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VR/AR AND HEARING RESEARCH: CURRENT EXAMPLES AND FUTURE CHALLENGES

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ABSTRACT

A well-known issue in clinical audiology and hearing research is the level of abstraction of traditional experimental assessments and methods, which lack ecological validity and differ significantly from real-life experiences, often resulting in unreliable outcomes. Attempts to deal with this matter by, for example, performing experiments in real-life contexts, can be problematic due to the difficulty of accurately identifying control-specific parameters and events. Virtual and augmented reality (VR/AR) have the potential to provide dynamic and immersive audio-visual experiences that are at the same time realistic and highly controllable. Several successful attempts have been made to create and validate VR-based implementations of standard audiological and linguistic tests, as well as to design procedures and technologies to assess meaningful and ecologically-valid data. Similarly, new viewpoints on auditory perception have been provided by looking at hearing training and auditory sensory augmentation, aiming at improving perceptual skills in tasks such as speech understanding and sound-source localisation. In this contribution, we bring together researchers active in this domain. We briefly describe experiments they have designed, and jointly identify challenges that are still open and common approaches to tackle them.

Keywords: *Virtual and augmented reality, hearing assessment, audiology, perceptual training.*

1. INTRODUCTION

Virtual Reality (VR) has been around for decades, but it's only in the last few years that it moved beyond research labs and professionals, towards the consumer market. Considering the areas of audiology, hearing science and hearing aids technologies, it is easy to see how VR could very soon become a major player, both in research environments and clinical practice. One of the main issues with standard clinical hearing assessments is the fact that these are not representative of what happens in real life. For example, the procedures and signals employed during pure-tone and/or speech audiometric assessments, albeit being very controllable, repeatable and precise, are rather far from what individuals would experience in their everyday life, and from the situations in which their hearing impairment would cause problems. On the other hand, assessing hearing in everyday-life could be rather problematic, as these are difficult to control and calibrate, and generally non repeatable (or at least not with sufficient precision).

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VR can easily allow the creation of realistic scenarios using both immersive visual and audio techniques, and at the same time being very controllable and repeatable, especially when the rendering is done through a headset and a pair of headphones (i.e. very close to the eyes and ears). This means that new hearing tests could be designed to be much closer to what people experience in their lives, simulating for example those specific situations where difficulties are encountered, such as a conversation in a noisy restaurant, or watching a film at the cinema. Furthermore, the same technology could be used to demonstrate the functionality of hearing interventions (e.g. hearing aids), or to improve the fitting and personalisation of a hearing device, or again to improve hearing performances through perceptual training, as we will see later on.

Despite the novelty of this topic, a substantial amount of research has been done in the past 10 years. Without aiming at being exhaustive, this contribution presents several examples of past research in this domain from various institutions across the world, including descriptions of lab setups, attempting then to identify some of the open challenges and suggesting common approaches to tackle them.

2. RESEARCH AND SETUPS

In the following sections, various studies and experiments carried out in the authors' institutions are briefly introduced, providing relevant references where additional information can be found.

2.1 Spatial speech in noise - virtual audio

In the clinical setting the size of patient populations are increasing while clinic space remains the same. This results in pressure on audiology clinics and private healthcare providers to streamline services and space usage. Many offer remote clinical appointments rather than inviting patients to attend in person. In the process many audiology clinics stop conducting speech perception tests as part of assessment and evaluation.

To overcome the issue that equipment is often not available in clinics to conduct spatial hearing assessments, the Spatial Speech in Noise - Virtual Audio (SSiN-VA) test has been developed [1], integrating headphone-based spatialisation done with the 3D Tune-In Toolkit [2]. The SSiN-VA was developed together with patients to have a speech-in-noise test that better reflected the cognitive challenges that they face in everyday life, patients often complain that the quiet sound booths in hospitals are not representative of normal hearing challenges. Two words are presented in sequence from two different but adjacent speakers in the presence of noise presented on the left or on the right. A dual response paradigm is used to increase the cognitive load during the task. Listeners have to identify the two words and say whether the second word was to the left or right of the first (relative localisation). The use of the SSiN-VA has been validated by ensuring that it produces responses that follow the same pattern as observed when testing in an actual speaker array for both speech and relative localisation results.

A brief description of the test, together with a video of the interface, can be found here: `https://www.youtube.com/watch?v=Yni-I9NW838&t=3s`.

2.2 Evaluating hearing devices in VR

Following some recent studies on the suitability of 3D audio reproduction techniques for the evaluation of hearing devices [3], the Sonova VR research lab was extended by the addition of an HMD (Head Mounted Display) and a perceptual evaluation interface used for assessing different hearing aid configurations.

Audio is reproduced via 32 loudspeakers using MaxMSP and Spat [4]. Auditory sound scenes consist of 4th order Ambisonics background recordings and, when appropriate, target sounds using anechoic speech convolved with 4th order Ambisonics spatial impulse responses (SIRs). These SIRs have been pre-processed using Higher Order Spatial Impulse Response Rendering [5]. This limits the effect of spatial aliasing artifacts, typically occurring in Ambisonics audio reproduction, on the hearing devices' multichannel audio processing algorithms, as shown in [3]. Video reproduction, as well as the management of a test interface (data collection, randomisation of the hearing aid settings) was developed in Unity. An administrator window is used by the experiment designer to choose the test conditions. When subjects switch program or scene items in the VR world, the VR tool connects via Open Sound Control (OSC) to other software, such as Max to control audio reproduction and other tools interfacing with the hearing devices to switch configuration.

Early exploratory tests with ten participants with and without hearing loss suggested that compared to standard listening tests, the setup significantly increases realism and plausibility of the listening experience. Subjects specifically mentioned that their personal experience of using hearing devices was well matched and that being able to look around them helped understand what was happening in the scene. Additionally, no participant felt any type of dizziness in this setup. The main challenge of the system was the use with glasses, and especially with varifocal ones. When used with these, the user interface should be adapted and moved to a part of the screen that is clear for the users.

2.3 Interaction between hearing devices and self-motion

Under adverse listening conditions, hearing device users typically have the greatest benefit from directional filters [6]. With increasing spatial selectivity, this class of algorithms increasingly interferes with their users' head movements [7]. Thus, for a systematic evaluation of such algorithms, self-motion need to be considered. In addition, by analyzing the user's behavior and relating it to the acoustic configuration of the environment, e.g., as provided by scene analysis methods, the device can distinguish between attended and unattended acoustic sources [8]. The development of such algorithms depends on the availability of natural self-motion behavior in interactive conversations.

To achieve more ecologically valid self-motion under laboratory conditions and to simulate interactive dynamic virtual acoustic and audiovisual environments, the Toolbox for Acoustic Scene Creation and Rendering (TASCAR) [9] has been developed. It provides acoustic simulation in the time domain, for loudspeaker or headphone playback. Most of the effects of the acoustic path are modeled as time-varying parametric filters. Early reflections are simulated in a geometric image source model. Diffuse sound fields can be added using first-order ambisonics recordings. A simple feedback delay network is included to simulate the later parts of room impulse responses. Extensions for multi-sensor data integration and recording enable a variety of experiments, see for example [10]. Recent extensions for network-based distributed virtual acoustic rendering allow interactive paradigms. It has been shown that interactivity is an important factor for the validity of self-motion, as opposed to the factor of using simulation and telepresence instead of real presence [11].

2.4 Studying speech perception under varying room acoustics

The impact of speech perception evaluations can be potentially increased with the use of audio-based VR technologies that can simulate different acoustic characteristics. Researchers have investigated the effect of noise and/or room acoustics on the perception of sentences or phonemes. However, experiments are usually not conducted in real rooms but rather by using stimuli within artificially simulated room acoustics effects. This is because the experiments have to be conducted under controlled environmental conditions, especially when testing several participants in geographically separated venues. The latter issue is particularly prominent when the study involves participants with different language background, e.g. native and non-native listeners, as such studies often require the recruitment of participants at multiple geographical locations. The use of VR technologies enable different acoustic characteristics to be replicated in a controlled manner. Because of the guaranteed reproducibility, they also allow researchers to conduct the identical experiment at multiple geographical locations.

A few recent studies investigated speech intelligibility in noise under virtually reproduced acoustic environments [12, 13]. The studies found both room acoustics and listeners' nativite language affect spatial release from masking, a phenomenon that occurs when listeners benefit from the spatial separation of target speaker and noise source when listening to speech in noise. The study [13] was also later conducted at another location by recruiting non-native participants with different language backgrounds [14]. These research studies employed Ambisonics-based sound reproduction system with 16 channel loudspeaker array installed in an anechoic chamber as shown in Figure 1 wherein the participants transcribed speech sentences in noise under various spatial acoustics settings. Another study also used the same sound reproduction system to investigate the effect of reverberation to the perception of non-native listeners of Japanese [15]. It found that prior exposure to the acoustic environment affects the performance of non-native listeners in distinguishing Japanese vowel lengths and the time required for them to complete adaptation is longer than native listeners.

2.5 Auditory hypersensitivity and VR-based intervention

50 to 70% of the autistic population experience some hypersensitivity to sound throughout their life [16]. This includes hyperacuity, misophonia and phonophobia. For many suffering such conditions, everyday sounds can provoke negative emotional or extreme behavioural reactions such as vocalisations or self-injury by hitting their ears

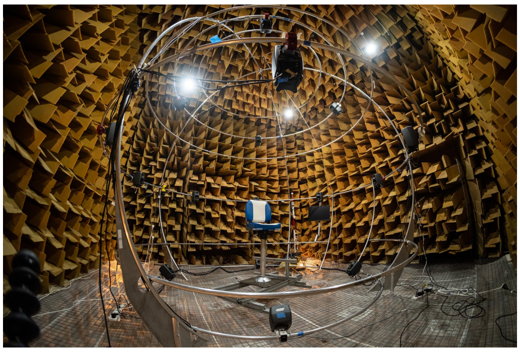

Figure 1. Sound reproduction system installed in the anechoic chamber at the University of Auckland (reproduced from [13]).

[17]. These responses to environmental stimuli can significantly impact an individual's daily life, limiting activities and restricting participation due to avoidance of sounds. This is particularly prevalent with autistic children - A recent study by Birkett et. al reported the sensory experience of many young autistic people in secondary schools to be overwhelming, confusing and chaotic [18].

Cognitive behavioural therapy (CBT) techniques such as systematic desensitisation are among the recommended treatments for such conditions [17]. Such techniques do not alter existing pathological structures, rather they form new and competing structures that aim to remove pathological associations [19]. However, a major consideration is the lack of accessibility in CBT. Ince et al. [20] noted that the rates of implementation for CBT are below the recommended levels for the United Kingdom. This gap in delivering successful mental health interventions has stemmed from several influences including lack of resources, limited dedicated therapy time and a lack of specialist training [21]. However, low-cost consumer VR offer significant potential for digital interventions to be deployed. *SoundFields*, is a novel VR game designed to address auditory hypersensitivity in autistic children and young people, with the capability to present naturalistic representations of feared auditory stimuli to the player using binaural-based spatial audio [22]. Feared auditory stimuli are incorporated into serious game mechanics established in CBT approaches. Following participation, a significant decrease in the self-reported levels of anxiety scores in the pre- and post-study measurement sessions were observed. Additionally, results showed a significant increase in tracked interaction time with those adverse stimuli between sessions one and four. These findings indicate that *SoundFields* has the potential to support young autistic people with their hyperresponsiveness to sound.

2.6 Auditory sensory augmentation

The integration of sensory augmentation via augmented-reality devices with context-aware computing provide the basis for new sensory augmentation paradigms and new applications. In this regard, the Computational Audio Research Laboratory at The University of Sydney and the Computational Intelligence and Brain-Computer Interface Centre at the University of Technology, Sydney have recently combined efforts to explore a sensory augmentation paradigm that we refer to as "acoustic touch" as a means to assist people who are blind to reach close objects [23]. The system uses the NReal Light AR glasses and a custom application running on an OPPO X3 android phone. The system uses cameras within the glasses to recognize and localize objects and then render the objects as sound within a limited field-of-view. The repetition rate of the sound depends on the location of the object within the field-of-view. We thus refer to the system as a "foveated audio device." The restriction of hearing to a particular field-of-view is quite unnatural. Nonetheless, this is exactly what will occur when auditory sensory augmentation is based on the camera vision of smart glasses. The introduction of a foveated audio device encourages head scanning to explore the world. As one turns the head, one encounters new objects as auditory icons. We refer to the combined action of head scanning and the sonification of objects as auditory icons as an "acoustic touch." The AR system enables exploration of spatial mapping and memory via an active task. Significantly, active memory tasks require one to work with the information, while passive tasks require recall only.

Our experiments employ a software experiment manager that is programmed on the Unity game engine and that is integrated with an Optitrack motion capture system to record hand reaching motions. The virtual sound sonification of the AR system is compared with real sounds produced by Bluetooth loudspeakers (Sony SRSXB13). We enable multichannel audio using an asset purchased via the Unity assest store. We measure cognitive effort via questionnaires and the measurement of bio-signals such as heart rate and electrodermal activity. The collection of various experiment data (mobile phone and external devices) are synchronized using the lab streaming layer software [24]. We have generally found this experimental

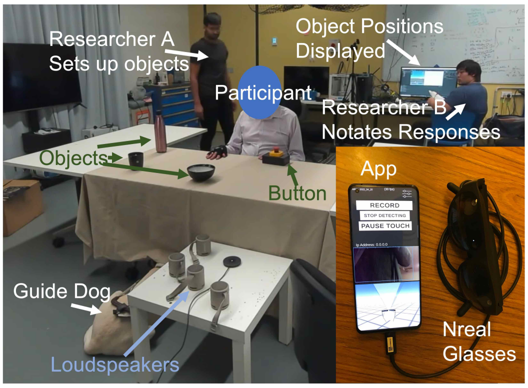

Figure 2. An example experimental setup is shown (reproduced from [23]). Note that twelve overhead cameras for the motion tracking are not visible.

setup quite flexible enabling studies of spatial cognition using both virtual and real audio and also the addition of EEG measurements during trials.

2.7 VR and hearing training

Hearing aids and cochlear implants are, by far, the most used and successful approach to dealing with hearing loss. The majority of the research and clinical efforts focus on fitting the devices to compensate for the loss of a specific individual and restore their lost cues and normal hearing functions – this approach can be referred to as system-to-user adaptation. Another promising, albeit significantly less explored approach is to train the hearing aid user to adapt to the altered cues (caused by the hearing loss and the hearing aid/cochlear implant) and recover near-normal hearing functions (user-to-system adaptation). These two diametrically opposite perspectives are not exclusive, but while with the first the technology is now so advanced that to gain a minimum advantage major research investments have to be made, with the second initial research shows that significant improvements can be obtained through a limited number of perceptual training sessions, which can be carried out exploiting VR applications and equipment.

There is increasing evidence that the adult brain is more adaptable than classically thought. Looking for example at spatial hearing and sound sources localisation (e.g. the ability to precisely locate a sound source in the surrounding space), we have shown that this adaptability (or plasticity), when performed using VR technologies, can lead to a decrease in localisation error over time when a listener's normal cues for sound location are disrupted/modified (see Figure 3) [25]. Evidence has shown that other perceptual skills, such as speech-in-noise understanding, can be trained using digital applications (e.g. [26]) and that, under certain conditions, the acquired skills can be transferred to other perceptual domains (e.g. [27])

Building on this research the BEARS (Both EARS) project builds on the knowledge that for training to be effective it should be engaging, multi-modal and interactive. The specific aim is to train spatial hearing skills in bilateral cochlear implant teenage users. A participatory design approach was employed to develop a suite of applications targeting three specific tasks [28]: sound localisation (target practice), speech-in-noise (ordering food at a diner and building a pizza) and music listening/making (beating a rhythm and being the DJ). The clinical trial to evaluate their effectiveness will start in January 2023.

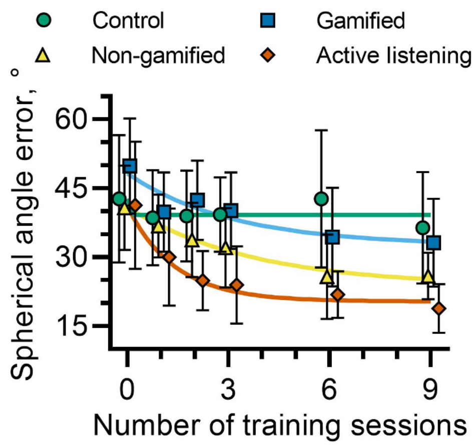

Figure 3. Decrease of localisation errors after each training session for the control group (no training) as well as for other trained groups, all showing significant improvements over time (reproduced from [25]).

2.8 Examples of facilities - the ARI lab (Vienna)

The ARI lab in Vienna runs two facilities related to VR-related experiments and the acquisition of listener-specific HRTFs: the "yellow" semi-anechoic room, and the loudspeaker array studio (LAS).

The yellow booth has a dimension of 6.2 m x 5.5 m x 3 m. It is available for acoustic measurements such as HRTF measurements with in-ear microphones, and behavioral experiments such as sound-source localisation experiments. The equipment includes a 22-loudspeaker array for HRTF measurements and a VR setup for offering a virtual visual and binaural-acoustic environment controlled with an infrared head tracker in real time. The HRTF measurements have been performed since 2005 in this setup (e.g., [29]). The VR-based experiments have been performed since 2006, starting with a Trivisio HMD (e.g., [30]), later with several versions of Oculus Rift (Kickstarter-raised DK1, DK2, and CV1). In that time a large number of studies has been performed (e.g. [31–33]), and further studies are currently under progress (e.g., projects Born2Hear, ConLoc, and Rhythm Perception Across Species, see https://www.oeaw.ac.at/en/ari/research).

Figure 4. ARI: Yellow booth showing the sound-source localisation setup consisting of a VR goggles and a pointing device.

The LAS is constructed as a semi-anechoic booth of 3 m x 3 m. In the booth, 91 loudspeakers are arranged in a spherical order, and together with two subwoofers (driven by two channels each) reproduction of virtual sound sources can be provided via loudspeakers. Further, the booth is equipped with in-ear microphones for listener-specific HRTF measurements, and combined with a VR setup (Oculus Rift) and an infrared head-tracking system, binaural virtual sound sources can be reproduced via headphones in real time. The combination of loudspeakers and headphones in the same room enable a strict comparison of behavioral data between the presentation in the free-field (virtual sound sources filtered by the natural acoustic HRTFs of subject's body) and the binaural presentation via headphones (virtual sound sources filtered by HRTFs measured in the same room). Currently, several projects are ongoing in the LAS, e.g., [34].

Figure 5. ARI: The loudspeaker array studio (LAS) consisting of 91 loudspeakers for listener-specific HRTF measurements and behavioral experiments requiring a direct comparison between the loudspeaker-based and binaural sound reproduction.

3. CHALLENGES

While a significant amount of work has already been done in designing, developing and evaluating VR tools and applications to facilitate hearing research, it is clear that still a lot is needed before such techniques will be widely standardised and, possibly, also available in clinical settings. In preparation for the Virtual Conference of Computational Audiology (VCCA) 2022, we have involved several researchers and clinicians in an exercise attempting to map the future challenges with VR applied to hearing research. Twenty six separate items were identified, and later grouped in four separate categories:

- Hardware and software development: designing and developing new equipment and tools.
- Validation and standardisation: assessing the benefits, comparing these with existing solutions, and contributing to the standardisation of the novel approaches and tools.
- Realism and control: better balancing the trade-off between realism of the simulation and control of what is being delivered to the participant/patient.
- Applications and use in clinical settings: explore uptake in clinical routine through extensive clinical trials.

Any large-scale implementation of VR in clinical practice would require a support infrastructure to keep the technology current, engaging and exciting, and to respond to any technological challenges that arise. The work we presented in this paper has already fostered progress in each of these areas, allowing more researchers, clinicians and patients to be actively involved in shaping what is likely to be the future of hearing research.

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