordable for everybody, and thus entertainment, gaming, and social networks are rapidly entering the concept of virtual environments.

However, the acoustic component of the virtual environment is generally rendered just as a sound “effect” and does not follow the strict principles of sound source calibration and sound propagation. The proper choice of sound in VR depends on the application, so it must be decided if the virtual sound should be as close to reality as possible or if a more or less plausible sound event is sufficient, such as in gaming.

In this context, a “virtual” sound is, in fact, a real audible sound that was created by simulation of a virtual scenario. This has many similarities to acoustic illusions, such as creating a specific auditory sensation of a musical experience.

In music production and audio engineering, stereo mixing or higher order spatial audio systems are designed to balance the sounds into a spatial sound event that contains both localization and distance cues as well as the relative levels and spectral filtering to achieve a “good” sound. Although current audio systems share some similarities with AVR, the spatial audio technology used by the music industry has a different goal, which is to produce an artistically designed reproduction of an enjoyable music event. In doing this, the sound engineer can use many degrees of freedom and add, suppress, and enhance sound components until, in the end, it is heard as it is in “What Does It Sound Like, Baby?” (Ray Charles; see bit.ly/2KaW0e0).

Challenges of Acoustic Virtual Reality

In contrast to what sound engineers do, the VR sound in the virtual environment is created from computer data, computational simulations, and audio signal-processing technology, with the goal of producing an auditory illusion that is, at its best, an exact copy of the real-world counterpart, if this exists.

If there is no real-world counterpart, it is even more challenging to create a virtual auditory event that exactly anticipates the sound that will be present when the space is actually built.

Another important feature of VR is that the virtual environment is presented in 3-D, and the user is embedded into the scene and is able to interact with the scene, move in the scene, or even change the environment on the fly. In contrast, sound engineering for music and films does not provide interaction. The interaction part makes the difference when it comes to VR.

Accordingly, there are requirements concerning processing speed for the digital signal-processing algorithms required for VR. One (for sufficient audio-frequency bandwidth) is that the sampling rate must be greater than the 40 kHz required to reproduce the frequency of human hearing.

The second requirement (for interaction) is the quick adaptation to scene changes that may result from (1) movement of the source and/or receiver, (2) changes in the orientation of one or both, and/or (3) changes in the virtual environment such as if a door is opened or closed. Thus the update rate of the VR environment for simulating a new direction, a change of distance to the sound source, or a new room-acoustic condition must be fast enough to provide consistency between the auditory and visual impressions.

Imagine that your VR experience is that you are entering a building from the street. You would expect that the VR system would react in such a way that you would have the sense of being indoors the moment you stepped through the virtual doorway rather than this happening several seconds later. The threshold of perceiving delays in an auditory presentation depends strongly on the type of the sound stimulus. Generally, update rates of greater than 20 Hz (or latencies of less than 50 ms) are considered sufficient for obtaining a smooth and realistic sound image.

So, to have a proper VR environment, we need sound sources and their signals, quick processing of the signals, and 3-D audio. What are the steps for creation of sound in virtual environments?

Workflow in Virtual Acoustics

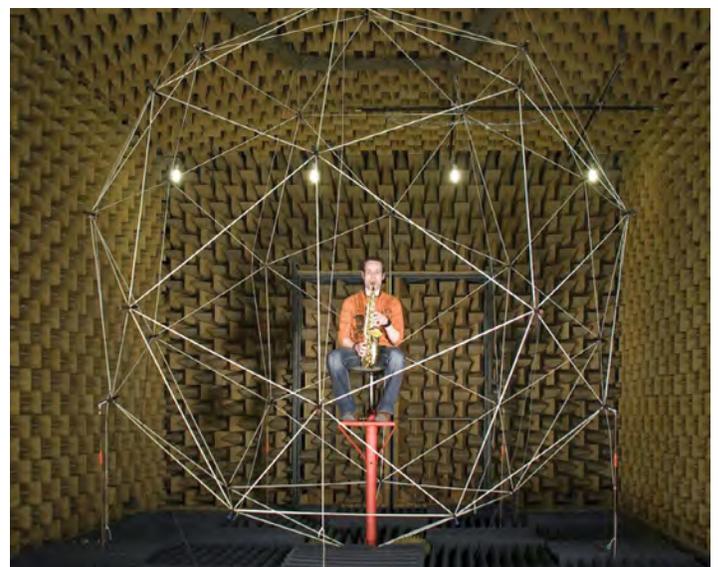
Source Characterization

Virtual acoustics (VA), like music production, starts by recording or synthesizing sound signals (see article in this

issue of *Acoustics Today* by Hawley et al. on new approaches to music synthesis). For VA, this step must be designed to enable reproduction of the recorded sound into a 3-D space in flexible settings. Examples for musical sounds captured in 3-D are multichannel recordings and simulations (e.g., Rindel et al., 2004). Behler et al. (2012) measured musical instrument directivities that were later optimized and published by Shabtai et al. (2017) for open access (e.g., **Figure 2**). Bellows and Leishman (2019) studied phoneme-dependent directivities of speech sound, whereas Ackermann et al. (2019) showed the importance of dynamic effects of source movements in musical expression. Thus, source characterization of musical instruments and the human voice is far more than a simple recording. Many factors are required, including the spatial radiation pattern stored in appropriate data formats (e.g., spherical harmonic modal decomposition), equalization filters between the nominal null direction and other directions, and the sound signal (audio stream) in the null direction sampled in digital-audio quality.

If we apply the same concept to noise sources such as moving cars, trains, or aircraft, audio signals and directivities will also be obtained. It is obvious that one cannot record the directional sound signals of a flying jet airplane with a surrounding microphone array. But theoretical, computational, or experimental methods can be applied to determine at least an approximated power spectral envelope for the stochastic noise components such as jet noise, tire noise, and wind noise. In this case, excellent and very plausible results can be

Figure 2. Thirty-two channel surrounding microphone sphere for simultaneous music recording and instrument directivity measurement.



derived from measurements or physical modeling that may result in noise spectra in frequency bands. White noise filtered with these spectral features sounds quite similar to, for example, the original jet noise or wind noise. For machines or engines with rotating components or for noise from rolling wheels, a pure-tone synthesis can be added that is controlled by using revolutions per minute (rpm) data. This was applied by Pieren et al. (2017) for a train simulation and in an excellent overview by Rizzi (2016) for aircraft noise simulation.

Coming back to musical sounds, the next question is how the musical instrument excites the surrounding space to create a sound field for an immersed listener.

Sound Propagation

The primary sound waves radiated from the source propagate through the environment to the listener. In the context of VA, the function between the excitation at the source and what is received at the listener is an impulse response or, in terms of signal processing, a “filter” transforming sound signals from the source to the listener. It is thus important to deal with sound propagation models as filters, always keeping in mind the audio time and frequency resolution of the source signals and the processing time (latency).

Now, let’s return to the marching band in the Mardi Gras parade. Up to this point, we have all the instrument sounds properly recorded in the free field in 3-D (for the whole band, this requires careful consideration of the players’ interaction and synchronization of the instruments) and we have source directivities for the instruments. In the virtual environment, the music sounds will propagate from the source position in spherical waves and directional weighting into the street canyon, where reflections and scattering will happen until the waves sum up at the listener’s position. The impulse response containing all sound paths connects the source and the receiver. In digital signal processing, the effect of the sound propagation on the source signal is introduced by filtering the sound sources signals with the impulse response.

Of course, at Mardi Gras, both source and listeners are likely to move, which sets a clear violation of time invariance and linear filter processing, both of which are prerequisite for simply filtering the source sound. Slow time variances, however, are usually accepted if stepwise time-invariant filtering with adaptive filters is applied. “Slow” movements simply mean slow compared with the speed of sound. With faster moving sources, such as road or rail vehicles or aircraft, we have to consider the

Doppler effect, which causes a frequency shift depending on the speed of the source related to the medium (normally air). The propagation times can be adapted to the relative movement in the trajectories between the source and the receiver by nonuniform resampling to introduce the Doppler shift (Wefers and Vorländer, 2018).

Thus, the acoustic environment model must include the relevant acoustic features such as reflection, transmission, diffraction, refraction, attenuation, wind speed, and temperature profiles in the atmosphere. In indoor spaces, the primary issues are reflection, transmission, and diffraction. However, for outdoor environments, all effects listed above may be relevant. Well-established models for all of these effects have existed for decades, so what’s the challenge in VA? It is real-time performance for audio signal processing!

Computationally expensive wave models and precomputed filters in look-up tables may solve the task of instantaneous adaptation to scene changes, but a more elegant solution is “real-time simulation” during use of the VA system. As soon as the scene changes, this simulation result is updated within the above-mentioned maximum latency of 50 ms. In the Mardi Gras scene, the band moves and the listener can move as well and/or turn the head as they look from one instrument to another.

For impulse-response calculation in real time, and for the present time, it is only possible to do approximations of “geometrical acoustics” (Savioja and Svensson, 2015). In geometrical acoustics, sound paths are constructed by connecting the source point and the receiver point with a straight line. Curved paths are also possible, as in the case of refraction in the atmosphere or in other layered media. For the sound propagation outside the direct path via the direct line of sight, reflection, scattering, and diffraction may lead to physically consistent paths. In this case, the computer must find those paths by checking their validity. This is as if one tries to target a billiard ball by bouncing another ball off a side wall (“cushion”).

Striking balls in various directions and detecting which ones hit the target is called “ray tracing,” a method used in both optics and acoustics. Ray tracing can also handle scattering when the sound interacts with bumpy walls. This means that the ball is “reflected” into odd directions and is not consistent with Snell’s law (angle of incidence equals angle of reflection) because that only holds for smooth walls. In ray-tracing

algorithms, this is accounted for by distributing the energy according to the physical properties of the boundary, which are the absorption coefficient (α) and the scattering coefficient (s). Needless to say, this also works if the billiard ball hits several walls sequentially.

The sound path can also be constructed from knowledge of the wall position by applying the “image source method.” Here, the exact point of reflection of the ball is marked with the aid of an image source so that this position can be perfectly targeted. This method, however, excludes scattering phenomena. This is a pity because it is known that acoustic scattering is a very strong effect that mostly dominates the sound propagation after a few consecutive wall hits. This is why the image source method has very limited relevance for accurate room-acoustic modeling.

The methods used in current practice are hybrid models of image source and ray-tracing algorithms to account for specular reflections and surface scattering, respectively. Good diffraction models are available, such as those based on the uniform theory of diffraction (UTD) by Biot and Tolstoy (1957) and implemented by (Torres et al., 2001). Geometrical acoustics models can thus deliver filter updates in real time (Savioja and Svensson, 2015).

A larger problem, however, is the uncertainty of input data about the environment. Boundary impedances of indoor and outdoor spaces, atmospheric conditions, fluctuations of wind, and turbulence are usually larger influences than numerical prediction errors. The main question that remains is whether these uncertainties are audible. Vorländer (2013) showed that uncertainties of absorption coefficients in room acoustics are above the just-noticeable differences (JNDs) of classical room-acoustic perceptual quantities. Research for decades has tried, without sufficient success to date, to reduce the measurement uncertainty of sound absorption coefficients. We have good sound propagation models, but there is a need for more research on acoustic material models and test methods!

Finally, with an appropriate propagation filter, the primary source signal can be converted into a receiver-related signal because it would be shaped, delayed, or duplicated by reflection by sound propagation in the environment. Now, we just need to present the virtual acoustic scene properly to a human observer.

We Live in a Three-Dimensional World

The listener perception in the real world is three-dimensional, and hence the 3-D sensation is present in any auditory event. Sound sources radiate into the 3-D space and so the virtual environment must be a 3-D sound field solver with 3-D sound pressure output signals that can be experienced by the listener. The type of 3-D coding of the sound arriving at the receiver depends on the sound reproduction system that is used. Several systems in professional audio engineering are directly applicable, including binaural technology produced with headphones or transaural loudspeakers. Headphones are the most popular solution despite drawbacks concerning the lack of exact headphone calibration when used by different individual listeners. Nonperfect headphone calibration may reduce the sensation of “true” 3-D sound down to the extreme case of front-back confusion or in-head localization, but there are very good solutions available (Lindau and Brinkmann, 2012).

Transaural (stereo) loudspeakers do provide sound pressure signals at the eardrum that are exact copies of the binaural signals in the virtual scene. But to achieve a clean binaural sound for the right and the left ear separately, the crosstalk between the left loudspeaker to the right ear and vice versa needs to be compensated for, a problem that obviously does not occur with headphones.

Binaural 3-D sound reproduction by headphones must include tracking of the head orientation relative to the direction of the virtual sound; otherwise the virtual sound would follow the head movements (such as head shaking). This does not happen in real-world listening. Therefore, head orientations must be determined by using head-tracking devices such as gyroscopic or infrared sensors.

If there is more than one listener experiencing a 3-D sound, it is necessary to not only allow for binaural eardrum signals but also for wave fields around the listeners. This is usually done by surrounding the listeners with loudspeaker arrays. The loudspeakers are controlled to simulate wave fronts that carry the information of the virtual sound components concerning amplitude, time of arrival, and direction.

Ambisonics, which is a surround sound format that produces signals not only on the horizontal plane but also above and below the listener, was introduced by Gerzon (1985). It is a rather popular technology used in 3-D audio recording and



Figure 3. Virtual reconstruction of the historic jazz festival in the Casino of Montreux (Switzerland). Available at bit.ly/2vnS8BX.

reproduction. The mathematical concept for ambisonics is based on spherical harmonics (SH), which is an orthogonal functional base that serves as a solution of the wave equation in spherical coordinates. This solution enables plane-wave decomposition of the virtual sound, and from this the voltages driving the loudspeaker are calculated so that the array creates the exact sound arriving from the correct direction. Other loudspeaker-based techniques are vector-base amplitude panning and wave field synthesis, both employing channels in various orders or numbers. More information can be found in Pulkki (1997) and Berkhout (1988).

Applications: Here We Go!

The main feature of VA is the separation of the chain of sound production to sound propagation to sound perception into its elements. Once this is done, it is then possible to do free combinations of sound events in various virtual environments for either indoor or outdoor scenes. There are numerous applications of VA environments in research, in sound design, in noise control, and in acoustic archeology, just to name a few areas. AVR is a meeting point for several technical areas of the Acoustical Society of America!

Revival of Historic Places: Architectural and Computational Acoustics Meet Signal Processing

The Casino in Montreux

The Casino in Montreux (Switzerland) at Lake Geneva was a unique venue that hosted the most important jazz festival in Europe. The Montreux Jazz Festival, started in 1967, highlighted the crème de la crème in jazz.

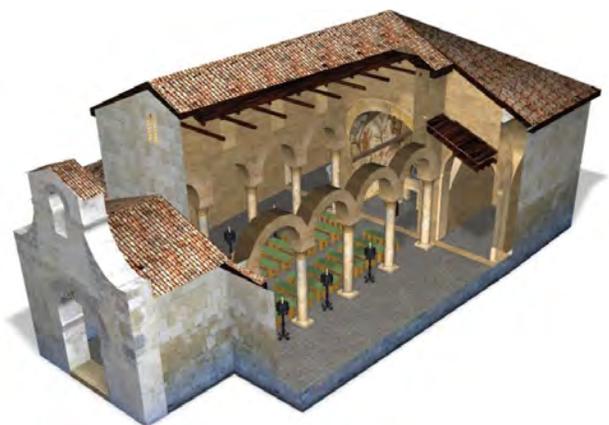
The historic casino building, however, was destroyed in a fire in 1971 during a concert by Frank Zappa and the Mothers of Invention. An interesting side note is that this disaster was referred to by the rock band Deep Purple with “Smoke on the Water” (see bit.ly/2Q8qMbg). From then on, of course, the famous Montreux Jazz Festival had to find another venue. Still, audience and musicians did feel nostalgic about the loss of atmosphere and passion. But there is help: virtual reality!

Imagine that the legendary casino building in Montreux is revived. In fact, Schröder et al. (2015) created a virtual Montreux Casino experience covering the years 1967–1971. This was presented to the audience during the Montreux Jazz Festival in 2014 (**Figure 3**).

San Juan de Baños

In a similar way, Pedrero et al. (2013) presented a reconstruction of an eleventh century church in Spain. The aim was to study “Mozarabic chant” (Asensio Palacios, 2004), which was used when Spain was under Arabic control and decoupled from the Catholic center in Rome (see bit.ly/2XayN0Y). The church is San Juan de Baños in Baños de Cerrato (Castilla y León, Spain), near the city of Valladolid (**Figure 4**). In the eleventh century, the rites and the music in the ceremony were created in an isolated region, which is very interesting for research on culture and music history. Accordingly, various settings found in historic documents and paintings were constructed in VR and the acoustic effect on the singing voices was studied. This included speculations about the existence of heavy curtains and their influence on the sound

Figure 4. The church San Juan de Baños in Spain in virtual reconstruction of the situation in the eleventh century. See video at bit.ly/2rIWuSp.



field and the comparison of standing singers with moving singers in processions.

Noise Impact on Auditory Attention: Architectural Acoustics Meets Psychoacoustics

The objectives in this example are investigations of methods for simulating sound insulation of complex architectural structures and application in cognitive science. It includes predictions of direct and flanking transmission sound energy paths in the building structures based on standardized insulation metrics and, from this, development of VR-rendering techniques for the interactive auralization of such structures. Calculation procedures and models have been developed for the characterization of the impact of airborne and structure-borne sounds in building acoustics. These models, based on certain assumptions and simplifications, incorporate typical room-to-room situations for predicting insulation metrics and sound transmission across adjacent rooms. The simulation was used for auralization in dynamically varying scenarios at interactive rates and was finally presented in VR with HMDs.

Historically, the study of the effective protection of humans from noise in buildings (e.g., apartments, office, classrooms) used subjective ratings that were combined with direct assessments of the noise (loudness, annoyance scales) in psychoacoustic experiments or in questionnaires. Such tests, in fact, draw the test subject's attention and concentration to the sound event, forming an implausible laboratory or field situation. In contrast to these sound-focused procedures applied in the laboratory or in the field, in real life, background noise

from neighbors, building equipment, and traffic is present while people are engaged in their normal activities such as working, learning, resting, and so on. Thus, the important question is the impact of real-life background noise on cognitive performance.

In a recent VR application in the game engine *Unity*, different background speech conditions, convolved with sound insulation filters of adjacent office rooms, were presented in a virtual office environment where the effects on cognitive performances and subjective ratings were measured (**Figure 5**). This exemplary study promises new options for research on noise effects by the use of virtual built environments that are of high plausibility and unlimited variability (Imran et al., 2019).

The Human Factor: Plausibility, Immersion, and Illusion All Meet Psychological Acoustics

Whatever the virtual scene and the sound will be (music, speech, noise), the user should feel present in the virtual environment to the point of feeling immersion in the sound (**Figure 6**). Immersion is defined by Lombard and Ditton (1997) as a partial aspect of "presence" in two levels of perception. The first level mainly depends on stimulating the senses by technology, while the second level refers to the acceptance of the virtual environment by the human. Slater and Wilbur (1997) define immersion as the extent to which simulated environments are capable of conveying an inclusive, extensive, surrounding, and living illusion of reality to the senses of a human. There is, however, no standard definition. Indeed, Witmer and Singer (1998) rejected the exclusive location of immersion at the level of technology. They refer

Figure 5. Virtual acoustic environments (VAE) in architectural acoustics for research in a selective attention task in cognitive science for the evaluation of work performance under background noise from the adjacent office room. **Left:** 3-D model of the Institute of Technical Acoustics (ITA) building with a view into the test room. **Right:** test subject solving the selective attention task (Imran et al., 2019). See video at bit.ly/2O73xvG.





Figure 6. This is a quite uncommon environment, but, hopefully, the listener (with head-mounted display sitting in an Ambisonics loudspeaker array) is immersed in the virtual scene.

to immersion as a personal experience, which usually occurs only in virtual environments and at most arises in other media when a human strongly identifies with the nature of the presented content.

No standard methodology yet exists for measuring immersion. In a study linking psychology and acoustics, Colman et al. (2017) created a catalog with questions in four categories, where room perception, source perception, attention (engagement), and causality are separate components of the feeling of presence in the environment surrounding us. Using this method, VR systems can be assessed if the sources, the rendering algorithms, and the audio reproduction are sufficient for the application.

Final Remarks

More studies in the field of VR are increasingly important because virtual environments offer ground-breaking opportunities for advances in sound assessment, psychoacoustic research, and hearing diagnosis and rehabilitation, just to name a few examples. The ability to process dynamic acoustic situations is an essential component for communication and orientation in everyday life. Nevertheless, the test methods in current practice are far from being under realistic conditions because of too-simple acoustic stimuli.

AVR is the solution because it can incorporate any scene condition with sources and sound propagation features in the environment. The main research direction in AVR is

focused on overcoming the constraints of (1) the number of objects in the scene (e.g., maximal number of sources) and (2) the number of reflecting or diffracting objects that can be handled in real time.

AVR can be used in consulting and acoustics in practice as well! Research and development today is unthinkable without computer tools. In acoustics, computer data as well as measurement data are analyzed regarding the criteria of interest, such as noise levels, speech quality, reverberation times, and source identification. Displaying the data in diagrams, tables, or color maps helps to interpret the acoustic situation. This is a solid basis, for example, in acoustic consulting. When it comes to communication with naive clients, local authorities, or the public, drawbacks are a lack of knowledge about acoustics and, hence, there is a risk of misunderstanding. Examples and case studies may help, but VR does a much better job. The acoustic information is now presented through headphones or loudspeakers. It is remarkable how immediate and unambiguous the relevant information is now conveyed to the listener!

Audiovisual Examples

Virtual acoustics at ITA RWTH Aachen University:

bit.ly/36ZlqUw.

Urban park and congress center: bit.ly/33L4foW.

Aircraft noise: bit.ly/33KzgcB.

Interactive scene in a park: bit.ly/2peKdnE.

Experience of reverberation: bit.ly/2X8CxQs.

Interaction with virtual humans: bit.ly/373l0hd.

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BioSketch



Michael Vorländer studied physics in Aachen, Germany, where he finished his doctoral degree in 1989 with a thesis in room acoustical computer simulation. He has worked in various fields of acoustics such as psychoacoustics, electroacoustics, and architectural acoustics. Since 1996, he has been a professor at the Institute of Technical Acoustics (ITA), RWTH Aachen University. He has served in several organizations as president (European Acoustics Association [EAA] 2004 to 2007; International Commission on Acoustics [ICA], 2011 to 2013) and as an executive council member (Acoustical Society of America, 2017 to 2019). His research focus is auralization. Michael has published 2 books and 15 book chapters, 107 journal articles, 360 conference papers, and 18 keynote lectures at international conferences.