Electronic Hearing Protection for Musicians

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Abstract

This is the final report of the project "Electronic hearing protection for musicians" (Muusikon elektroninen kuulonsuojaus) funded by the Finnish Work Environment Fund (Työsuojelurahasto) [project nro 115145]. This document includes background information of the project, introduces common hearing problems and the need for hearing protection, and proposes a new hearing protection device. The device was designed and evaluated during the project with good results.

Contents

1. INTRODUCTION

Musicians, among others, are exposed to large sound pressure levels that may over time lead to hearing loss, hyperacusis, and tinnitus. Since the sound pressure caused by the musicians' instruments or the PA system often cannot be limited to safe levels during rehearsals and especially during concerts, personal hearing protection must be used to limit the noise exposure. Hearing protection – typically earplugs when it comes to performing musicians – is effective for attenuating the sound of other musicians playing in an ensemble. However, plugging the ears with hearing protection devices makes the sound of the musician's own instrument unnatural. The main reason for this is that part of the sound reaches the inner ear through bone conduction. This bone-conducted sound is not attenuated by the earplugs, but instead amplified by them, and is often very different from the normal air-conducted sound of the instrument. For many musicians this is not a problem, but, e.g., for wind instrument players, who get a large degree of bone-conducted sound from their instruments, it is.

An earplug-occluded ear canal amplifies bone-conducted sound up to 30 dB at low frequencies due to the occlusion effect (Stenfelt and Reinfeldt, 2007). Together, the attenuation of air-conducted sound and the amplification of bone-conducted sound causes the sound of a wind instrument to appear distorted to the musician him- or herself. For this reason, many musicians are reluctant to use hearing protection (Laitinen, 2005) and therefore often suffer from hearing disorders (Kähäri, 2002). Another problem when using earplugs is the change in timbre when the ear canal is blocked (Albrecht et al., 2011).

This problem not only affects wind instrument players, but also violinists, who rest the instrument against their jaws. Singers are equally affected by the problem, as is any musician or other person talking while wearing hearing protection. In other words, earplugs make the sound of the musician's own instrument unnatural and therefore musicians tend to avoid using hearing protection.

In this project, we propose, design, and evaluate an electronic hearing protection solution aimed particularly at musicians. The solution consists of noise-attenuating insert headphones with microphones both inside the ear canal and on the outside of the headphones. The in-ear microphones are used for partial cancellation of the occlusion effect with the help of a negative feedback circuit, while the microphones outside can be used for hear-through purposes, resulting in hearing protectors with adjustable attenuation. Additional microphones are used to pick up the sound of the instrument. This sound can then be reproduced at a desired level, in order to restore some of the natural balance between the air-conducted and the bone-conducted sound of the instrument.

2. BACKGROUND AND RELATED RESEARCH

2.1. Hearing problems and risks for musicians

Laitinen (2005) surveyed hearing problems and the use of hearing protectors in five major classical orchestras in the Helsinki region. Among the musicians that answered the questionnaire, 31% reported some degree of hearing loss; 37% reported temporary tinnitus (15% of the women and 18% of the men reported permanent tinnitus); and 43% reported having hyperacusis. These hearing problems were also associated with a high level of stress: the musicians with hearing problems had three to nine times more stress than the other musicians.

2.2. Use of hearing protection among musicians

In the survey by Laitinen (2005), 69% of the musicians were at least somewhat worried about their hearing. However, only 6% of the musicians always used hearing protectors. Musicians often only start using hearing protectors once they have developed hearing problems: 20% of the musicians with hearing problems used hearing protectors, while 6% of the musicians without hearing problems used hearing protectors. Among the musicians that answered the questionnaire, 47% used custom-molded earplugs, while 25% used disposable earplugs.

2.3. Challenges with hearing protection for musicians

According to the study by Laitinen (2005), the main reason why many classical musicians do not use hearing protectors is that it hinders their own performance (n=155). The second largest reason is that earplugs make it difficult to hear other musicians in an ensemble (n=88). Further reasons are that the sensation of hearing protectors is unpleasant (n=15) and that they are difficult to insert (n=12).

2.3.1. The occlusion effect

One specific problem when using hearing protectors both hindering the musician's own performance and making it difficult to hear others play is the occlusion effect. In a normal situation the ear canal is open and the bone-conducted sound energy transmitted from the musician's own instrument into the ear canal exits to a large degree through the ear canal opening. When the ear canal is blocked with an earplug, most of the bone-conducted sound is directed to the eardrum. This causes the amplification of low-frequency sound, which is referred to as the occlusion effect.

Killion et al. (1988) showed the frequency dependency of the occlusion effect, depicted in Fig.1. It can be seen that the occlusion effect is also signal dependent, in addition to frequency dependent. The low-frequency boost caused by the occlusion effect causes two problems for musicians using earplugs. Firstly, it colours the sound, making it darker and boomy. This makes it difficult for the musicians to hear the nuances of the sound of their own instruments. Secondly, the boost makes the musicians own instrument sound louder when compared to the sound of the rest of the orchestra. This makes it difficult for the musician to hear the rest of the orchestra, and to balance the dynamics of his or her own instrument with

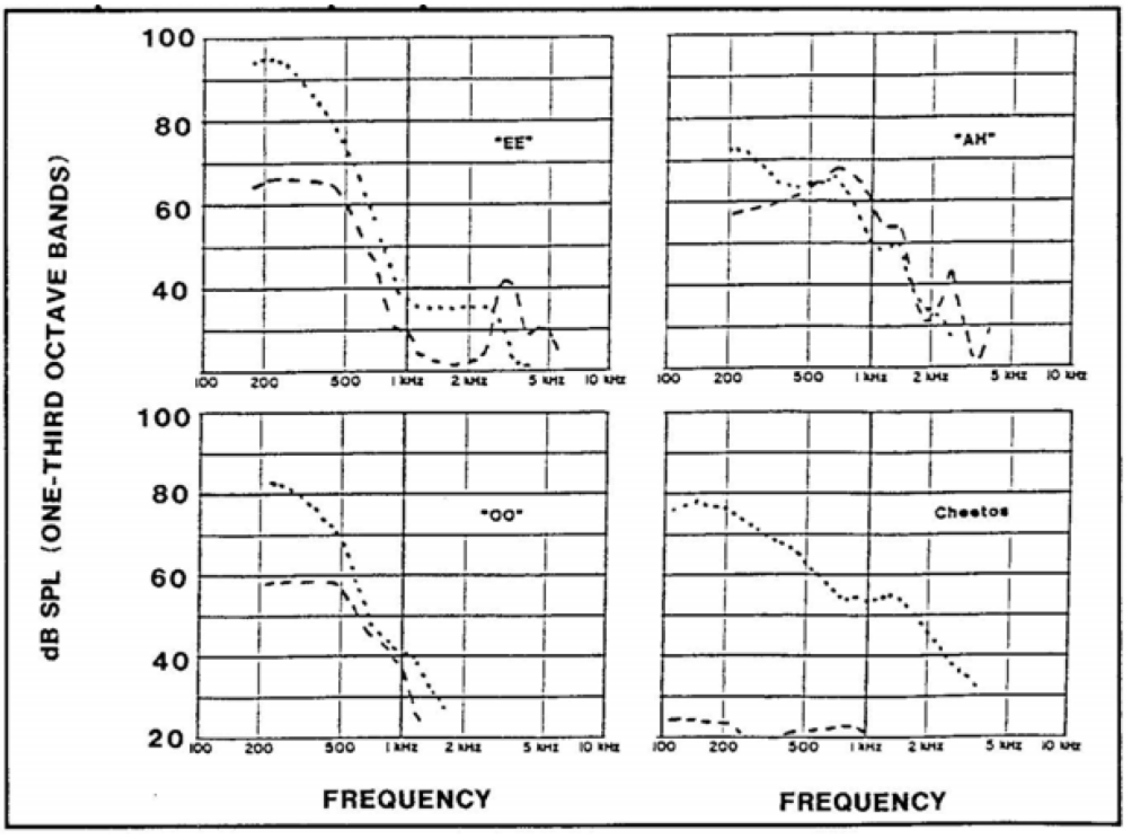

Fig. 1. Ear canal SPLs produced behind a well-sealed, non-vented BTE earmold (hearing instrument turned off) while female subject vocalized vowels or chewed corn chips (....). SPL produced at hearing instrument microphone shown for reference (----).

Figure 1: The occlusion effect, reprinted from (Killion et al., 1988).

the orchestra.

Stenfelt and Reinfeldt (2007) constructed a simple lumped-element model to predict the occlusion effect on sound pressure in the ear canal. The model results bear good resemblance to measurements. With a plug at the ear canal entrance, the maximum occlusion effect is produced: almost 50 dB amplification at 100 Hz. When the plug is inserted deeper into the ear canal, the occlusion effect is reduced, since the surface area of the ear canal that radiates the bone-conducted sound is decreased. The occlusion effect at 100 Hz is approximately 40 dB with 10 mm insertion depth and just below 20 dB with 23 mm insertion depth. Stenfelt and Reinfeldt also simulated the effect of different ear canals, but concluded that the size of the ear canal has a minimal impact on the occlusion effect. When using earmuffs instead of earplugs, the occlusion effect can be reduced by increasing the volume inside the earmuffs.

Stenfelt and Reinfeldt (2007) also measured the sound pressure level in the ear canal together with bone-conduction hearing thresholds. The results were measured with shallow (7 mm) and deep (22 mm) insertion of a foam earplug. With shallow insertion, the ear-canal sound pressure at 100 Hz increased by approximately 30 dB (median for 20 subjects), while the bone-conduction hearing threshold increased by 20 dB. With deep insertion, the ear-canal sound pressure increase was 20 dB, while the corresponding bone-conduction hearing threshold only increased by 10 dB. The ear-canal sound pressure component of bone-conduction hearing thus has a magnitude approximately 10 dB smaller than the sum of the other components at low frequencies. At 300 Hz, the bone-conduction hearing threshold is approximately the same as at 100 Hz, but the ear canal sound pressure has decreased and is at the same level as the threshold. Since the maximum effect of a shallow insertion on the bone-conduction hearing threshold is 20 dB, occlusion reduction strategies typically only need to reduce the ear canal sound pressure by this amount. Greater reduction will have a minimal effect, since the other transmission paths of bone-conduction will dominate. However, there were large intersubject differences between the thresholds in these measurements, so larger reduction might still be beneficial in some cases.

The bone-conducted sound radiated into the ear canal can be cancelled through noise-cancellation techniques. In other words, the bone-conducted sound is recorded inside the ear canal and played simultaneously back from the earplug in opposite phase. This causes the sum of both sounds to be close to zero, thus significantly reducing the occlusion effect. Stenfelt (2007) showed that also the other components of bone-conducted sound can be cancelled by introducing air-conducted sound with the correct frequency, amplitude and phase, implying that both air- and bone-conducted sound are transmitted to the inner ear through linear systems and that these stimulate the basilar membrane in the cochlea similarly.

In addition to noise-cancellation techniques, the occlusion effect can be reduced through different approaches. As mentioned earlier, inserting earplugs deeper into the ear canals reduces the area of the ear canal walls that radiates bone-conducted sound and thereby also reduces the occlusion effect. Deep earplugs are, however, often perceived as uncomfortable. On the other hand, using large earmuffs instead of earplugs also reduces the occlusion effect (Stenfelt and Reinfeldt, 2007). These are usually not used by performing musicians due to aesthetic reasons. Finally, vents can be used to allow the low-frequency energy in the ear canal to escape. This might be useful in hearing aids, but in hearing protectors it will not only reduce the occlusion effect but also reduce the effectiveness of the hearing protection at low frequencies.

2.4. Related research

Several studies have tried and succeeded in reducing the occlusion effect caused by an earplug using miniature microphones and loudspeakers inside the ear canal. Majority of this research has been done in the field of hearing aids. Mejia et al. (2008) combined analog negative feedback with an acoustic vent, and were able to reduce the occlusion effect in hearing aids by 15 dB. Test subjects reported that their own voice was more natural when using this occlusion reduction.

Borges et al. (2013) developed an adaptive occlusion canceller for hearing aids, obtaining an average attenuation of 6.3 dB. The test subjects reported that the occlusion canceller created a sensation of their ears "opening." Sunohara et al. (2014) also proposed an adaptive system for reducing the occlusion effect. Computer simulations of the proposed algorithm showed a maximum occlusion reduction of 30 dB. However, due to the adaptive nature of the algorithm, the effectiveness of the reduction varied over time.

Bernier and Voix (2015) proposed a hearing protection solution for musicians similar to the one presented in this report, but without monitoring of the musicians' own instruments. Analog negative feedback was used to reduce the occlusion effect, while signals from microphones on the outside of the hearing protectors were processed with a digital signal processor and reproduced through the miniature loudspeakers inside the ear canals in order to obtain adjustable attenuation with natural timbre. The solution was able to achieve a reduction of the occlusion effect of approximately 10 dB. Bernier and Voix also proposed to compensate for the non-linearity in loudness perception in order to make the timbre of sounds independent of the attenuation of the hearing protectors. Thus, this research group in Canada (http://critias.etsmtl.ca/) is worth of following in the future.

3. TECHNICAL SOLUTION

Our electronic hearing protection solution combines several different techniques in order to solve the problems mentioned earlier. The whole solution is illustrated with a block diagram in Fig. 2, while Fig. 3 depicts the location of the microphones connected to the hearing protectors. The designed system consists of the following parts:

- We utilize insert headphones as earplugs to provide passive attenuation of air-conducted sound.
- Microphones inside the ear canal are used to reduce the occlusion effect through analog negative feedback.
- Microphones outside the headphones pick up sound from the environment. The microphone signals are amplified to a desired degree and reproduced through the headphones, resulting in hearing protectors with adjustable attenuation. The microphone signals are also equalized to flatten the headphone magnitude response inside the ear canal, at the eardrum, and to account for the altered resonances in the ear canal when it is blocked. This approach leads to the attenuated sound having a natural timbre.
- Additionally, the musician's own instrument can be close-miked to provide in-ear monitoring of the instrument, increasing the ratio of air-conducted to bone-conducted sound and thus providing the musician with a more natural sound of the instrument.

The current solution uses up to two pairs of Akustica AKU143 MEMS microphones for instrument monitoring. The microphone signals are processed with an Analog Devices ADAU1442 digital signal processor (DSP) before they are reproduced with the Sennheiser OCX 686G insert headphones. Two MEMS microphones, the hear-through microphones, are attached to the outside of the headphones. The microphone signals from these are equalized using the DSP before passing them to the headphones. Two MEMS microphones, the in-ear microphones, are located close to the headphone drivers, inside the ear tips. These are used for the occlusion cancellation, which is performed through a negative feedback loop. The processing in this loop is performed with analog electronics in order to minimize the phase shift and allow the occlusion cancellation to be effective at as high frequencies as possible.

3.1. Occlusion reduction

As stated earlier, there are many approaches available to alleviate the occlusion effect, but all of them have their disadvantages. Our solution is an analog electroacoustic negative feedback circuit, which partly cancels out the amplification of low frequencies caused by the occlusion effect.

The feedback loop contains an inverting operational amplifier stage, two passive low-pass filters with a cutoff frequency of 1.1 kHz, in series, and a non-inverting buffer operational amplifier stage.

The chosen approach not only attenuates low frequencies amplified by the occlusion effect, but it attenuates low frequencies inside the ear canal independent of their origin. The negative feedback loop thus also provides improved attenuation of low-frequency air-conducted sound.

3.2. Adjustable attenuation and natural timbre

Employing microphone hear-through techniques (Lindeman et al., 2007; Albrecht et al., 2011) provides the possibility to adjust the amount of attenuation provided by the headphones, from the full attenuation provided by the ear tips of the headphones together with the occlusion cancellation, to no attenuation at all. The level of attenuation can thus be chosen for different situations according to the need of the user.

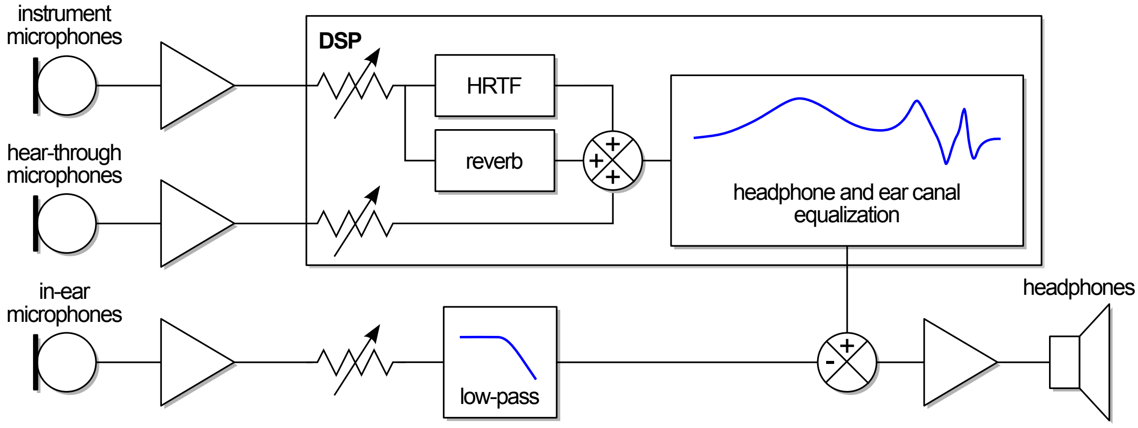

Figure 2: Block diagram of the electronic hearing protection solution.

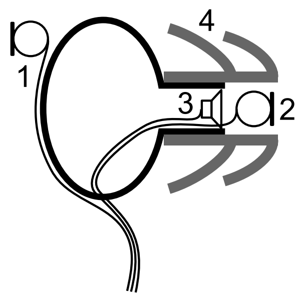

Figure 3: Diagram of one earpiece of the headphones and the microphones attached to it: 1. hear-through microphone, 2. in-ear microphone. 3. headphone driver, and 4. headphone rubber tip.

The microphone hear-through technique utilizes microphones attached on the outside of the headphones, one at each ear. The signals from these microphones can be amplified to the desired level, and reproduced through the headphones. To achieve natural timbre, however, the signals must also be equalized, in order to compensate for the magnitude response of the headphones as well as the changes in resonances when blocking the ear canal. For this task, the digital signal processor (DSP) was used. The headphone response with the active occlusion cancellation was first flattened using peak and notch filters, to produce an approximately flat response at the eardrum inside an ear canal simulator. The quarter-wavelength resonance present in an open ear canal was then added using a peak filter, together with the three-quarter-wavelength resonance using another peak filter. The filters were tuned to match the target response proposed by Hoffmann et al. (2013).

3.3. Monitoring of the musician's own instrument

The occlusion cancellation circuit eliminates much of the amplification of low-frequency bone-conducted sound caused by occluding the ear canals. However, even if all of this amplification is eliminated, the attenuation of the air-conducted sound causes the bone-conducted sound to be more prominent than with unoccluded ear canals. The timbre of a musician's own voice or instrument will thus sound unnatural. To compensate for this imbalance, we use up to four microphones attached to the instrument. These microphones pick up the air-conducted sound of the instrument that can be appropriately amplified and reproduced through the headphones to achieve a satisfactory balance between bone-conducted and air-conducted sound and thus a more natural timbre.

It is, however, not adequate to simply reproduce these microphone signals as such. First of all, the air-conducted sound heard from the instrument is normally affected by the body and especially the head and pinnae of the musician, altering the spectral and temporal characteristics of the sound that enters each ear.

These modifications to the sound serve as cues for the human auditory system to infer that the sound source is in a specific direction. If these modifications are absent, the sound will be perceived to originate from inside the head, and it will also have an unnatural timbre.

Second, sound from the instrument normally also reaches the musician's ears through reflections from different surfaces in the surrounding space. Since the microphones are placed close to the instrument, in order to pick up the sound of this instrument and as little as possible of the other musicians' instruments, they will also pick up very little of the reflections from the environment. Without these naturally occuring reflections, the sound of the instrument will feel "dry" and "out of place," and the absence of reflections will also make it more likely that the sound of the instrument is perceived as originating inside the musician's head.

To solve the mentioned problems, two different approaches were combined. First, head-related transfer functions (HRTFs) were applied to the mixed instrument microphone signals. HRTFs describe the effects that the head and torso have on the sound reaching each ear from a certain direction, under otherwise anechoic conditions. With HRTFs applied to the sound of the instrument, it will sound as if arriving from a certain direction, due to the HRTFs containing different cues that the auditory system uses for sound source localization. Additionally, since people normally perceive sound through HRTFs, so to speak, they are accustomed to the timbre that these produce, so applying HRTFs will make the timbre more natural.

In addition to using HRTFs, we employ reverberation in order to integrate the "dry" sound of the instrument in the surrounding acoustic environment. For the evaluation, we utilized the reverberation algorithm readily available on the digital signal processor, and adjusted the parameters to fit it to the surrounding environment. Adding reverberation not only helps with integration, but also aids in externalization (Begault et al., 2001; Catic et al., 2015).

3.3.1. Details on HRTFs

Because people have different sizes of heads and ears, ideally the individual HRTFs of the person in question should be used, in order to achieve totally natural localization cues and timbre. Measuring individual HRTFs is, however, currently not feasible on a large scale, so generic HRTFs were here instead chosen. For the evaluation, we used near-field HRTFs of a KEMAR head and torso simulator (Qu et al., 2009). To represent the direction of many wind instruments, with respect to the ears of the musician, an elevation of -30° was chosen. An azimuth of -10° was chosen in favour of an azimuth of 0° (straight forward), since HRTFs measured at 0° azimuth often reduce externalization (Begault and Wenzel, 1993; Catic et al., 2015), i.e., sounds presented with them are perceived as originating from inside the head. The HRTFs were measured at a distance of 20 cm from the centre of the head, thus simulating a sound source a small distance in front of the mouth.

Naturally, different instruments are played in different positions, so the HRTFs should be selected based on the instrument. If the instrument is not always kept in the same direction with respect to the head, tracking of the instrument position might be beneficial, in order to present the sound from the correct direction. With most wind instruments, however, this should not be a problem, since they are normally kept in the same direction with respect to the head.

Although the chosen azimuth and elevation of the HRTFs may not correspond perfectly with the location of the instrument, this should not be a problem unless the mismatch is large. Due to the ventriloquism effect (Thurlow and Jack, 1973), small mismatches are ignored and the sound should be heard as if coming from the instrument. The musician also receives some air-conducted sound from the instrument, which would aid in the correct localization, depending on the differences in level and timing between this air-conducted sound and the reproduced microphone signals.

4. VALIDATION

Measurements were performed to quantify the effect of the occlusion reduction circuit. To evaluate the sound of the electronic hearing protectors, they were tested by seven professional musicians.

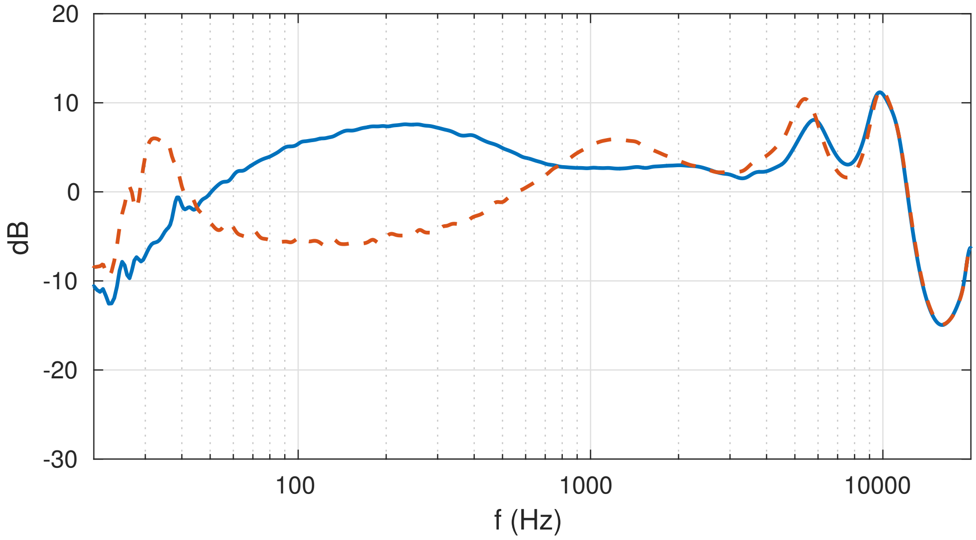

Figure 4: Magnitude response of the headphones, measured in the ear canal simulator with the eardrum microphone. The blue solid line represents the unprocessed response, while the red dashed line represents the response with the occlusion cancellation circuit active.

4.1. Measurements

For the measurements, we constructed an ear canal simulator out of a silicone tube with an inner diameter of 10 mm and a length of 27 mm. One end of the tube was glued to a piece of hard plastic, simulating the eardrum, and a MEMS microphone was attached to the plastic. The magnitude response of the headphones under different conditions was measured using white noise.

Figure 4 shows the magnitude response of the headphones without and with the occlusion cancellation circuit in action. Figure 5 shows the reduction of the occlusion effect achieved with the occlusion cancellation circuit. The occlusion reduction is at most approximately 13 dB at 150 Hz, and more than 10 dB between 100 and 300 Hz. At the same time the peak in the headphone response between 5 and 6 kHz is amplified since the feedback loop is not in opposite phase any more at this frequency. Much further amplification in the feedback loop results in an even larger peak and finally instability at this frequency. The amplification of the feedback loop was thus chosen as a compromise between attenuation at low frequencies and amplification and stability at high frequencies.

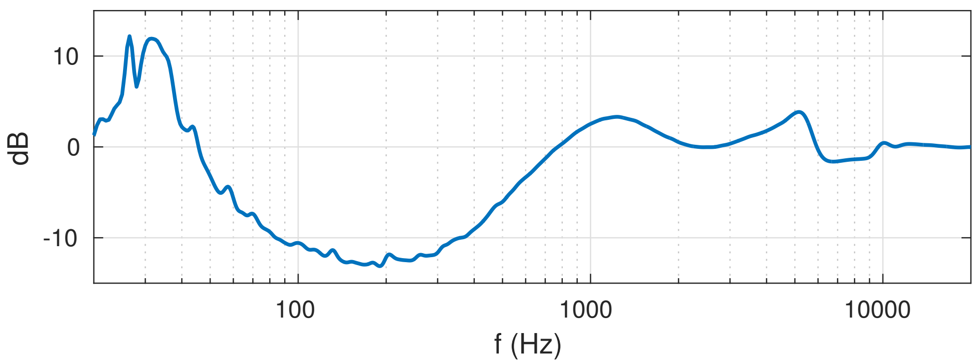

Figure 5: The effect of the occlusion cancellation circuit on the magnitude response of the headphones, i.e., the difference between the blue solid line and the red dashed line in Fig. 4

Frequencies below 50 Hz are amplified, with a maximum amplification of 12 dB. This low-frequency

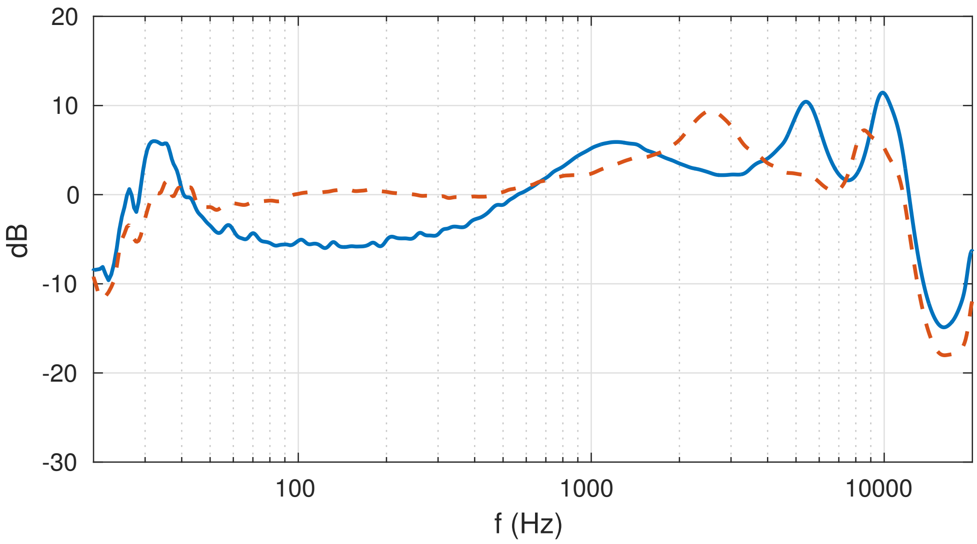

Figure 6: Magnitude response of the headphones, measured in the ear canal simulator with the eardrum microphone. The blue solid line represents the unequalized response with occlusion cancellation. The red dashed line represents the equalized response.

boost is due to the phase shift introduced by DC-blocking capacitors in the occlusion cancellation feedback loop. Using larger capacitances would shift these high-pass filters to lower frequencies and reduce this boost.

Fig. 6 depicts the equalization of the headphone response. The unequalized response, with low frequencies attenuated by the occlusion cancellation circuit, is shown. The magnitude response flattened using four notch filters and one peak filter is also shown, with the quarter-wavelength and three-quarter-wavelength resonances of the open ear canal added using two peak filters.

4.2. Subjective evaluation

The prototype electronic hearing protection solution was evaluated by seven professional musicians. The musicians were either members of the Helsinki City Orchestra or the Finnish National Opera, while one of them was a jazz musician. All musicians tried the hearing protectors with their own instruments, which were the viola, bassoon, trumpet, flute and piccolo, tenor saxophone, clarinet, and oboe. The evaluation was performed in the listening room of the Department of Computer Science, where different orchestral compositions could be reproduced as if played in different concert halls (see, e.g., Lokki et al. (2016)). This gave the musicians the possibility to play and evaluate the hearing protectors with a virtual orchestra.

4.2.1. The need for and use of hearing protectors

Some of the musicians reported music-induced hearing loss and tinnitus, while others did not have any hearing disorders. All musicians recognized the need for hearing protection in their work, some occasionally while others more often. A few musicians mentioned that their need for hearing protection had decreased due to, e.g., seating arrangements in the orchestra.

When using hearing protection, the musicians typically used foam earplugs, and some often only in one ear. The trumpet player said he felt a strong need for using hearing protectors, but that he never uses them when playing in an orchestra, since the booming sound caused by the earplugs overpowers the sound of both the rest of the orchestra and his own instrument. The other musicians mentioned different reasons for why they do not use hearing protectors more often: the sound of the instrument is bad; trebles get cut off; buzzing and other unwanted sounds get amplified and annoying; it takes a lot of time and effort to get used to playing with earplugs; you feel isolated from the rest of the orchestra; it is difficult to play in balance with the rest of the orchestra.

4.2.2. Occlusion reduction

The occlusion reduction had a different effect depending on the instrument. The trumpet player said that the booming sound caused by the earplugs vanished, and that he now was able to hear himself playing. The saxophonist reported a clear but small improvement of the instrument sound. The bassoonist said that the sound in some cases – depending on the note played – was more natural, but that it otherwise just made the sound different and more distant. The viola player felt that the timbre of the instrument became too bright. The clarinetist reported a clear change in the timbre, but it did not improve the sound; the unwanted sounds that were amplified by the earplugs remained. The flutist said that the sound became brighter and more spacious, which was an improvement over the stuffy sound caused by the earplugs.

4.2.3. Monitoring

The placement of the instrument microphones was chosen based on experimentation to provide a balanced and natural sound of the instrument. On the viola, the microphones were placed at the bridge. On the bassoon, trumpet, saxophone, oboe, and clarinet, the microphones were placed at the side of the bell. On the flute and piccolo, the microphones were placed approximately one-third length from the end of the instrument closest to the mouthpiece. The two microphones were placed close to each other.

Amplifying the sound of the instrument microphones, processed with HRTFs and with reverberation added, clearly improved the sound of the instrument. Most musicians commented that the sound was not completely natural, but quite pleasant. In many cases, slightly amplifying the equalized signal from the hear-through microphones further improved the sound.

Some of the musicians thought that the reverberation added to the sound was pleasant, while others felt that it was unnatural, or that there was either too little or too much reverberation. Clearly, the level and quality of reverberation must be easily adjustable depending on the surrounding space, the instrument, and the preferences of the musician.

4.2.4. Playing alone

Especially the trumpet player, the saxophonist, and the piccolo player all thought that the electronic hearing protectors would be good for practicing alone. When practicing in a small room, the sound of the instrument is often too loud due to strong reflections. With the electronic hearing protectors, however, the sound of the instrument can be attenuated, while still remaining quite clear and pleasant, unlike when using normal earplugs. The piccolo player summarized the experience: "It sounds good and natural, but it doesn't hurt, like it usually does."

4.2.5. Playing with an orchestra

The musicians tried the electronic hearing protectors while playing with a symphony orchestra recording. The musicians commented that they were able to hear both their own instrument and the rest of the orchestra well. The flutist also commented that the sound of her own instrument was richer and more inspirational when playing with the electronic hearing protectors compared with regular earplugs. The saxophonist said that he could hear his instrument well and play with the orchestra, but wondered how he would be able to adjust his dynamics with respect to the rest of the orchestra, since the electronic hearing protectors alter the level of the own instrument and the orchestra independently.

4.2.6. Technical implementation

The rubber tips of the headphones did not fit well in the ears of all the musicians, and thus different sized tips would naturally be needed for different ear canal sizes. The need for custom ear molds also came up.

Based on the musicians' comments, the sound of the hearing protectors (timbre, balance between the own instrument and the orchestra, and reverberation) should be easily adjustable, but preferably minimal adjustments should be needed to get the sound right. A few musicians also pointed out that it might be beneficial to adjust the hear-through level separately for each ear, since sometimes there are loud instruments that should be attenuated only on one side.

A couple of musicians commented on how much they would be willing to pay for this type of hearing protectors. One of them said approximately 200–300 euros, while the other would be willing to pay up to 500–600 euros.

Based on the evaluation, the instrument microphones could be mounted on so called goosenecks, allowing easy adjustment of the microphone position. A single microphone might be enough in many cases, and seemed to provide a pleasant sound with the instruments in this evaluation (we actually used two microphones in all cases, but these were positioned very close to each other).

4.3. Discussion

So far, we have performed informal and preliminary subjective evaluations of the proposed electronic hearing protection solution. These evaluations have shown that the occlusion cancellation improves the experience for the musician, by attenuating amplified bass frequencies and thus providing a timbre that is more natural. With the ears plugged, the sound of the instrument can often appear as if it originates from inside the head, but in some cases the occlusion cancellation can alleviate this problem.

The occlusion cancellation comes with a noticeable degree of noise. During the evaluation, however, this noise was considered not to be loud enough to be disturbing, and the spectrum of the noise was also considered not to be disturbing. The noise could be reduced with more advanced circuit design, but it was out of the reach of this project.

Adding the instrument microphone signals with HRTFs and reverberation makes the timbre brighter and more natural, and also makes the sound of the instrument seem as it originates from the instrument and not from inside the head. For most wind instruments, a bone-conducted buzzing sound from the reed or lips is normally prominent when playing with the ears occluded, making playing with ear plugs uncomfortable for many musicians. Adding the instrument microphone signals alleviates this problem, by altering the balance between air-conducted and bone-conducted sound to be more favourable and closer to natural.

Amplifying the instrument microphone signals will, however, affect the balance between the musician's own instrument and the other musician's instruments when playing in an ensemble. The musician's instrument will thus sound louder than normal when compared with the sounds of other instruments. This balance will be, among other things, instrument specific, since all instruments have a different natural balance between air-conducted and bone-conducted sound. The balance between the musician's own instrument and the other instruments can of course be affected by amplifying the signals from the hear-through microphones. However, heavy amplification of these signals will of course counteract the function of the hearing protectors.

Adding reverberation to the instrument signals may be useful not only to aid in externalization and integrating the sound of the instrument into the surrounding acoustic environment. It also can be used for personal practice, making the instrument sound like it's being played in, e.g., a much larger hall.

4.4. Demonstration of the prototype

The constructed prototype was demonstrated also at the Audio Engineering Society (AES) international conference on Headphone Technology in Aalborg, Denmark, August 24–26, 2016[1]. About 40 participants (engineers, marketing people, designers, all working on headphone technology) tested the prototype and gave immediate feedback (see Fig. 7). They all said that the idea is novel and that the prototype worked surprisingly well. In addition, the sound quality was said to be good and natural.

5. FUTURE WORK

The prototype seems to work well, although there are naturally many small issues that could be developed further. Therefore, larger user tests of the designed electronic hearing protection device should be performed among musicians. However, the bottleneck that hinders larger user tests in real situations (playing in an ensemble) is the clumsy large circuit boards and cumbersome usability. The next steps would be to redesign

[1] http://www.aes.org/conferences/2016/headphones/

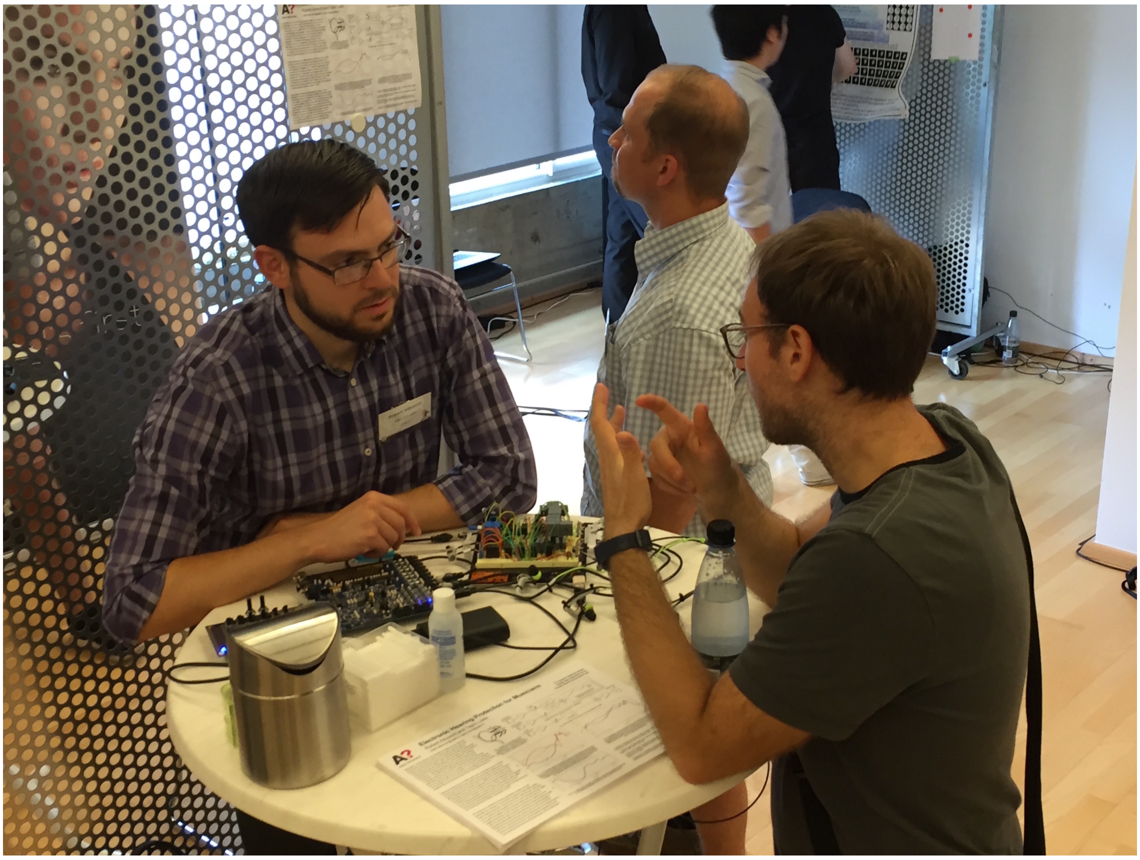

Figure 7: The constructed prototype demonstrated at the AES Headphone Technology conference, August 2016.

the analog and digital circuits to fit them in a small box so that musicians could carry all required electronics in their pocket. Such extra work would need either another product development project or a company that would be interested in developing and manufacturing the current prototype.

6. FINANCIAL REPORT

The financial report of this project contains a few items that might need a few additional words. The main cost was salary (with side costs) for Mr. Albrecht during the project. Travel expenses are related to the conference trip to Denmark in August 2016, see section 4.4. Finally, the extra costs (6000€) are related to a study done at the University of Helsinki (emeritus professor Jukka Ylikoski and Dr. Ulla Pirvola). This study is basic research for hearing protection of musicians and is one piece in a puzzle of trying to understand what are the levels of sound (and noise) that causes the death of hearing organs in human hearing system. The results that were obtained suggest a novel function for c-Jun phosphorylation in the adult cochlea, not as an intrinsic mediator of cell death, but as a part of a paracrine response that regulates hair cell death following traumas. These results are important for the development of protective therapies against hair cell loss.

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7. CONCLUSIONS

In this report, we presented an electronic hearing protection solution designed especially for musicians. The solution combines the following features: reduction of the occlusion effect, monitoring of the musician's own instrument, adjustable attenuation, and natural timbre. Seven professional musicians evaluated the implemented solution and confirmed that these features together alleviate problems associated with musicians' hearing protection. Thus, the findings presented in this report will hopefully lead to better hearing protectors in the future and more musicians that are able to satisfactorily protect their hearing.

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