Active musician's hearing protection device for enhanced perceptual comfort

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Summary
Professional musicians are exposed to high levels of sound and should protect their hearing to avoid permanent hearing loss which could compromise their career. Because sound is an inherent part of a musician's work, the logical solution would be to wear hearing protection devices (HPDs) when appropriate. However, musicians rely heavily on auditory perception during their performance and wearing currently available HPDs unpleasantly alters this perception, to the point where many musicians choose to opt out of wearing HPDs. The perceptual discomfort associated with HPDs is attributed to two effects: the occlusion effect and the isolation effect. This paper presents a prototype active electronic earplug that addresses the issue of perceptual discomfort through active control of the occlusion effect and digital signal processing compensation of the isolation effect. First, the occlusion effect reduction capabilities are presented. Second, preliminary performance of the prototype along with a method to address the isolation effect are presented.

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1. Introduction

Musicians are sound-exposed workers who heavily rely on their auditory sense to perform. Losing the acuteness of this sense directly threatens their career as they can no longer adjust to some musical subtleties, potentially decreasing the quality of their work. There is indication that this threat is real: studies reveal that 25 % to 70 % of musicians show signs of hearing loss [1][2][3]. This is to be expected considering the high sound levels that musicians are exposed to and the low usage rates of hearing protection devices (HPDs). Sound levels that musicians are regularly subjected to are in the range of 80 to 110 dB(A) for classical musicians and 88 to 117 dB(A) for amplified musicians [4]. Recently surveyed usage rates of HPDs by professional musicians are generally low: 6% in Finland, 15% in Denmark and about 10% in Germany [5]. In the Netherlands, 52% of musicians reported using HPDs in rehearsal, but only 29% in concerts.

In a recent study [6], it was revealed that the source of these low usage rates cannot be solely attributed to a lack of awareness but also to musicians finding HPDs inadequate. In Australia, 80 % of surveyed musicians reported a risk of hearing damage in the orchestra, 64 % used HPDs at least some of the time and 83 % reported finding the use of HPDs difficult or impossible. The most common reasons for this were players hearing themselves (79%), hearing others (72%), intonation (57%), and balancing with other players (50%). While an adaptation period can be required to function with HPDs, it was found that 88% of musicians who had been using musician's custom-molded earplugs for 10 to 20 years still found them difficult or impossible to use [6].

2. Problem

All of the most reported reasons in [5][6][7] for finding HPDs difficult or impossible to use originate from a perceptual discomfort experienced by musicians directly attributable to two detrimental effects associated with HPDs: the occlusion effect and the isolation effect.

2.1. The occlusion effect

The occlusion effect (OE) is often reported as an unnatural and annoying perception of one's own voice when wearing HPDs. It affects all musicians whose instrument induces vibrations to the skull, including singers and musicians whose instrument is pressed against any part of the head, such as a trumpet or violin, due to bone and tissue conduction from the source to the ear canal and the cochlea. Although there is a direct solid borne sound path to the cochlea, the main objective occlusion effect is due to another solid borne sound path that causes the ear canal walls to vibrate, generating sound in the ear canal and ultimately reaching the cochlea [8].

When the ear canal is open, most of the energy transferred to the ear canal walls is radiated outward because the ear canal has an open end, which exhibits a much lower acoustic impedance than the eardrum. When this is the case, what is heard by the musician is predominantly the sound wave arriving from the air conduction path between the source (e.g. his/her vocal tract) and the ear. However, when the ear canal is occluded, the ear canal walls have a strong coupling with the cavity. Their vibration causes pressure changes in the cavity, generating greater sound pressure level (SPL) than in the open case. Since this sound is directly picked up by the eardrum and the air conduction path is blocked, what is heard by the musician is predominantly the sound wave traveling through bone conduction. Because this path is dominant at low frequencies, below 1000 Hz, the result is an augmented and unnaturally "boomy" perception of one's own voice when wearing HPD.

2.2. The isolation effect

The isolation effect regroups acoustic and psychoacoustic factors causing a perception shift and/or a feeling of being isolated from a given sound environment:

1. Earplugs usually offer less attenuation at low frequencies than at high frequencies;
2. Occluding the ear canal with HPDs causes the natural ear canal resonance to be shifted upwards;
3. The earplug may provide excessive attenuation;
4. Non-linear loudness perception makes uniform attenuation not perceived as uniform in frequency.

2.2.1. Non-uniform attenuation

Conventional HPDs do not provide uniform attenuation in the frequency domain: low frequencies are typically less attenuated than high frequencies. This is partly explained by the fact that the earplug and the soft ear canal flesh form an acoustic system much like a mass-spring system that behaves like a low-pass filter.

2.2.2. Ear canal resonance

Analogous to a tube, the ear canal has an average diameter of about 7 mm, a length of about 25 mm [9] and a natural resonance frequency that depends on its length, diameter, and conditions at its extremities. A tube that is closed at one end and open at the other is analogous to an open ear canal: the ear canal entrance is the open end, and the eardrum is the closed end. Such a tube exhibits a quarter wavelength main resonance that amplifies a peak frequency and its close surroundings. The ear canal properties, the geometry of the pinna and the termination impedance presented by the eardrum cause the resonance to be around 2.7 kHz [10] and reach 15 dB [11] on average.

A tube that is closed at both ends is analogous to an occluded ear canal: the ear canal entrance is completely obstructed, such as is the case when wearing HPDs. The same tube with new conditions at its extremities exhibits a half wavelength resonance that is significantly higher than in open conditions. The occluded ear resonance has been found to be around 5.5 kHz on average [10], but it partially depends on the remaining ear canal portion between the tip of the HPD and the eardrum, which in turn depends on the length of the ear canal and the insertion depth of the occluding device. The occluded resonance is around 8 kHz for musician's custom molded HPDs [12].

2.2.3. Excessive attenuation

Ideally, an earplug should provide an attenuation that adequately protects a musician's hearing, but not too much to avoid isolating him from his sound environment. The overall value of the attenuation that would meet both conditions is difficult to define, since musicians are exposed to SPLs that can range from 80 dB(A) to 117 dB(A) [4]. It is likely that the lower range of the sound pressure level exposure occurs when a musician is practicing, and the higher range, when a musician is performing.

Musicians may practice for more than 20 hours a week [13], or 4 hours a day. Levels of 80 dB(A) to 100 dB(A) for 4 hours a day would require an attenuation anywhere between 0 and 12 dB to respect exposure limits recommended by NIOSH (88 dB(A) for 4 hours). Additionally, the length of a performance may be about two hours. Levels of 100 to 117 dB(A) for 2 hours would require an attenuation anywhere between 9 dB and 26 dB. No single attenuation value could therefore cover all musicians without over-protecting some of them and therefore causing unnecessary isolation effect through over-protection.

2.2.4. Loudness and hearing protection

Equal loudness contours represent the non-linear relationship between how loud a given sound stimulus will be perceived depending on its frequency and SPL [14]. The shape of the curves is different depending on the loudness value that they represent, revealing the non-linearity of loudness perception that has been found in many loudness models, especially at low frequencies. Considering the non-linearity of loudness, it follows that in order to cause the least perceptual shift, earplugs should not attenuate by a uniform dB value but rather by a uniform phon value. In other words, if an earplug provides a uniform attenuation in dB, it it is probable that it will result in some frequencies feeling softer than others when they originally should not.

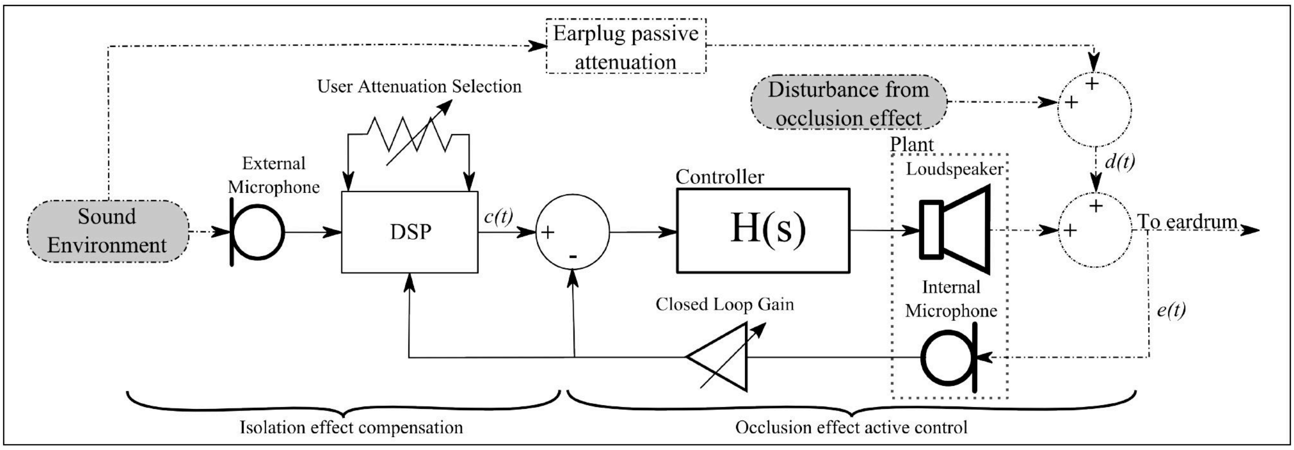

Figure 1. Architecture of the proposed system

3. Prototype active HPD

To solve the detrimental impact of the occlusion and isolation effect, a prototype HPD incorporating feedback active noise control and digital signal processing capabilities is proposed. The complete system architecture is shown in figure 1. The physical system is arranged into a belt-pack, containing circuits relevant to an active occlusion effect reduction system (AOER) as well as digital signal processors present in an Auditory Research Platform (ARP), and an earpiece containing acoustic transducers. Figure 2 shows the prototype's enclosure, circuitry, and several earpieces using universal-fit coupling to the ear or custom-fit coupling. A cross-sectional view of a universal-fit earpiece is shown in figure 3.

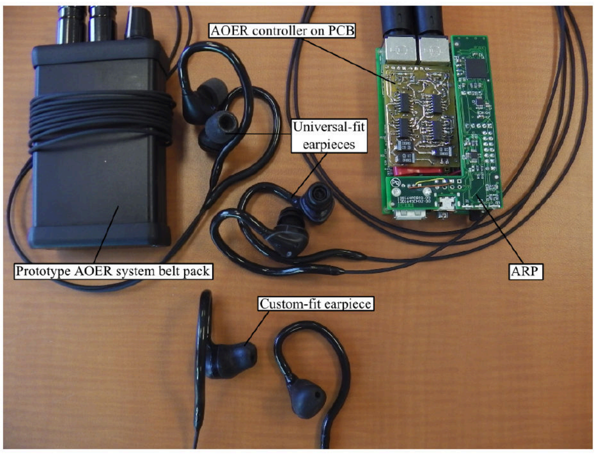

Figure 2. Several versions of a prototype musician's HPD

The left section of figure 1 encompasses elements mainly associated with isolation effect compensation. An external microphone is used to capture the sound environment and a digital signal processor allows compensation algorithm to filter the signal so that the

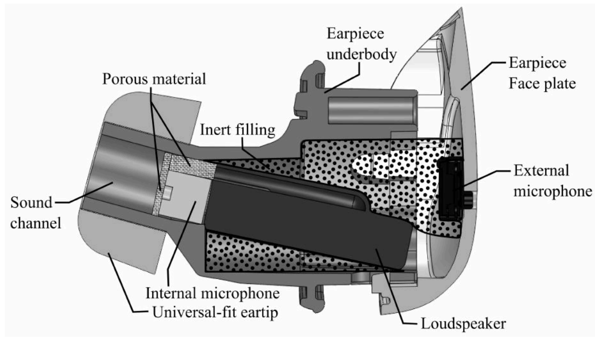

Figure 3. Cross-sectional view of a earpiece containing acoustic transducers.

user's auditory experience is as natural as possible. This signal is eventually played back through an in-ear loudspeaker. The right section of figure 1 encompasses elements associated with active control of the occlusion effect. A fixed analog controller H(s) is used to control the closed-loop transfer function between an in-ear microphone and loudspeaker assembly (defined as the plant). The controller is designed to cancel frequencies where the occlusion effect is felt the most while providing enough gain and phase margin to remain stable under variable conditions.

3.1. Active occlusion effect control

The frequency responses of the plant, controller, and compensated plant are shown on figure 4. A lead-lag controller topology allows to increase gain in the bandwidth of interest while keeping phase as close to minimum as possible. This compensated plant allows reduction of the occlusion effect by about 10 dB from 100 Hz to 500 Hz, where most of the energy resulting from occlusion effect normally is. The expected performance by design and the actual performance measured on a human subject are presented in figure 5.

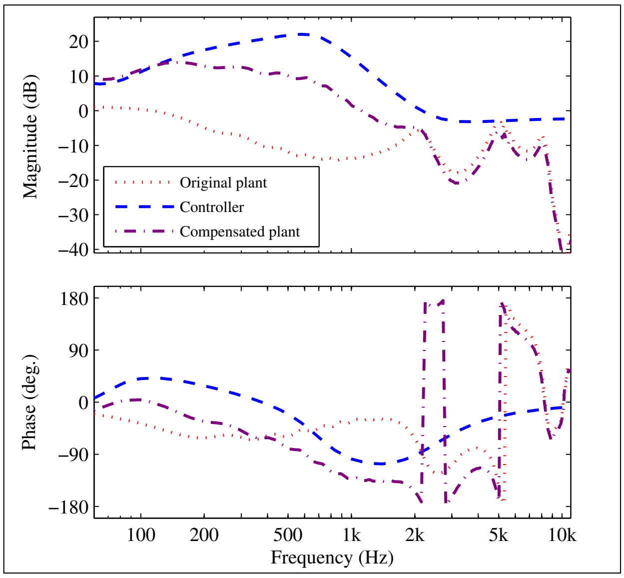

Figure 4. Frequency responses of the plant, controller and compensated plants

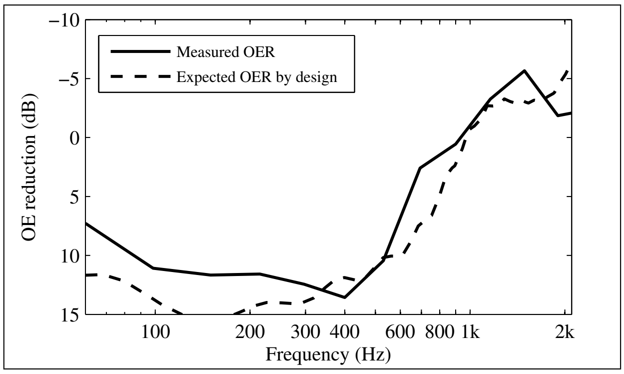

Figure 5. Expected and measured OE reduction

3.2. Isolation effect compensation

To properly correct for the isolation effect, a full characterization of the paths by which ambient sound reaches the eardrum is required. Figure 6 illustrates a conceptual view of the system with emphasis on the isolation effect solution from a design perspective. In this conceptual view, there are two paths from the sound environment to the eardrum. The paths and their elements are as follows:

1. The attenuation path, comprised of:
   a) the passive attenuation, provided by the earpiece;
   b) the active attenuation, if the active occlusion effect reduction system is turned on;
2. The electro-acoustic path, comprised of:
   a) the external microphone;
   b) the DSP;
   c) the playback mean, altered by the active occlusion effect reduction system if turned on;
   d) the occluded ear canal.

When the two paths meet at the eardrum, destructive and constructive interference is expected to occur because of phase difference between signals from both paths. This is a problem and needs to be compensated for at frequencies where both signals are in the same order of magnitude, but does not have significant impact at frequencies where the electro-acoustical path prevails. To properly characterize these paths, an acoustic test fixture (ATF), a Bruel & Kjær 4157 head and torso simulator model, is used to obtain models of each paths. Four important microphone measurement points are shown on the conceptual view of figure 6.

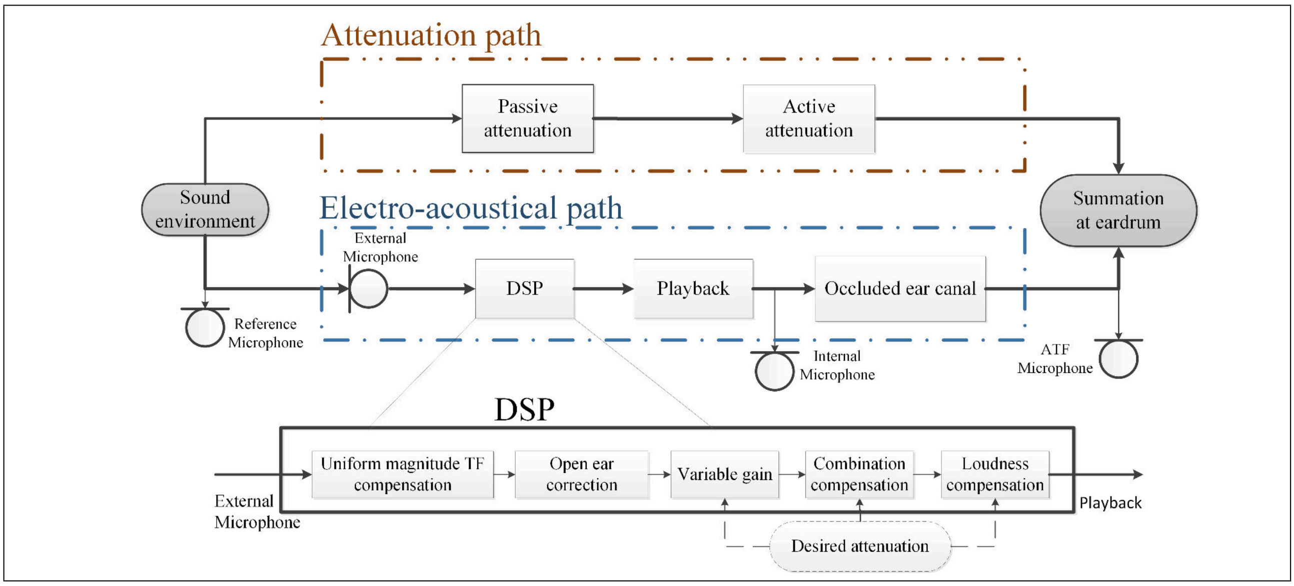

Figure 6. Conceptual view of the isolation effect solution from a design perspective as well as the compensation strategy and its explicit steps inside the DSP.

Using the microphones illustrated in fig 6, each element of both paths were measured and modeled by finite impulse response filters using a system identification procedure. This allows the simulation of compensation strategies to achieve an overall attenuation target. The explicit compensation procedure occurring in the DSP is illustrated in the lower part of figure 6. The electro-acoustical path is first equalized to yield a uniform frequency response. A wide boost around 2.7 kHz is then applied to mimic the frequency response of an open ear. The gain, combination compensation, and loudness correction are then applied depending on the selected attenuation value. These algorithms are automatic and only require a target attenuation value as an input.

As a first target and to validate the method, a uniform attenuation of 15 dB was chosen and the occlusion effect reduction system was turned off. This is achieved if the combined transfer function of both paths matches the theoretical frequency response on an open ear, reduced uniformly by 15 dB. Figure 7 shows the target transfer function, the frequency responses of the electro-acoustic path comprising compensation algorithms, the attenuation path, their combined theoretical frequency response as well as a measurement of the overall transfer function of the implemented system.

Using this validated method, it is theoretically possible to achieve a maximum quasi-uniform attenuation of about 25 dB when the occlusion effect reduction system is active and incorporating an automatic loudness correction based on ISO 226:2003 yields variable attenuation values of up to 25 phons. Figure 8 shows the overall transfer functions that the system can achieve, representing quasi-uniform attenuation of up to 25 dB.

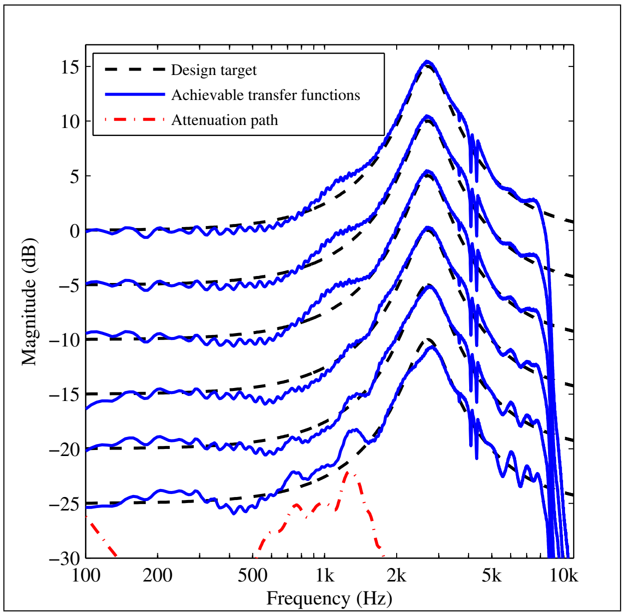

Figure 8. Achievable transfer function corresponding to various quasi-uniform attenuation

4. Future work

The greatest limitation of the current work is that the isolation effect compensation algorithms are currently tuned to an ATF. Because of inter-individual differences in ear canal acoustics this tuning will most likely be sub-optimal for a given individual. In order for the isolation effect compensation to be precise and adequate, it needs to be adapted to its user. As can be seen on figure 1, the architecture of the system is such that the DSP can use information gathered by the in-ear microphone to adjust the isolation effect compensation algorithms. It is intended in future work

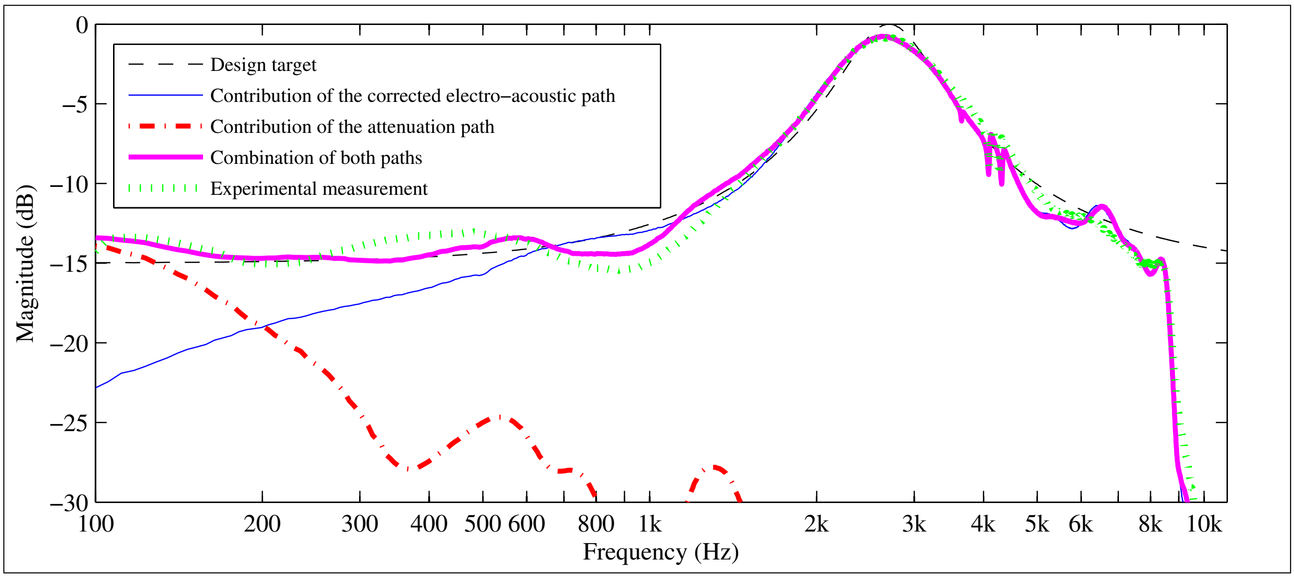

Figure 7. Example of obtaining a transfer function corresponding to a uniform attenuation of 15 dB within the constraints of the system, and experimental validation

that the isolation effect compensation algorithms automatically tune themselves to a given user.

Another limitation lies in the AOER system's fixed controller. Because it is fixed, the analog controller provide inconsistent performance from user to user. For example, if the occluded ear canal volume is small, the system provides higher performance but is potentially unstable. On the other hand, performance may be insufficient if the occluded ear canal volume is larger. In further work, the AOER should adapt itself to its user and therefore it is intended that the controller be implemented digitally for maximum flexibility. In the current prototype, this has been mitigated to some extent through the inclusion of a user controllable variable closed-loop gain that allows tuning of the performance. This enables achieving a good compromise between performance and gain margin on an individual basis. Furthermore, this control makes it possible to directly vary the SPL resulting from occlusion effect in the ear canal. Therefore, it is an ideal platform to investigate the relationship between ear canal SPL, objective occlusion effect in hearing threshold level, and perceived annoyance caused by the occlusion effect. This will allow to define OE reduction target that are likely to please musicians. Additionally, because the prototype is practical and sturdy enough to be used outside of a laboratory setting, subjective testing can now be performed in the musician's usual environment.

5. Conclusions

In this work, a strategy, architecture and prototype of an active musician's hearing protection device for enhanced perceptual comfort are presented. To enable musicians to protect their hearing without reducing the quality of their work, a prototype HPD incorporating active noise control of the occlusion effect as well as isolation effect compensation algorithms has been presented. This prototype shows promising performance and would benefit from further research: the target occlusion effect reduction value that would be acceptable to musicians is yet to be defined, as is the degree of isolation effect that a musician can adapt to. The prototype presented in this work provides a way to tackle these research questions. Future work is also targeted at the customization of a HPD to its user, given the widely varying inter-individual needs and morphology, which seems to rule out universal, fixed solutions.

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