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Experiments on authenticity and plausibility of binaural reproduction via headphones employing different recording methods ☆

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ABSTRACT

Major criteria for a successful binaural reproduction are not only a suitable localization performance, but also the authenticity and plausibility of the presented scene. It is therefore interesting to examine whether the binaural reproduction can be perceptually distinguished from a real source. The aim of the presented investigation is to compare the quality of the binaural reproduction via headphones with two different microphone setups (miniature microphone in Open-Dome and ear plug) for individual head-related-transfer-function (HRTF) and headphone-transfer-function (HpTF) measurements. Listening tests with a total of 80 subjects were carried out focusing on plausibility and authenticity. In the examination of plausibility detection rates showed that subjects were not able to match the reproduced pink noise to its reproduction system (real source vs. binaural reproduction via headphones). The authenticity of the static binaural reproduction was highly dependent on the stimulus. Pink noise could often be distinguished due to coloration in higher frequencies and small differences in location. A difference between microphone setups could not be found in neither of the listening tests.

1. Introduction

The idea of binaural recordings and reproduction has been explored from different points of view in various facets for several decades with profound results. However, binaural synthesis and reproduction, especially in practical application, can still be improved as it does not always yield perfect results. Therefore, this investigation focuses on the perceived quality of binaural reproductions.

Experiments in terms of listening tests are common for psycho-acoustic validations of binaural reproductions. Comparisons between real sources and binaural reproduction via headphones have been drawn in psycho-acoustic experiments especially regarding localization by for example Møller et al. [1], Wightman and Kistler [2] as well as Bronkhorst [3]. Investigations differed in stimulus type, duration, directions of sources, room conditions, headphone equalization and answering methods, among others. Overall a good agreement between results could be verified. Localizing with binaural reproduction was nearly as exact as localization with real sources for investigations for all three investigations [1–3].

Besides the demand of a physically correct reproduction and good localization, it is also important that the subject does not sense or hear a difference between real sources and the binaural reproduction. The indiscernibility between a binaural reproduction and a real source is a very high demand that can only be analyzed and proved in a direct comparison of the real and the virtual reproduction method. After Blauert [4], the perceptual identity is subsequently called authenticity. If a subject is only exposed to the binaural reproduction the perceptual identity is not essential, but it is sufficient if the subject rates the scene as plausible. Plausibility should be understood as "a simulation in agreement with the listener's expectation towards a corresponding real event" as defined by Lindau and Weinzierl [5]. Hence, for a plausible binaural reproduction the perceptual quality of the reproduction needs to be close enough to natural listening.

An early investigation on authenticity was carried out by Hartmann and Wittenberg [6]. In a listening test of forced choice design with four subjects they examined whether subjects were able to distinguish between the real source and the "virtual" binaural reproduction depending on a change of phase and level effects. Individual HRTFs were measured with probe microphones remaining inside the ear during the whole experiment. Using a synthesized vowel "a" as the stimulus the subject was asked to match

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the reproduction method to loudspeaker or binaural reproduction. Acoustically open headphones (*Sennheiser HD 40s*) were used to explore the perceived externalization.

Zahorik et al. [7] conducted a listening test with a 2-alternative-forced-choice design (2-AFC) to compare virtual and real sound sources with four experienced listeners. Individual HRTFs were measured with probe microphones for the binaural reproduction via supra-aural headphones (*Aiwa HP-M16*). Gaussian noise bursts (bandpassed: 300 Hz and 12 kHz) were presented from 15 different positions and results were analyzed as a function of filter length. Zahorik et al. [7] concluded that the virtual free-field was indistinguishable from the real free-field if a sufficiently long filter length was applied.

This result, however, was questioned by Langendijk and Bronkhorst [8] who carried out a listening test with a number of six listeners using a revised design to verify the results of Zahorik et al. [7]. Besides a 2-AFC design they also presented band limited noise bursts (500 Hz and 16 kHz) with an "oddball"-design and in a forced choice design (real vs. virtual) like Hartmann and Wittenberg [6] to examine the "fidelity of the three-dimensional-sound reproduction using a virtual auditory display" [8]. Detection rates were slightly but significantly above chance for the "oddball"-design. For the binaural synthesis HRTFs were measured with a probe microphone positioned at the eardrum and stimuli were played back by a midrange dome tweeter (*Sony MDR E-575*) mounted on a trolley.

One of the latest experiment on plausibility was carried out by Moore et al. [9] who tested the perceptual indistinguishability of a binaural reproduction using cross-talk-cancellation with eight subjects. The binaural synthesis was also based on individual data measured with probe-microphones in ear with one source position located in the frontal direction. In an "oddball"-design noise click-trains and harmonic pulses were presented yielding to the result that error rates were slightly but significantly underneath chance. Moore et al. [9] reported how perceived differences were due to an insufficient signal to noise ratio in high frequencies.

In another investigation published by Schärer and Lindau [10] in 2009 it was also analyzed whether binaural simulations could be perceptually distinguished from real sources. However, the main focus of this investigation was on seven headphone equalization methods and two different acoustically transparent headphones (*STAX SR5 2050II* and *STAX Lambda Pro New*) which were directly compared in a listening test with real sources. Most of the 28 subjects rated the binaural reproduction based on non-individual HRTFs as "boosting in high frequencies as well as ringing artifacts" [10]. The spectral coloration of the binaural simulation was also described as a major shortcoming by Lindau et al. [11]. Similarity rates between 0% and 70% were detected for pink noise and an acoustic guitar depending on the headphone equalization method. The authenticity of a binaural reverberant acoustical environment was tested in an ABC/HR-design.

Assuming that historical limitations of measuring techniques were the major reason for the use of probe microphones, it would be interesting to know whether a binaural reproduction measured with equipment that is state-of-the-art is comparably plausible. Difficulties as for example resonances in tubes and the notch filter effect are present in probe microphones and can be countered by new equipment. Different types of microphones used to measure HRTFs within the ear canal as well as the most adequate and applicable position in or around the ear have been investigated by several researchers [12–14]. Probe microphones were used by Wightman and Kistler [2] as well as Bronkhorst [3] among others due to size and signal to noise ratios, whereas in recent time measurements are more commonly made using miniature microphones placed at the entrance of the blocked ear canal [12,15]. In 1995, Møller et al. [16] measured HRTFs with an open auditory canal, but reported better results when HRTFs were measured with a blocked ear canal. However, the application and positioning of miniature microphones with silicon Open-Domes (cf. Section 2.1) is very simple, precise and little time consuming when HRTFs are frequently measured. Therefore, it could be asked whether the recording method (open meatus vs. blocked meatus) plays a significant role for the perception of the spatial sound reproduction.

Another technical aspect which should be taken into consideration are the headphones used for the binaural reproduction. Langendijk and Bronkhorst [8] criticized the headphones used by Hartmann and Wittenberg [6] as well as Zahorik et al. [7] and suggested the use of smaller headphones. In these investigations HRTFs were measured with headphones placed over the subjects' ears, resulting in deviations in higher frequencies, a spectral region known to contain important spectral localization cues [17]. For localization experiments this would surely be a major constraint, however, for the analysis of authenticity of a virtual sound source in a direct comparison, correct localization is not essential and HRTF measured with headphones could be used. However, the reproduction quality of the ear buds used by Langendijk and Bronkhorst should be questioned regarding transfer function and band-pass limitations. Acoustically open circumaural headphones (Sennheiser HD 600) were used in this investigation to reproduce binaural stimuli.

The demand for a plausible binaural reproduction is important in investigations where the binaural reproduction is only used as a tool and the aim of the analysis is to focus on other effects than localization or the perceived quality. Otherwise, experimental results will be biased. This is especially true for experiments that assess psychological effects like auditory attention [18–20] using binaural reproduction to simplify complicated laboratory situations. Frequently, individual HRTF are measured in different laboratories or at another time than the listening tests are conducted. Therefore, microphones need to be taken out of the ears and headphones are inevitably repositioned. In the present investigation HRTFs and HpTFs were measured separately as if measurement and experiment would have been taking place at a different place and time, even though the listening test was performed subsequently and in the same room.

The aim of this investigation was to examine the authenticity and plausibility of a binaural anechoic reproduction via open headphones depending on two different recording methods. In the method called "open meatus" a miniature microphone was positioned at the entrance of the open ear canal. "Blocked meatus" described the other method where the miniature microphone was placed into a foam closing the ear canal. Two listening tests were carried out. In the first listening test three different types of stimuli were used for a direct comparison of real sources and the binaural synthesis (authenticity). In a 3-alternative-forced-choice design (3-AFC) subjects were asked to find the stimulus which was different from the other two and therefore it was asked whether the subjects were able to distinguish between reproduction methods. In a second test pulsed pink noise was presented either by loudspeakers or as a binaural synthesis by headphones. Subjects were asked to define the reproduction method. In this indirect comparison the plausibility of the binaural reproduction was analyzed.

2. Methods and equipment

2.1. Microphones

To measure individual HRTFs and HpTFs, miniature microphones (*Sennheiser KE-3*, for the microphone's frequency response,