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5pPP1. What can we learn from simulated acoustic environments?

Bernhard U. Seeber*

***Corresponding author's address: Audio Information Processing, Technische Universität München, Arcisstrasse 21, Munich, 80333, BY, Germany, seeber@tum.de**

Psychoacoustic research has often used headphones to reproduce sound stimuli. Recently, the spatial dimension has regained attention in basic research. Here I make a case for the importance of binaural hearing when assessing sound quality. Technological advances made it possible to accurately reproduce real and artificial sound stimuli with high spatial fidelity for their assessment. The Simulated Open Field Environment (SOFE) is a laboratory setup to reproduce sounds from multiple loudspeakers in an anechoic chamber. The free-field presentation allows participants to interact with sound stimuli in a natural way using head turns and movements - important when working with participants inexperienced with laboratory procedures. In connection with room simulation software the SOFE can also create acoustic scenes with multiple sources and sound reflections - thereby increasing the realism. The article gives an overview of application areas for simulated acoustic environments, recent findings gained with the SOFE, and it relates them evaluating sound quality.

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INTRODUCTION

Recently, the spatial dimension has (re-)gained attention in basic and applied research. Technological advances made it possible to accurately reproduce real and artificial sound stimuli with high spatial fidelity for their assessment. The Simulated Open Field Environment (SOFE) is a laboratory setup to reproduce sounds from multiple loudspeakers in an anechoic chamber. The free-field presentation allows participants to interact with sound stimuli in a natural way using head turns and movements – important when working with participants inexperienced with laboratory procedures. In connection with room simulation software the SOFE can also create acoustic scenes with multiple sources and sound reflections – thereby increasing the realism. This paper gives a brief overview of the SOFE and related methods to reproduce 3D sounds for listening experiments and an overview of application areas of the SOFE, recent findings gained with the SOFE, and their relation to evaluating sound quality.

SPATIAL SOUND REPRODUCTION WITH BINAURAL SYNTHESIS AND THE SIMULATED OPEN FIELD ENVIRONMENT (SOFE)

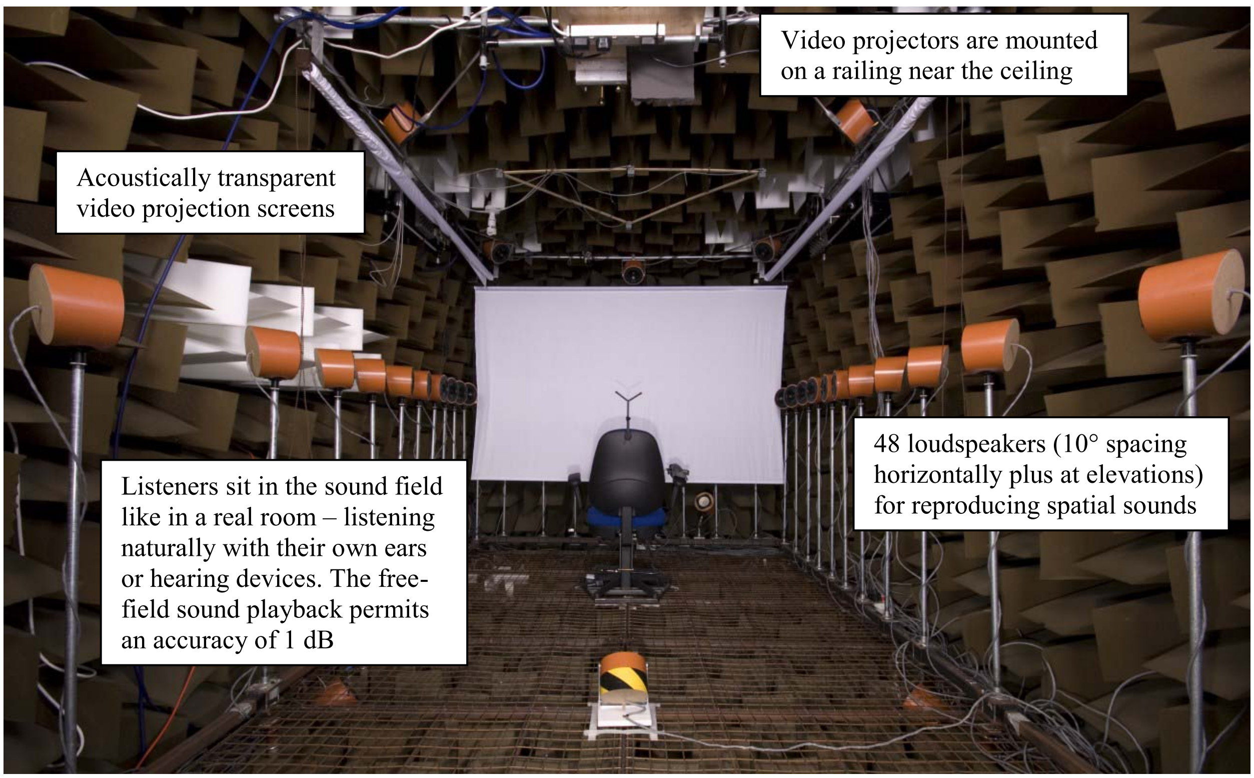

FIGURE 1. Picture of the SOFE in the anechoic chamber at the MRC Institute of Hearing Research in Nottingham (UK).

Sounds can be presented from different virtual directions in rooms using two principles: 1) sounds are played by headphones and spatialized using head-related transfer functions (HRTFs); 2) sounds are played by loudspeakers for which various methods exist to create the spatial sound field, amongst them the approach employed in the SOFE (Schroeder and Atal, 1963; Kirszenstein, 1984; Blauert, 1997; Pulkki, 1997; Spors and Ahrens, 2007; Vorländer, 2008; Favrot and Buchholz, 2010; Seeber *et al.*, 2010). Virtual acoustics using headphones relies on HRTFs which are measured either on an artificial head or with microphones in the ear canals of a person. Filtering the sound with the HRTFs of a certain direction lets the sound virtually appear from that direction. The filtering is done for the direct sound and for all reflections. The impulse responses for direct sound and reflections are summed into a room impulse response for each ear.

Loudspeaker-based auralization came only recently into the focus because of its versatility for research in audiology. Figure 1 shows a photo of our most recent SOFE implementation in Nottingham (Hafter and Seeber, 2004; Seeber *et al.*, 2010). The loudspeakers used to synthesize the sound field are clearly visible. Loudspeakers are equalized for distance-related delay, phase and amplitude such that sounds are reproduced at the listener's head with microsecond-accurate timing and a frequency-dependent error of less than a Decibel. Customized software is used to simulate the sound field in rooms with a variant of the mirror-image source method (Kirszenstein, 1984; Seeber *et al.*, 2010). The software computes impulse responses for each SOFE loudspeaker which contain the sound reflections originating near that speaker. Alternately, using head-related transfer functions the sound reflections can be spatialized for binaural sound reproduction with headphones. In addition to the sound reproduction system, the SOFE contains an interactive visual environment which is projected by three high-definition video projectors. The visual environment is used not only to give and obtain feedback, e.g. with the *ProDePo*-method for indicating the perceived location of a sound by positioning a light pointer (Seeber, 2002), but also to increase realism by embedding the participant into an interactive audio-visual world like in a CAVE. This is important not only for basic research, but particularly for applications with untrained participants, e.g. for product sound quality assessment and when working with children. Recently, McCartney presented a new method for assessing the sound localization ability of toddlers and young children (ages 1-5) which uses the visual environment to interactively engage the child in the sound localization task (McCartney *et al.*, 2011; McCartney, 2012).

APPLICATION AREAS FOR THE AURALIZATION OF ROOM ACOUSTICS

Audiological research

The SOFE was initially developed for research in audiology and basic psychoacoustics. Because the spatial sound field carefully reproduces that found in real spaces such as rooms, one application area are measurements on hearing devices. For example, noise and reverberation cancellation algorithms can be evaluated in a controlled, known, reproducible, but nevertheless realistic sound field. The directionality of microphones and their adaptive behavior in complex acoustic spaces can also be studied. Further, the free-field approach is ideal for measuring the behavior of the complete signal processing chain in a realistic space. For example, Kerber and Seeber (2012) studied the impact of dynamic range limitations of cochlear implants on binaural cues transmitted by the implant. Another application area is studies of sound localization ability and binaural hearing with users of hearing devices. For example, an early version of the SOFE has been used to study localization ability of patients with bilateral cochlear implants and with patients wearing a cochlear implant and a hearing aid. We found that selected patients in either group showed unexpectedly good localization ability (Seeber *et al.*, 2004). We then showed that localization ability with cochlear implants in quiet is predominantly based on the evaluation of interaural level differences (Seeber and Fastl, 2008). Room reverberation impairs localization ability with hearing aids (Seeber *et al.*, 2008) and cochlear implants (Seeber *et al.*, 2011), often severely, and the precedence effect is also impaired. Background noise can severely impair localization ability with cochlear implants and implant users need a considerably higher signal-to-noise ratio than normal hearing listeners to show relatively unimpaired performance (Kerber and Seeber, 2012). Virtual auditory space techniques are a valuable tool when stimuli need to be manipulated independently at both ears. Seeber and Hafter (2011) showed that normal hearing persons listening through a vocoder have problems similar to cochlear implant users when localizing sounds in the presence of a reflection.

Product sound quality

The ability to play sounds in the free field and to listen naturally unencumbered by earphones, which allows for free head movements, is an important benefit of the SOFE when evaluating product sounds. Wiggins and Seeber (2011a; b; 2012) have conducted a range of studies which evaluated aspects of spatial sound quality and how it was affected by wide-dynamic range compression as employed in hearing devices. For example, Wiggins and Seeber (2011b) used the semantic differential method to find that dynamic range compression increases the perceived width of sounds, changes the location of certain sounds, particularly high-frequency sounds with slow onsets, and changes the externalization of sounds. When the SOFE is used to create the spatial sound field found in cars or that created by products, the product sound can be explored in a play-like, natural way. I expect that future research will make increased use of these techniques to more accurately evaluate product sounds under realistic conditions.

Research on sound-field synthesis

Loudspeaker setups in anechoic space like the SOFE are ideal for studying sound synthesis via multiple loudspeakers. Further advances in spatial sound synthesis can be expected through exploiting perceptual effects. Seeber and Hafter (2013) present at this conference a new technique for equalizing amplitude panning such that the panned sound source appears perceptually identical to a physical sound source at the same position. This means that spatial, timbral, and loudness artifacts from the interfering two sources are controlled for and are inaudible in most situations and for most listeners. Further advances through exploiting perceptual limitations for temporal and spectral equalization can be expected for wavefield synthesis and ambisonics.

Research on the perception of sound reflections and the precedence effect

For advances in sound-field synthesis and other areas related to reverberation, an in-depth understanding of the perceptual effects of reverberation and the precedence effect is paramount. We have conducted various studies on the perception and auditory processing of sound reflections. For example, Seeber (2011) showed that the evaluation of interaural time differences is necessary for the precedence effect to function at high frequencies. Cochlear implant users without the ability to use interaural time differences will thus encounter problems localizing sounds in reverberant spaces.

CONCLUSIONS

Virtual acoustic space that includes room reverberation is important for basic and applied research. Recently, the free-field auralization of room acoustics via loudspeakers has become technically feasible. The article describes several application areas of this approach and results gained with the Simulated Open Field Environment (SOFE). Future applications of the SOFE will likely include sound quality research where sound environments – such as the sound field in a car – could be accurately simulated and reproduced. In connection with a visual environment realism will be increased – important for an accurate, natural assessment of sound quality (Fastl *et al.*, 2010).

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