Virtual Acoustics in Psychoacoustics and Audiology

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Introduction

While initially being focused predominantly on the visual modality, research and applications in the field of augmented and virtual reality environments recently started expanding towards the auditory modality. In this context, two major fields of research interrelating virtual reality and Psychoacoustics or hearing research in general have attracted growing interest: 1) the evaluation of virtual acoustics (VA) systems using methods of psychoacoustics, and 2) the presentation of predefined stimuli in hearing research, as targeted by certain virtual acoustics methods. In detail, 2) can be further separated in 2a) the generation of exactly defined stimuli, for example required in basic Psychoacoustics and audiology, and 2b) the simulation of hearing impairment, as it might be desirable for research in audiology.

This contribution covers aspects of fields 2a) and 2b). It is initiated by a classification scheme for approaches to virtual acoustics based on the respectively underlying concept. Using this scheme, the selection of methods applicable to hearing research is addressed. Using binaural synthesis (BS) as an exemplary method, the realization of the audio playback in hearing research by procedures of virtual acoustics and the simulation of hearing impairment in that context is discussed theoretically and demonstrated in practical applications by means of selected pilot studies.

Classification of Virtual-Acoustics Approaches

According to Völk (2013), eliciting specific hearing sensations is considered the final goal of virtual acoustics. Two fundamentally different approaches exist:

- Application of stimuli known to trigger under defined conditions approximately the hearing sensations intended, making use of knowledge about the connections between stimuli and sensations (psychoacoustic relationships, cf. Fastl and Zwicker 2007). The degree of authenticity achievable with these *psychoacoustically-motivated approaches* depends on the situation simulated, the psychoacoustic relationships employed, the implementation, the listening environment and conditions, and the listener.
- Recreation of the acoustical reference scene stimuli (the physical signals acoustically contributing to the hearing sensations to be generated, cf. Fastl and Zwicker 2007). If successful, these *physically-motivated approaches* theoretically trigger, under the non-acoustically not modified reference scene conditions for the same subject, the sensations intended. However, inter-modal, cognitive, and memory effects may influence the hearing sensations.

Presenting predefined stimuli in hearing research requires physically motivated VA approaches. One of these, BS, is selected as the exemplary method discussed here. BS is a sound reproduction technology, for normal hearing listeners based on the convolution of the sound signals to be reproduced with the impulse responses (IRs) of the sound pressure propagation paths from the sources to be simulated to the eardrums. The convolution products are presented by adequately equalized and appropriate headphones (HPs; for details cf. Völk 2013). The simulation of discrete sound sources in arbitrary acoustical reproduction environments is possible as long as the situation can be regarded as a linear system. If the signal processing is implemented with real-time capability and adaptively, the IRs can be adjusted based on the listener's head position and orientation. This allows the listener to move freely while the simulated acoustic scenario, encoded by the ear signals, remains correct (Völk 2013). If HP playback is required or may be tolerated, BS can be applied directly. However, if BS is to be employed for listeners with hearing aids, HP playback only is not appropriate in all situations. BS for listeners with hearing aids is discussed in the following section, with regard to research and fitting of different kinds of hearing aids.

As BS is designed to reproduce ear signals by means of HPs, it provides detailed control over the main input to the normal hearing system. In the last section, exploiting this property for approximately eliciting hearing sensations occurring with hearing aids for normal hearing subjects is discussed.

Binaural Synthesis with Hearing Aids

For research and fitting purposes in the field of hearing aids, BS can save effort and time by providing arbitrary acoustical environments in the laboratory. Conventional hearing aids pick up sound and stimulate the hearing system acoustically, whereas cochlear implants (CIs) pick up sound acoustically but encode it for electrical stimulation of the auditory nerve. Since BS is based on reproducing ear signals, it is not directly applicable to listeners using hearing aids or CIs, especially when the sound pressure at the eardrums is not present or not involved in the hearing process. For CIs combined with conventional hearing aids or the partly remaining normal hearing system, as for example in electro-acoustic stimulation (EAS), the situation becomes more complicated.

Völk and Fastl (2010) extended the traditional BS theory for the application in combination with hearing aids. It was shown that acoustic-only playback (Aid Only Synthesis, AOS) is applicable for hearing aids completely blocking the auditory canal or if the ear signals are not involved in the hearing process. In every other case, a combined system is necessary, supplying the hearing-aid input electronically and the eardrum acoustically (Combined Synthesis, CS). Using this procedure, BS is capable of synthetically generating the physical signals involved in the hearing process in a specific listening situation for hearing-impaired listeners with hearing aids. These signals may include the time-varying hearing-aid input signals and the ear signals. Highly detailed synthesis might not be necessary in every case, as hearing-impaired listeners typically use only a few localization cues. Therefore, it may be sufficient to simulate these cues. However, it is not the aim of this procedure to allow for good localization results, but to synthesize the physical conditions of the reference scene as correctly as possible. Typical applications of BS with hearing aids are research and fitting of conventional hearing aids or CIs. In this context, BS can save effort and time by providing different acoustic environments in the lab. The major advantage over traditional loudspeaker (LS) or HP-based procedures is the high reproducibility of controllable ear signals, especially not only reproducing typical stimulus properties as level or spectral content, but also the time signals. This way, freely configurable but controllable and repeatable conditions are provided using a computer, an audio interface, a head-tracking device, and the software algorithm implementing the BS. Dependent on the specific system, HPs, the actual hearing aid, or a hearing-aid dummy are required in addition. Combination with hearing-aid simulation is possible using a hearing-aid dummy, opening further applications as for example the evaluation of hearing-aid algorithms (Kayser et al. 2009).

Simulation of Hearing Impairment

Approximately eliciting the hearing sensations assumed for CI and hearing-impaired patients in normal-hearing listeners has proven helpful in research and development (e. g. Blamey et al. 1984) and additionally provides a demonstration tool for hearing-loss prevention. In the actual hearing-aid listening situation, one or more microphones located behind the ear or at the auditory-canal entrance represent the hearing-aid input ports. The detected signals are then passed on to a processing device, traditionally referred to as speech processor, whose output signals are by conventional hearing aids played back with a miniature LS in the auditory canal, in CIs encoded and applied to the intra-cochlear electrode.

In general, it is possible to present acoustic stimuli by means of HPs or LSs. While omitted by some authors, the specification of the playback system appears crucial for interpreting listening-experiment results acquired with hearing-aid simulation for normal-hearing listeners, especially for the following reasons: In contemporary hearing aids, the microphones are mounted in the proximity of the listener's ears. Therefore, the hearing-aid input signals vary if the listeners move or rotate their heads, whereas the transfer path from the hearing-aid output ports to the final receiver remains constant in normal operation. The variability of the in-ear LS position for conventional hearing aids is neglected for this conceptual discussion. Taking into account the typically non-linear signal processing of the speech processor (Clark 2003), the structure of the transmission chain consisting of the paths

a) from the sources to the head-position-dependent and head-orientation-dependent hearing-aid input signals (defined as the hearing-aid-microphone output signals),
b) from the hearing-aid input signals to the speech-processor output signals, representing the typically non-linear processing by the speech processor, and
c) from the speech-processor outputs to the final receiver

must not be changed for simulation purposes. However, correctly including all partial paths is necessary for realistic simulations.

That being said, conventional LS presentation of the simulated hearing-aid outputs to normal hearing listeners results in erroneous ear signals, since the transfer paths from the LS to the eardrums vary on listener movements, erroneously modifying partial paths c) and thereby the ear signals. Furthermore, the speech-processor input signals are constant, since the partial paths a) are erroneously independent on listener movements. It is not correct to argue that ear-signal variations on listener movements are taken into account by partial paths c) instead of a), since the intermediate paths b), representing the speech-processor signal processing, typically show non-linear characteristics. However, some authors study perceptual aspects of CI listening with normal hearing subjects using LS presentation (e. g. Fu et al. 2005).

Conventional HP presentation provides constant playback conditions and therefore constant partial paths a) and c) for static and moving subjects. Early studies involving acoustic CI simulation for normal-hearing subjects typically employed consumer HPs (e. g. Blamey et al. 1984), whereas a tendency is visible towards audiometric (Yoon et al. 2011) and high quality studio models (Qin and Oxenham 2003).

However, independently of the HP model, the simulation-input signals remain constant on listener movements in conventional HP presentation, incorrectly reflecting partial-paths a). For a static situation, the partial-paths a) are represented correctly with static BS. However, if the listener moves, the speech-processor input signals erroneously remain static, incorrectly simulating partial-paths a), compared to the reference scene. Dynamic BS presentation on the contrary allows correctly reproducing partial-paths a). Goupell et al. (2010) and Völk et al. (2012) for example addressed the median-plane localization with a vocoder and individual dynamic BS, restricted to rotational head movements.

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