Augmented Reality: Hear-through

Karolina Prawda
Aalto Universtiy
Master's Programme CCIS / AAT

karolina.prawda@aalto.fi

Abstract

Augmented Reality has recently become very popular and new applications utilizing this concept emerge frequently. From signal processing point of view, Augmented Reality Audio (ARA) is a challenging concept. This is caused by the requirement that natural sounds in ARA are delivered to listener's ears without any perceivable changes, whilst virtual audio is indistinguishable from real-world sounds in terms of quality. At the same time users should be able to differentiate between real and augmented sounds easily. This paper provides overview of different technologies used in ARA. Multiple types of headsets are discussed, including those utilizing regular headphones as well as bone conduction devices. Problems concerning hear-through, such as coloration and comb filtering effect, and available solutions for them are presented as well as examples of studies evaluating usability and User Experience.

1 Introduction

Augmented Reality is gradually becoming more available and affordable for a regular user and therefore its popularity grows quickly. Audio is a very important feature of AR environments and therefore it is a subject to research. Crucial issue to achieving good Augmented Reality Audio (ARA) is making virtual sounds audible on top of real ones without causing attenuation or masking. This can be achieved by designing special headsets with hear-through properties. The overview of current state of ARA technology with special focus on hear-through is the topic of this paper.

There are multiple ARA applications available and even more are possible to be built in the future [11] [12] [18]. However, in order to provide the users with best possible experience, the headsets used for ARA must meet various requirements. First, the right type of headphones should be chosen, so that the natural listening of real-world sounds in ensured [9] [22] [34]. Available headphone types, however, are not free from features that lead to deterioration of sound quality [31] [32]. Because of this, methods aiming at equalizing natural sounds transferred through headset to listener's ear as well as virtual audio [10] [16] [23] [24] [25] [26] [29] are being developed constantly. As the wearable ARA systems are supposed to be worn over long periods of time, they should also take into account the issues related to usability [33] and User Experience [1] [35] as well as manual control over equalization parameters [16].

ARA headsets using traditional headphones are the main focus of this paper, as the works concerning them are most advanced. However, there are also solutions that utilize bone conducted sound in Augmented Reality Audio. This paper discusses those examples and compares them to regular headphones [2] [3] [4] [14] [15].

2 Overview

The first thing to do when discussing technologies for AR is to distinguish between real, Virtual and Augmented environments as the requirements for achieving good acoustic experience within each of them may vary.

The basic difference between real and virtual sound environment is that the former may either be created in an completely artificial way or originate from a real, but distant, environment. Augmented Reality Audio is grounded in reality and combines virtual sounds with the natural ones so that the former are perceived as extension to the real life scene [11] [18].

AR sounds can be approached in two extreme ways. First is to set the primary goal of audio to "suspension of disbelief" [12]. This means that the listener cannot distinguish between real and virtual sounds. Excellent binaural rendering and tracking of listener's position and orientation combined with source attenuation and directivity customization should be incorporated in the headset design to achieve that goal. On the other hand, virtual scenarios should be rendered so that the listener will not confuse them with natural sounds [11] [18].

Regardless of the approach adopted, the devices used to reproduce ARA should provide "transparent hearing", meaning that the real world sounds should not be attenuated at the default state. Only the user's own manipulation should be able to alter the way both the natural and virtual sounds are heard [12]. Usually to separate listening to natural sounds with ARA headset from listening without any devices, the term pseudo-acoustics is used [11] [34].

Nowadays various applications using ARA are available. Among them, the solutions for speech communication are thought to be amid the most important. This type of applications may take various forms. One of them is presenting a remote talker to the user by the means of binaural auralization [11]. Slightly different concept, where a distant user is virtually transported to the location of the talker is called telepresence [11]. It may be also extended to a form of teleconference, where it is possible to separate and localize different attendees, which makes the event feel more natural [11] [36].

Other types of ARA applications are connecting sounds to the real world objects. By superimposing virtual sounds on top of real ones, a soundscape with alerting sounds, instructions, advertisements etc., is created [11]. This approach may be used in automated tour guides [5], navigation systems [1] [6] [35] or auditory Post-it messages or stickers, that can be attached to objects and left in certain places [11] [18].

ARA applications can also use the concept of freely-floating acoustic events, that are not connected to any particular object or location in space, for example news, calendar reminders, announcements [11].

3 ARA headset design

The ideal case for ARA headset is when all the necessary hardware is already included in it. In that situation, the user will only wear a pair of wireless headphones equipped with additional microphones used for recording the real world sounds. The important issue in device design is to make it small as people are nowadays used to carrying portable devices that are not big in size. The ARA headset should also be light, which is crucial to ensuring comfort of users who are supposed to wear it for long periods of time [34]. Those requirements are, however, hard to meet while still maintaining good sound quality for both natural and virtual sounds.

The resonance of ear canal is crucial in perceiving natural sound without coloration. When the ear is blocked with the earphone, the normally occurring quarter-wavelength resonance is replaced with half-wavelength one [20]. In order to obtain natural sounding pseudo-acoustics, the equalization that will damp the unwanted resonance must be applied. The response of headphones, which causes mid- and high-frequency attenuation must also be corrected. As the positioning of the headset is important factor that may cause leakage and, in result, prevent the pseudo-acoustics from sounding natural, it must also be considered when the equalization is applied [32] [34].

Moreover, the ARA headset, as all electronic devices, introduces latency to the signal due to performed processing (e.g. AD/DA conversion and equalization). When the headphones' positioning is poor and results in leakage, the real-life signal and its delayed version are summed and cause a comb filtering effect, example of which is presented in Fig. 1. Provided that ARA headset has strong attenuation of external sounds, good equalization filters and low latency, the undesired effect cannot be heard in speech signals but is audible when music is played [24].

ARA headsets are usually designed as regular headphones with addition of binaural microphones, which capture the real sounds. Studies were conducted to test how

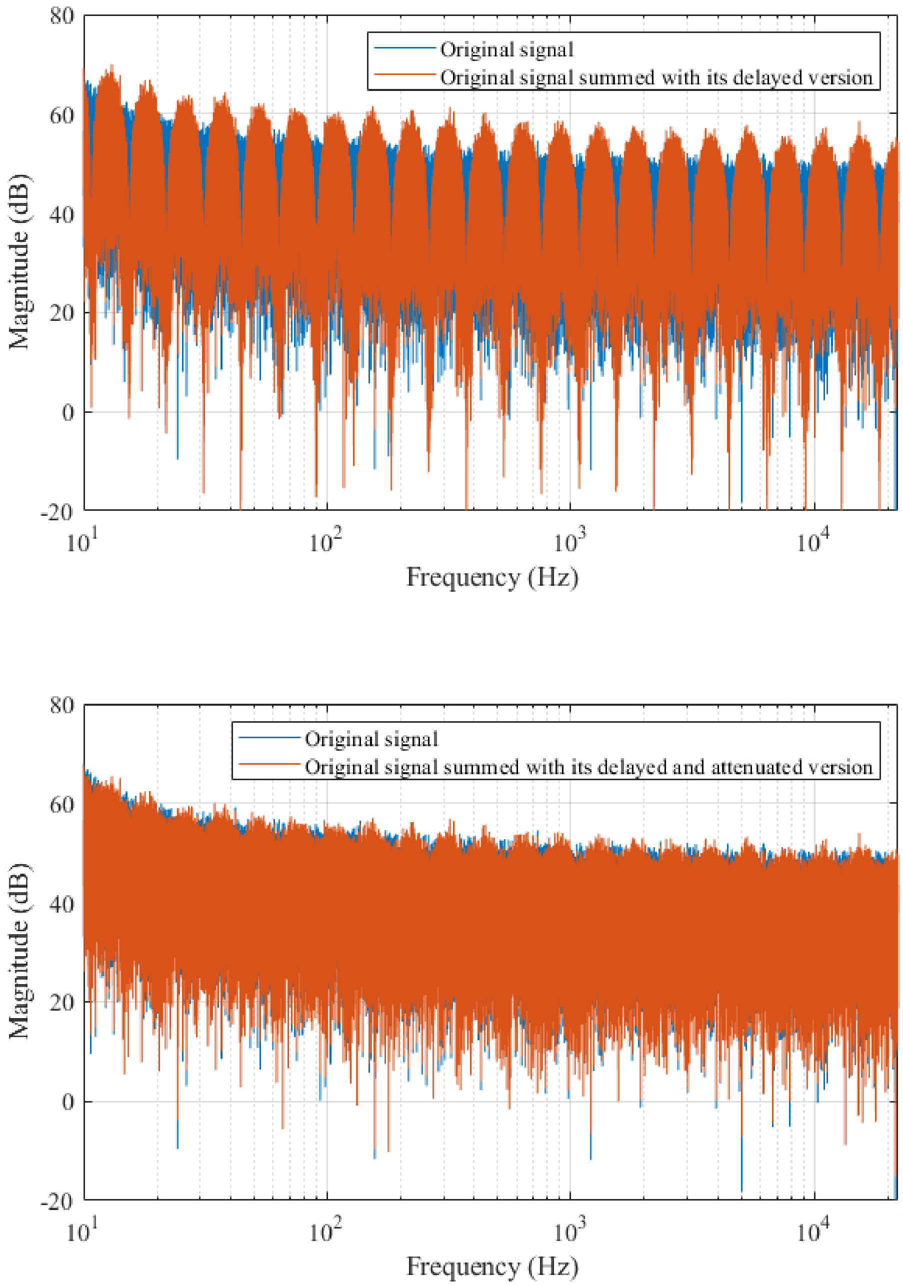

Figure 1: *Comb filtering effect. Top: pink noise signal summed with its version delayed by* 1 *ms. Bottom: pink noise signal summed with its version delayed by* 1 *ms and attenuated by* 15 *dB.*

different headphones perform when used as an ARA headset. The open-back [25], closed-back [9] and in-ear [12] [34] headphones were evaluated.

In [25], the isolation of different types of headsets was measured as a function of frequency and azimuth. The study found that open circumaural headphones attenuate sounds least and reflect the frequency notches present in the reference response obtained using dummy head. They were also found the most convenient for placing

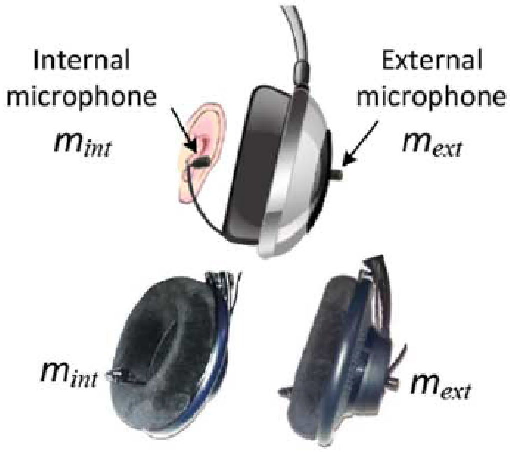

Figure 2: *ARA headset proposed in [25].*

of internal and external microphones. Those headphones were chosen for further work and the approach trying to make virtual sounds indistinguishable from real ones was adopted. With the use of adaptive filters and equalization good similarity between real and virtual sources was obtained, making listeners unable to tell when only real or only artificial or both types of sources were used. It was also shown that the designed headset reflects the localization of virtual sources quite accurately.

Two pairs of microphones were used in the headset presented in [25]: external, positioned outside the headphones ear cup to capture the environment's sounds, and internal, placed very near to ear opening and used for adapting to the desired virtual sound field measured at listener's ears. Both sets of microphones are also performing off-line measurements of the transfer functions that can be stored in the personalized HRTF database. Microphones placement is the proposed headset is pictured in Fig. 2.

Approach using closed-back headphones was used in [9] in order to overcome the problems with weak high frequency attenuation in open-back headphones and change of ear canal resonances observed for in-ear headphones. The closed-back headphones showed best isolation properties when the Active Noise Cancellation (ANC) mode was on, having strong attenuation of external sounds across entire spectrum. Similarly to the headset discussed above, each ear cup is equipped with an internal and an external microphone, positioned as in [25] and serving similar purposes. Additionally, equalizing (EQ) filter for the hear through setup were derived using adaptive algorithm. This resulted in obtaining ideal hear-through (HT) EQ filter for each angle and two simplified average EQ filters. The headset was tested used both objective (Spectral Difference for each EQ filter) and subjective (MUSHRA listening test) methods. The evaluation showed that ideal HT filter's response is very close to open-ear reference [9].

ARA headset utilizing in-ear headphones was presented in [34]. The devices used in the headset were Philips SHN2500 earphones, which are advantageous by already

Figure 3: *ARA headset proposed in [34]. Left and middle: earphones used for evaluation. Right: prototype ARA mixer as described in [29].*

being equipped with electret microphones due to their noise cancellation properties. The devices are depicted in Fig. 3. This solution experiences problems of modified ear canal resonance discussed in previous paragraphs and therefore dedicated mixer must be included in the design. The ARA mixer used for headset proposed in [34] was described in [29]. In order to minimize latency which may lead to comb filtering effect, it utilizes analog circuits instead of digital solutions. The mixer equalizes the external sounds captured by binaural microphones by feeding them to first-order high-pass filter as well as biqudratic peak and notch filters as presented in Fig. 4. The Q-values, frequencies and gains of filters can be adjusted. The mixer is also used for mixing the external and virtual sounds. The evaluation of the headset proved that it is applicable in everyday situations [34].

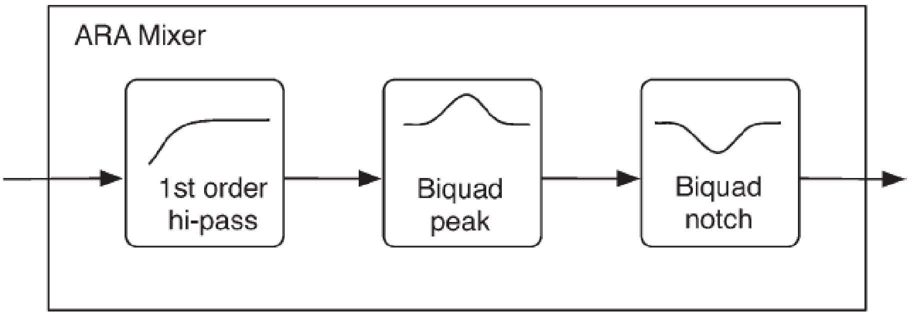

Figure 4: *Filter sections in ARA mixer as described in [29] [34].*

In various commercially available headsets, e.g. Sony Xperia Ear Duo, the highest fidelity of real-world listening is obtained by means of mechanical solutions. The ear canal is not entirely blocked, and a hollow "ring supporter" with a small transducer allows to play audio from the device and listen to natural sounds at the same time. However, such headsets have limited quality of synthesized audio and they do not provide user control over the sound parameters [12]. An example of such headset is presented in Fig. 5.

Figure 5: *Commercially available ARA headset [21] that does not block the ear canal entirely.*

4 Requirements and technologies

When discussing hear-through and Augmented Reality Audio headsets, many problems can arise, as presented in Sec. 2 and Sec. 3. To avoid unwanted phenomena, certain improvements must be introduced to the design. Users' comfort must be brought into attention as well. The present section discusses some of the methods that were developed to improve both technical parameters of ARA headsets and User Experience.

4.1 Equalization

One of the most important issues in achieving natural hear-through experiences is providing good equalization of the real-world sounds. This can be only done by first providing that the external signals are strongly isolated from the processed sounds, which is rarely met in real life, especially for low frequencies. Then, the environmental signals captured with binaural microphones should be processed in a way that preserves their characteristics, thus making them sound natural [9]. In order to meet those requirements, filters must be applied to reduce the perception of comb filtering effect and compensate for the ear canal resonance changes, at the same time introducing low latency [22]. The manual control over the equalization is also desired, as it increases the comfort of using the ARA headset.

The equalization was first obtained by using special mixer, that was based on active LRC-filter [29] and later changed to digital version [22]. It provides first-order high-pass filter together with biquadratic peak and notch filters (as shown previously in Fig. 4). The parameters of filters can be adjusted, so that the quarter-wave

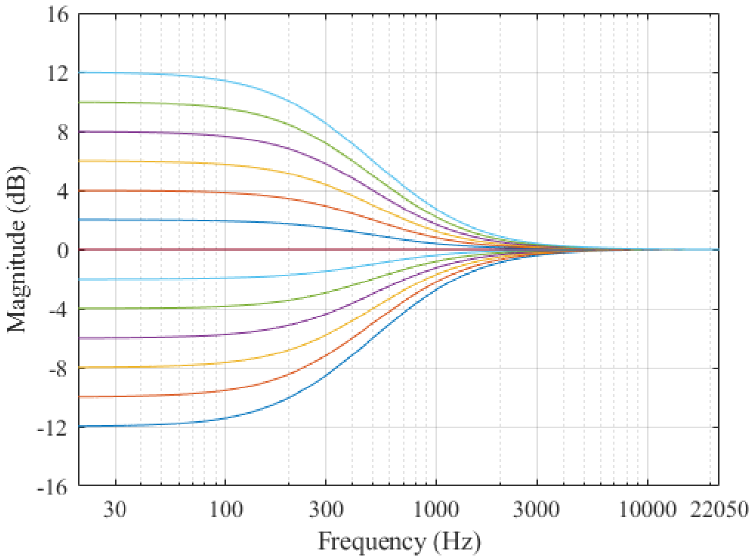

Figure 6: *Frequency responses of equalizing filters proposed by Regalia and Mitra [28] [13] [39]. Top: responses of low shelving first-order filters plotted for constant crossover frequency and gains changing in range* -12 *dB to* $+12$ *dB. Bottom: responses plotted for peak-notch second-order filters. Positive gains have a constant value of* 8 *dB, whilst negative gains are set to* -8 *dB. Center frequencies change in one octave steps and bandwidth is set to one octave.*

resonance of the unblocked ear canal is recreated and half-wave resonance of blocked ear-canal is compensated. Those parameters are: the Q-value, responsible for the bandwidth and steepness of the peak or notch, frequency, which determines where on the frequency scale the peak or notch appears, and gain that specifies whether the filter's response appears as peak or notch.

Another idea utilizes the filter design method suggested by Strube [30], which presents the method to design allpass filter with desired beginning of the impulse response. Based on this, the transfer function of ARA system was designed to be an allpass transfer function. This approach is proven to be able to flatten magnitude response to be the same as the maximum level of the headphone's isolation curve [23]. The real-time implementation of this solution is, however, not yet available.

One of the important concepts in ARA is live equalization, which operates in real-time on sounds heard through the earphones. The idea was originally brought to light with growing interest in hearing protection, especially in situations when sounds should be quieter while enhancing good quality, such as at concerts. [24] introduces live equalization system that consists of a first-order low shelving filter and a three band graphic equalizer. The shelving filter is aimed at attenuating lowest frequencies, which are usually played very loud. Common practice is to use equalizing filters proposed by Regalia and Mitra [28] [13] [39], examplary frequency responses of which are presented in Fig. 6. The GEQ enables live music equalization and the number of bands can be increased, decreased and adjusted according to needs.

Filters used in the live equalization system presented in [24] introduce some delay to the processed signal, which results in unwanted comb filtering effect. However, since the equalizer does not reproduce low frequencies due to low shelving filtering and the headset itself attenuates high frequencies, the undesired phenomenon is decreased in those areas.

The idea of live equalization is still being extended and improved. The solution proposed in [16] is performing adaptive equalization by constant estimation of headphones' isolation curve in relation to the surrounding soundscape and compensating for the effect the headset has on the acoustics of the ear based on the attenuation estimate.

The equalization method presented in [16] calculates the isolation curve for each earpiece of the headset independently by using microphones that are internal and external to the earphones. The block diagram of the system is shown in Fig. 7. x_{int} represents signal from internal microphone, referred to as in signal and x_{ext} stands for external microphone signal, also called out signal. Both of them are first fed through the disturbance detector to remove low-frequency artefacts. The in signal is then fed through DC blocker and out signal is allpass-filtered to compensate for the group delay. Then, the out signal undergoes spectral whitening and in signal is filtered correspondingly. The momentary isolation is calculated from the preprocessed x_{int}

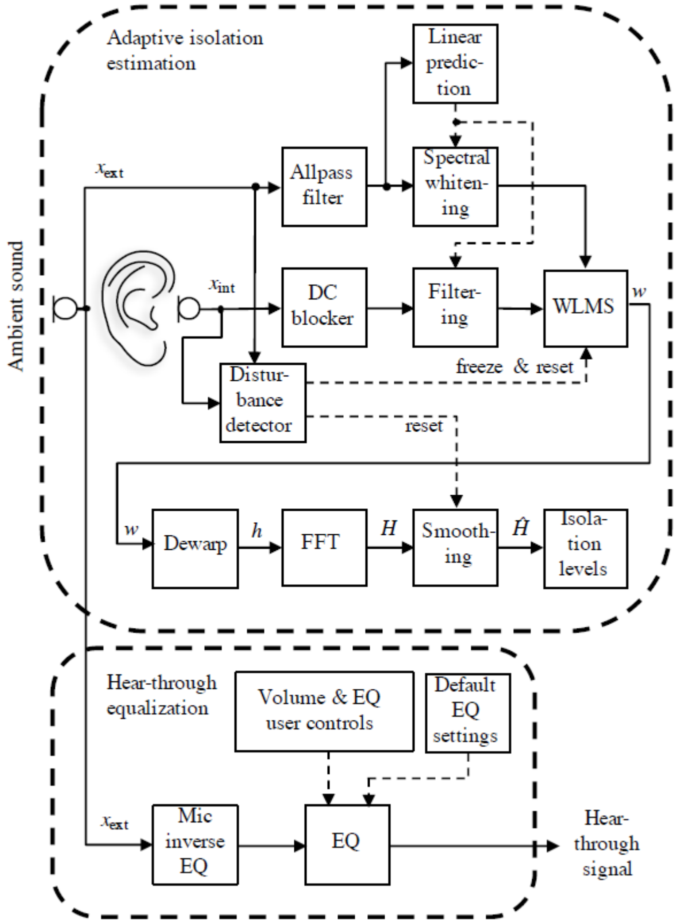

Figure 7: *Block diagram of the adaptive equalization algorithm proposed in [16]. Thick dashed lines divide the diagram into two parts: adaptive isolation estimation and HT equalization. Thin dashed lines represent control signals, whilst solid lines depict signal paths in time or frequency domain.*

and x_{ext} signals with a Warped Robust Variable Step Size Normalized Least Mean Squares (WRVSS-NLMS) algorithm [16]. After that, postprocessing, which includes dewarping, FFT and smoothing, is applied in order to obtain final isolation curve.

The second part of the algorithm described in [16] is HT equalization. First, microphone inverse equalization is performed to level the boost in frequencies between 10 and 20 kHz, which occurs due to headset mechanics. Then, equalization of captured ambient signal is done with parametric equalizers that have adjustable parameters. The default settings are chosen to obtain acoustic transparency in ideal conditions. The method uses the same types of filters as mentioned in [24].

Solution presented in [16] allows manual transparency control as well. The slider that ranges from −30 dB to 10 dB boosts or attenuates the HT with additional adjusting of shelving filter when going down the scale.

Figure 8: *Different ways sound leaks when wearing headphones [32].*

Different approach regarding adaptive equalization was shown in [9] [26]. The equalization is calculated based on the difference between response of the internal microphone, referred to as reference, and external microphone. The additional use of Filtered-x Normalized Lest Mean Squares (FxNLMS) algorithm [27] computes ideal hear-through equalization.

4.2 Sound quality

The sound quality is a very important issue in Augmented Reality hear-through devices and applications where the pseudo-acoustics should be reproduced in a realistic manner. The main problem that ARA headsets face and which can deteriorate sound quality is leakage. Very common cause of low sound quality is wrong fitting of the headset, which usually happens when in-ear headphones are worn, and has usually strongest effect on low frequencies. Additionally, the blocked ear canal results in occlusion effect, which makes the user's own voice sound hollow and boomy [31].

The goal of ARA headset is to reproduce the signal inside listener's ears identically as when no headphones are worn. Although some sound-altering leakage is always present, as depicted in Fig. 8, correct positioning of the devices allows the negative effects to be reduced with equalization [32]. This work briefly describes most common reasons for sound leakage that causes deterioration in ARA headset sound quality.

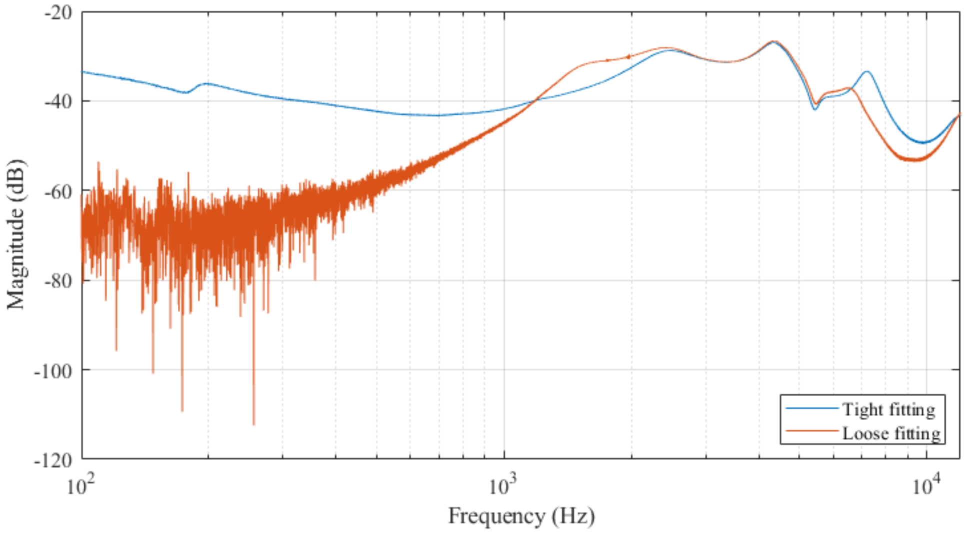

Figure 9: *Frequency response of tightly and loosely fitted 1More Triple Driver in-ear headphones. The loose fitting of earpieces causes leakage that changes the response of headphones and lowers the quality of sound that reaches listener's ear drum.*

When the insert headphone is fitted loosely in the ear, it is usually not centered around the ear canal. This results in different path length that the sound travels from outside the headset to inside the ear canal. Some parts of the earpiece can also be fitted more tightly than others. The wide opening can be then considered either as one big and one small slit around the headphone or as a number of parallel narrow slits [32] [37]. The frequency responses of in-ear headphones with tight and loose fit are presented in Fig. 9.

When headphones are used with a porous, foam-like cloth covering the casing, one big slit between the headphone and the skin is represented with many small ones, making the leakage purely resistive (headphones without cloth can have leakage modeled as circuit with resistance, inductance and capacitance). Fabric affect earpieces responses as well, making them less dependent on fitting. Both of those factors result in the loosely inserted headphones being more predictable in terms of their acoustic behavior [32].

There are many other factors that introduce leakage. One of them is related to human skin, which is elastic and thus allows the headphone to vibrate. Depending on the skin elasticity and damping and the earpiece mass the vibration characteristic may vary. Insert headphones usually have openings at some parts of casing as well. Bone and tissue conduction also create some leakage but sound transmitted this way is very much attenuated [32].

The leakage colorates the sound, lowering its quality. Therefore, compensation must be included in the system, taking into account that the leaked sound is not delayed, so the part of the systems that reduces its impact should ideally have no latency [31]. This requirement is impossible to meet in practice, so low latency DSP and AD/DA converters are used.

4.3 Usability and User experience

The ARA headset is aimed and being worn for long periods of time, therefore its usability was tested. The main focus was to evaluate the device in the situations when its performance was not optimal. The participants of the experiment were given the ARA headset and mixer and were supposed to wear it during their daily activities for as long as possible. They were instructed to note their observations and to evaluate usability of the headsets for certain actions, for example reading out loud, drinking water or chewing gum. Sound quality test was also performed by using sounds such as finger snapping and speech. The task was to evaluate spatial impression, timbre and externalization [33].

The results of the test showed that whether listening to the natural sounds with the ARA headset is found annoying or not was primarily the matter of individual experience. Loud sounds, such as biting crisp bread, were further amplified by occlusion effect and therefore found mostly unpleasant, whilst there were no big differences in perception of drinking water sounds with or without the headset. The subjects also were adapting to having the device on after some time and the sound quality of pseudo-acoustics was found to be good as well as the sense of space and directional hearing. The subjects also reported good externalization of sources, which is probably also the result of the real-time cooperation between sound and vision [33].

The user experience while wearing the ARA headset was also a subject of research. Following the formula of the experiments conducted in [8] and [17], the participants were given ARA headsets which they were supposed to use for navigation in the city environment. The 3D audio guide, which used looped horse walking sound to give directions, was leading to a point straight ahead of the listener, with signals aimed to raise user's attention before making turns and indicating reaching the destination. The participants had to rely only on the audio guide during the whole task, with no help from the visual User Interface [35].

The study showed that navigation using only sound-delivered directions is available and even preferred compared to regular systems [35]. Similar test were also conducted using different types audio signals and for navigating not only pedestrians, but also cyclists. The results varied considerably based on the user's preferences, nevertheless they proved that this type of guide provides good navigation in the city environment [1]. The hardware setup used for the studies is presented in Fig. 10.

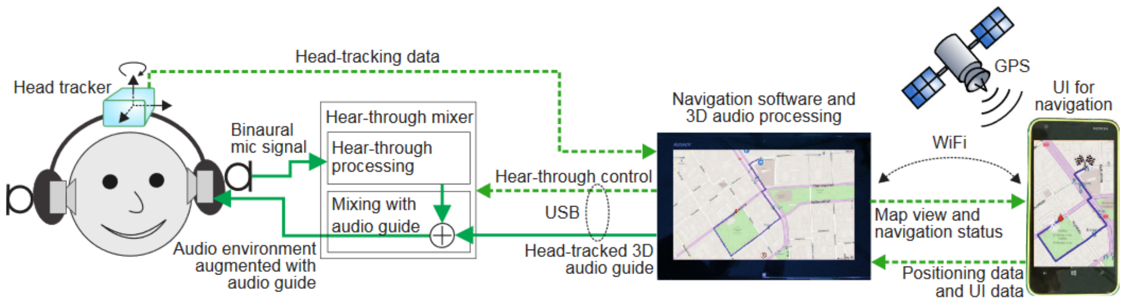

Figure 10: *Hardware setup used in User Experience studies [1].*

5 Hear-through using bone conduction

Bone conduction is mostly associated with hearing aids. In the last twenty years, however, it was recognized as being applicable for non-clinical purposes as well. Wrist-worn bone conduction device that passes audio from the cellular phone to the ear after the listener puts his or her the finger into their own ear canal may serve as an example of this approach [7]. The use of bone-related transfer functions (BRTFs) was also suggested to enable providing spatialized cues using bone conduction [38].

Hear-through using bone conduction was first tested more than ten years ago [14] [15] [19] using static and moving tones as well as Gaussian noise. The earpieces were positioned on the subjects' cheek bones as depicted in Fig. 11, leaving the ears unblocked. This simplifies the process of delivering high fidelity real world sounds to the listener, as no processing or equalization is required.

The first tests showed that both stationary and moving sounds were usually easy to lateralize using bone conduction, but the right location of sound was considerably harder to determine. It was suggested that adding information provided by HRTFs may be of help in localizing the sound sources, as it was shown in [19] for Gaussian noise stimuli. It was also shown that the ability to localize the sound using bone conducting devices was similar or better in comparison to regular headphones [14] [15] [19]. However, taken into account that some bone conducting units have significantly narrower frequency response than traditional headphones, their performance in hear-through may be worse for sounds more complex than tones or noise (e.g. speech signals) [14] [15]. Navigation using auditory cues delivered with bone conduction also proved to be less correct compared to regular headphones [38].

Binaural cues were used in research using bone conduction devices only recently. The commercially available, inexpensive software and hardware was tested in terms of localisation accuracy in the horizontal plane. It was shown than the localisation errors between 30^o and 35^o occurred and the externalization was reported by 92% of the participants [3]. The source separation was recognized as sufficient and adequate for the equipment quality and price, but worse than in traditional headphones. Other studies showed that when the subjects were asked to localize the sound source in

Figure 11: *Bone conducting headset used in test in [14] [15].*

horizontal and vertical plane, the results were considerably worse than when only one plane was used [2]. Binaurally spatialized cues delivered over a bone conduction headset were also found to be efficient in redirecting the attention when participants were playing a game that used both visual and auditory displays. Best results were obtained when the sound source was of outside of visual range [4].

6 Summary and conclusions

Present works presents an overview of both recent and older techniques and methods used to provide most transparent hear-through in Augmented Reality Audio.

There are many types of headphones that can be used in ARA headsets. Studies show that open circumaural headphones allow the natural sounds reach listener's ears similarly to situation when no headphones are worn. When equalization is added, virtual sounds that are almost indistinguishable from real ones and good source localization properties can be obtained.

Other approaches utilize headphones that have high isolation parameters and prevent the external sounds from entering the user's ear canal effectively. Closed-back headphones with Active Noise Control proved to serve that purpose well. With the use of equalization filters, response very similar to open-ear reference can be obtained.

Most studies, however, use in-ear headphones in ARA headsets. They block the ear canal almost thoroughly, which results in good isolation characteristics. They are also small, light and comfortable to use over long periods of time. Apart from those advantages, they also have some drawbacks. Blocking the ear canal changes the naturally occurring quarter-wavelength resonance to half-wavelength one, leading to sound coloration. The earpiece never covers the entrance to the ear canal entirely, which along with other factors provides sound leakage, resulting in undesired comb filtering effect. Taken those disadvantages into account, equalization is introduced to overcome them.

Regardless of the type of headphones used in ARA headset, they mostly are equipped with two pairs of microphones: external and internal ones. The outer ones are used to pick up the environmental sounds while the internal ones give information about ear canal response. Based on both sets of data, the adaptive filtering algorithms can adjust the equalization to efficiently reduce unwanted phenomena, such as comb filtering effect and sound coloration.

ARA headsets are aimed at transferring natural sounds in realistic way and also provide virtual sounds that are indistinguishable from the real ones. Therefore, the sound quality is a very important issue in Augmented Reality Audio and factors that deteriorate it must be compensated, ideally by systems that do not introduce latency.

The studies show that users of ARA headsets with in-ear headphones consider them to be sufficiently comfortable to be worn throughout the day. The sound quality and sense of space were also found to be good. The tests using ARA systems for audio navigation proved this idea to be worth developing and in many cases better than traditional visual guides.

Bone conduction is also considered when it comes to ARA. It has the advantage of the ear canal not being blocked by earpiece, which does not generate problems with natural sounds processing. However, the bone conduction headsets available nowadays prove to be worse in terms of determining the source location compared to regular headphones. They also do not provide good source separation and are unsuitable for navigation purposes.

The future of ARA possibly lies in creating more efficient adaptive algorithms that allow instant equalization preventing any unwanted effects from occurring while using ARA headsets. Also, the comfort of wearing headphones will be increased and more applications that utilize ARA will appear, making it more common. Hear-through using bone conduction may also be improved, making it more applicable for AR.

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