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COMPARING ROOM ACOUSTICAL RATINGS IN AN INTERACTIVE VIRTUAL ENVIRONMENT TO THOSE IN THE REAL ROOM

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ABSTRACT

To transfer listening experiments from the real world to the laboratory, audio-visual environments can be used. Interactive virtual environments (IVEs), with head-tracked binaural audio playback via headphones and visualisation via a head-mounted display (HMD) are a promising tool for this task. Audio reproduction within an IVE can be evaluated for authenticity, plausibility, and transfer plausibility. However, these paradigms do not indicate whether experiments in an IVE, typically located in a completely different room, yield the same results as real-world experiments. In a previous study, plausibility was evaluated using an IVE in the original room. A high degree of plausibility was observed as long as the directivity of the sources was taken into account in the room simulation. The current study utilizes the same IVE for multi-stimulus rating experiments. Participants had to rate five room acoustic related attributes for head-tracked binaural auralisations based on measured and simulated binaural room impulse responses and a loudspeaker reproduction in the real room. Participants could perceive small differences in reverberation and gave higher ratings to auralizations based on simulated BRIRs compared to the real loudspeaker in the room.

Keywords: *virtual acoustics, auralization, interactive virtual environements, head-mounted display*

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1. INTRODUCTION

Interactive virtual environments (IVEs) are a promising tool for bringing real-life auditory testing into the laboratory by combining highly ecologically valid environmental conditions with a high degree of experimental control. Additionally, IVEs allow the study of human perception in audiovisual scenes without the necessity of accessing the actual physical environment representing the audiovisual scene. To ensure the validity of such experiments, IVEs need to be validated to ensure that listening tests in IVEs produce results comparable to those in the real world. In this paper, we will focus on validating acoustic renderings to assess their potential to replace real-life audio. While auralisations can be done using either headphones or loudspeakers [1, 2], the aim of this paper is to investigate the realism of auralizations over headphones as a replacement for a physical source in a room.

Previous studies have compared simulation-based and measurement-based auralisations, assuming that measurements accurately represents reality [3–6]. A direct comparison between a loudspeaker and an auralization over headphones brings us a step closer to reality. Oberem et al. [7] found that static binaural auralisations can be highly plausible when compared to a loudspeaker in anechoic conditions. However, especially with noise stimuli, there are perceptible differences in authenticity tests, mainly related to colouration and localisation cues. Brinkmann et al. [8] added head tracking to the binaural auralisations. Differences were found for noise but not for speech stimuli when compared to loudspeakers. This was also found by Blau et al. [9] who presented head-tracked binaural auralisations in a typical seminar room. They also compared binaural room impulse responses (BRIRs) based on a room simulation with the room acoustic simulator RAZR [10] to loudspeaker presentations in the original room. Participants rated the simulations lower than measured BRIRs because RAZR, at that time, used omnidirectional source directivity. Subsequently, RAZR was improved by adding the ability to use a loudspeaker directivity database as the source directivity [11]. The addition of loudspeaker directivity enhances the ratings of BRIRs based on simulations. The subsequent study achieved a convincing agreement between auralisations based on simulated and measured BRIRs and loudspeaker reproduction in the real room [12]. Furthermore, it was found that if the visual and auditory modalities are reproduced as closely to reality as possible, generic head-related transfer functions (HRTFs) can be used for speech stimuli in a reverberant environment. Using room simulations simplifies the auralisation process. Simplification is also introduced by using generic HRTFs as opposed to individual HRTFs. A head-mounted display (HMD) introduces a promising tool to reduce the complexity of visually being present in the real room. In the study conducted by Blau et al. [12], they compared different auralisations with a loudspeaker reproduction in a real room. As a result, they perfectly preserved the visualisation. A known problem of replacing the visualization of the real room with another room is known as the 'room divergence effect' [13]. Auralisation may suffer, leading to the demand that the visualisation be as close to reality as possible. When a virtual room model is presented through an HMD, a small visual mismatch is introduced. It remains unknown whether this visual mismatch impacts the comparison of head-tracked binaural auralisation and loudspeaker reproduction.

In this study, we conducted a multi-stimulus rating test to assess the reproduction of a speech stimulus in a lecture room with respect to different room acoustic attributes. We compared head-tracked binaural auralisations, based on measurements or simulations for both generic and individual HRTFs, to a hidden reference (loudspeaker reproduction in the room). We preserved the visualisation of the room by presenting a 3D-visual sibling of the room via HMD.

2. METHODS

2.1 Room setup

The room studied was a small lecture room (7.12 x 11.94 x 2.98 m^3) at the Jade Hochschule in Oldenburg, Germany. The room features a window front with open curtains and three plastered brick walls. One wall is equipped with a large blackboard, while another wall has some pinboards. The ceiling is acoustically treated with a broadband absorbing plasterboard suspended about 35 cm including 5 cm of mineral wool. The floor is covered with linoleum.

The participants were positioned slightly off-axis in the center of the room at an ear height of 1.3 m. We placed a loudspeaker (Genelec 8030b, Genelec Oy, Iisalmi, Finland) directly in front of the participant at a height of 1.6 m, approximately 4.3 m away. Please refer to Fig. 1 for visualisation.

Figure 1. Top: Real seminar room. Bottom: Virtual sibling of the real room.

2.2 Interactive Virtual Environment

Participants wore a HMD (HTC VIVE Pro eye, HTC Corporation, Xindian, New Taipei, Taiwan) with attached headphones (AKG K1000, AKG Acoustics GmbH, Vienna, Austria), as described in [14], while being seated in the real room. A visual sibling of the real room Fig. 1 was presented on the HMD using the UNREAL engine

4.27.2 (Digital Extremes, London (Ontario), Canada and Epic Games, Inc., Raleigh, NC, USA). Architecture students at Jade Hochschule Oldenburg modeled the room in 3Ds Max (Autodesk, Inc., San Rafael, CA, USA). The visual simulation included a graphical user interface (GUI) on the right-hand blackboard, with six sliders representing different auralisation, as shown in Fig. 2. Participants interacted with the GUI using a valve index controller (Valve Corporation, Bellevue, WA, USA) that was visible in the virtual environment. They used a joystick to switch between the sliders and the trackpad to rate the auralisations. Participants could listen for as long as they wished, switching freely between the auralisations. They were also able to rearrange the sliders according to their ratings at any time.

2.3 BRIR Sets

Participants had to rate different attributes for five different binaural room impulse response (BRIR) sets and the hidden reference (loudspeaker reproduction in the real room). One of these sets, in the following referred to as 'meas:HATS' was based on a measurement in the real room using a head-and torso simulator (HATS) (KEMAR type 45BB, GRAS Sound and Vibration A/S, Holte, Denmark).

The measurement in the real room was done for 37 azimuth head-over-torso orientations in a range from −90° to 90°, resulting in a resolution of 5°. The height of the ear canal was set at 1.3 m and the elevation was fixed at 0°. MEMS microphones (TDK type ICS-40619, TDK InvenSense, San Jose, CA, USA) were used in a blocked ear condition, inserted into the ear canal with the PIRATEs earplug [15]. Measurements were made using the modified multiple exponential sweep method [16, 17] in the range from 20 Hz to the Nyquist frequency with a sampling rate of 44.1 kHz. An external audio interface (RME Fireface UCX, Audio AG Haimhausen,Germany) and a laptop with Matlab (The MathWorks, Inc., Natick, MA, USA) and Pure Data [18] scripts were in use.

All other BRIR sets were based on a room simulation with an improved version of the room simulation tool RAZR (version 0.962b) [10, 19]. This version of RAZR accounted for the directivity of the loudspeaker. For more details on the loudspeaker directivity database refer to the study by Blau et al. [12]. BRIRs were simulated based on the given room details, source-receiver positions and previously measured head related impulse responses (HRIRs). RAZR was used with a combination of a 3rd order image source model (ISM) and a feedback delay network (FDN). Since the exact room absorptions of the real room are not known, the simulated reverberation time T_{20} was fitted to a previously measured monaural impulse response of the seminar room. Typical absorption characteristics of the walls were estimated and retained during the fitting process. This fitting was done for the BRIR sets 'sim:HATS' and 'sim:indivHRIRs'.

RAZR calculated BRIRs using a previously measured subset of HRIR sets. HATS HRIRs, denoted as 'sim:HATS', and individual HRIRs, denoted as 'sim:indivHRIRs', were used for this purpose. A simulated BRIR set contains 333 head orientations, 37 azimuth angles (−90° to 90° in 5° steps) and nine elevation angles (−30° to 30° in 7.5° steps). Detailed information about the HRTF measurement setup can be found in [12, 20].

For the last two BRIR sets, we manipulated the reverberation of the simulated room in order to achieve a condition that differed in a well-defined manner from the most optimal simulation method. The condition 'sim:indivHRIRswet' represents an increase in reverberation of approximately 15 %, achieved by reducing the room absorption coefficients of the RAZR simulation. Likewise, for the reduced reverberation condition, denoted as 'sim:indivHRIRsdry', we increased the room absorption coefficients by approximately 15 %.

In a post-processing step, we truncated all BRIR sets to a length of 18000 samples using a half-Hann window with a length of 50 samples. We compensated for the influence of the MEMS microphones by applying a regularised inverted impulse response. Similarly, we compensated for the influence introduced of the headphone playback. We derived a headphone equalisation filter (HPEQ) using regularised inversion [21]. It is important to note that we did not perform any further calibration on the BRIR sets. The resulting level and spectrum at the eardrum were obtained by convolving measured or simulated BRIRs with inverted filters to compensate for the influence of headphones, microphones and HRTF measurement loudspeakers.

Neither BRIR nor HRTF measurements were performed with headphones and HMD on the measured participant or HATS. It is important to note that this condition differs from the loudspeaker playback scenario where participants wore HMD and headphones. We found no effect on plausibility in a previous study comparing measured BRIRs with and without HMD and headphones [20]. Furthermore, we found a rather small passive spectral influence for our HMD and headphones setup for an incidence angle of 0° up to 7 kHz [14]. On the basis of these results, we decided to reduce the duration of the listening test and not to investigate the passive influence of the HMD and headphones any further.

2.4 GUI - Multi Stimulus Rating

Participants used a slider ranging from zero to 100 in increments of ten to rate each auralisation in terms of one attribute, as shown in Fig. 2. They rated one attribute at a time. In total, five attributes were rated. Four of these were taken from the room acoustical quality inventory (RAQI) [22] with minor adjustments: reverberance (dry/wet), tone colour (dark/bright), loudness (soft/loud) and source distance (close/optimal/distant). Source distance was adjusted by adding 'optimal' as a pole, which refers to the comparison between the visual and acoustic position of the loudspeaker. We also added reproduction quality (low/high) to see if there were any artefacts in the reproduction that were not present in the reference condition. Participants rated all attributes twice for the same stimulus in a blockwise randomised fashion with the constraint that reproduction quality was the first attribute rated in each block for each participant. Prior to the listening test, participants were instructed to read a test explanation. All attributes were introduced with their respective poles. In addition, they were instructed to rate source distance in relation to the visual loudspeaker position observed in the IVE. For reproduction quality, it was explained that a rating should be given in the context of room acoustic evaluation. It was made clear that reverberation does not necessarily indicate poor reproduction quality.

Figure 2. Virtually presented GUI for rating attributes in a multi-stimulus rating listening test.

2.5 Listening Test - Multi Stimulus Rating

A listening test was conducted as a multi-stimulus rating experiment with a speech sample. Participants had to blindly rate five different auralisations and the real loudspeaker in the room as a hidden reference. Six participants, consisting of one female and five male with a median age of 32 years, took part in the listening test. These participants were familiar with listening tests and had previously listened to head-tracked binaural auralisations.

2.6 Stimuli

We used a speech stimulus, specifically an excerpt from 'Der Froschkönig' spoken by a layman speaker in German [23]. It was normalised to EBU R 128 using the loudness function built into the Matlab audio toolbox [24]. We achieved the playback of the headphone audio using a time variant partitioned convolution algorithm [25]. Based on the head tracker data of the HMD, the stimulus was convolved with the appropriate BRIR. The average A-weighted sound pressure level at the listening position was 60 dB for both loudspeaker and headphone playback. The A-weighted background noise level in the room ranged from 20 to 25 dB.

3. RESULTS

Fig. 3 shows the average ratings for various attributes and different reproduction settings. As the sample size is rather small, we used descriptive analysis to interpret the results. Participants rated the reproduction quality highest for the conditions using room simulations with both individual and generic HRTFs. The simulated BRIR set with increased reverberation received a lower rating. The real loudspeaker received ratings between the simulations with HATS and individual HRTFs, as well as the simulation with increased reverberation. The 'meas:HATS' BRIR set received the lowest rating. In terms of reverberation, participants found the real loudspeaker and the 'sim:indivHRIRs' to be similar, with a median rating of around 50. The BRIR sets 'sim:HATS' and 'sim:indivHRIRsdry' were rated as dryer, with a median score slightly below 40. Participants rated the BRIR sets 'meas:HATS' and 'sim:indivHRIRswet' as wetter, with a median score above 70. There is a trend towards higher scores for 'meas:HATS'.

Participants rated the real loudspeaker, 'sim:indivHRIRs', 'sim:indivHRIRswet' and 'sim:indivHRIRsdry' similarly in terms of tone colour,

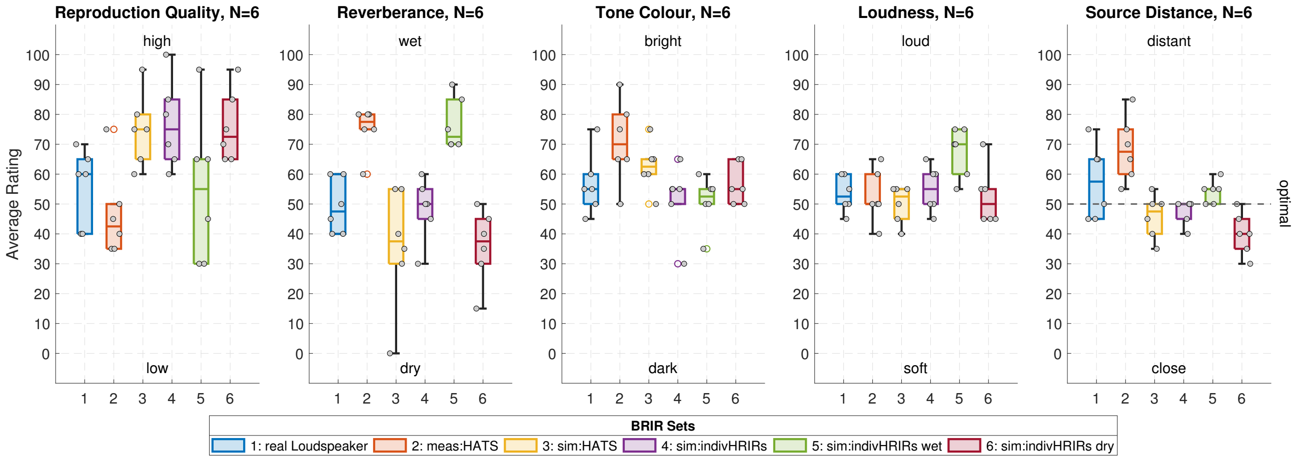

Figure 3. Average ratings from a multi-stimulus listening test for six different loudspeaker reproduction methods, presented for five different attributes.

with a slight tendency towards 'bright' and a score just above 50. The BRIR set 'sim:HATS' shows a tendency to be perceived as slightly brighter, with a median score above 60. The highest score of about 70 is obtained for 'meas:HATS'.

In terms of loudness, all sets except the BRIR set with the altered reverberation were perceived as being as loud as the real loudspeaker with a score of around 50. The BRIR set with the increased reverberation was perceived as louder with a score of 70. There is a slight tendency for 'sim:indHRIRsdry' to be perceived as slightly softer. Both results are consistent with the expected level changes when manipulating reverberation time in a real room.

In terms of source distance, participants rated the simulated BRIRs close to optimal, with a slight tendency to 'distant' for increased reverberation and to 'close' for decreased reverberation. The real loudspeaker was perceived as farther away than optimal, and the highest rating, indicating the largest distance, was given to 'meas:HATS'.

4. DISCUSSION

Interestingly, participants rated most of the simulated auralisations higher than the real loudspeaker in the room for the attribute reproduction quality. Originally we expected that the real loudspeaker would perform with the highest score. There seems to be a relationship between reproduction quality and reverberance. BRIR sets that were perceived as wetter were rated lower in reproduction quality compared to the real loudspeaker. BRIR sets perceived as dryer were rated higher. However, 'sim:indivHRIRs', which was rated the same as the real loudspeaker for reverberance, was rated higher for reproduction quality.

Another explanation could be the passive influence of the HMD and headphones on the perceived signal during playback from the loudspeaker. This influence has been reported in [14, 26–28] and can be described as a low-pass like behaviour with additional angle dependent reflections in the higher frequencies. This influence deviates from a real-life scenario and could be considered disturbing. By using extra aural AKG K1000 headphones we reduced this influence and found no significant difference in the plausibility of BRIRs measured with or without HMD plus headphones in a previous study [20]. We also conducted a pilot study which showed no noticeable effect. The setup used has the lowest spectral influence for a source positioned at an azimuth angle of 0° [14] which we are investigating here. Furthermore, since the passive influence of headphones and HMD leads to a spectral deviation from the loudspeaker reproduction, we would expect an effect on the tone colour rating. This is not the case, at least not for individual HRIRs.

It is also possible that reproduction quality interacts with the source distance. The acoustically perceived position of the real loudspeaker was judged to be further away than the visually perceived position, which was also found by Sloma et al. [29]. It is possible that this discrepancy could result in a lower rating of reproduction quality.

It is important to note that participants rated 'meas:HATS' the lowest for the attribute of reproduction quality, which is not consistent with previous findings by Blau et al. [12]. In that study, BRIRs based on measured generic HRTFs were rated high for the overall quality attribute. It is not clear why generic measured BRIR sets performed poorly in this test. One possible explanation, based on informal discussions with participants, is that one of the sets heard was noticeably sharper and more reverberant than others. Comparing these statements with the results 'meas:HATS' best fits this explanation. Further investigation of the measured BRIR condition is required.

Participants demonstrated their ability to perceive and rate the introduced difference in reverberation using head-tracked binaural auralisations. An increase in reverberation is perceived more clearly than a decrease, resulting in a higher score difference compared to the baseline 'sim:indivHRIRs'. It could be shown that small changes in reverberation can be heard with head-tracked binaural auralisation over headphones. It also needs to be mentioned that the reduced direct-to-reverberant ratio for 'sim:indivHRIRsdry' resulted in a closer distance perception of the source.

In addition to the comparably close ratings for the other attributes tested for simulation-based auralisations, it may be possible to evaluate room acoustics in a divergent room with IVEs, if the visual model is replaced by a visually simulated 3D model. One possible application would be to evaluate changes in room acoustics in the office rather than in the room being tested. To do this, it would be necessary to obtain the same results when the listening test is carried out in a different room.

5. CONCLUSION AND OUTLOOK

Participants rated the simulated BRIRs higher than the loudspeaker presentation in terms of reproduction quality. Possible explanations are higher ratings for dryer reproductions, the effect of the passive influence introduced by the HMD and headphones, or that the simulated BRIR better matches the visual model in terms of source distance. Participants successfully perceived the small changes introduced in the simulated reverberation, with an increase in reverberation being more noticeable than a decrease. Only small differences were observed for simulated BRIRs based on individual and generic HRTFs. The greatest deviation was found for measured BRIRs, which tended to be perceived as brighter, wetter and further away. Further investigation is required to determine whether the ratings remain consistent when the experiment is conducted in a different room.

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