EFFECT OF EAR CANAL OCCLUSION ON LOUDNESS PERCEPTION

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1 Introduction

In a recent paper [1], some of the benefits of in-ear noise dosimetry were brought forward together with its challenges with regard to the prevention of Noise Induced Hearing Loss (NIHL). As part of the challenges, the influence of ear occlusion on noise sensitivity had to be further studied. This is to ensure that appropriate acoustic corrections are used to make in-ear noise levels truly representative of the noise dose received by someone having those noise levels measured under a potential HPD (Hearing Protector Device). In other words: if a given sound pressure level is applied to the eardrum of an occluded ear, is it likely to provoke the same hearing damage as if it were to be applied to the eardrum of an open ear? Keidser et al. [2], who compared the equal loudness noise contours in the open and occluded ear, found that "when balancing or rating loudness, normal-hearing listeners tend to select an average of 10 dB higher level for low-frequency sounds at 500 Hz when listening with the ear occluded".

This paper presents data from an experiment that was made using a rather innovative methodology, while sharing the hypothesis that loudness should well represent the damage that noise can inflict to the hearing system. The results, which confirmed and generalized earlier findings to a wider frequency range, also allowed to remove several factors to explain the observed difference.

2 Method

The experiment led six human participants to carry out a one-hour loudness balance test with headphones. As narrowband noise was played in both ears simultaneously, the subject was to balance the left and right channels to have the same loudness on both sides. In the last two tasks, the balance was done having one ear occluded by an earplug.

2.1 Instrumentation

The test took place in an audiometric sound booth and used FitCheck headphones [3]. During all the experiment, in-ear sound signals were recorded on both sides by means of miniature electret microphones (Knowles GA series) placed inside the ear canal, and connected to a PXI-4462 (National Instruments) acquisition module. Sound pressure levels (SPL) were computed using Matlab scripts. Each subject had access to a computer mouse connected to a laptop for balancing the audio channels using PureData software. ETY plugs [4] were used to balance noise in the open vs. occluded condition.

2.2 Subjects

Ten volunteers were pre-selected for the experiment. Those all had hearing threshold levels of 20 dB HL, or less, across the frequency range 125-8000 Hz, and an otoscopic examination on both ears revealed no abnormalities. Each subject's ability to balance loudness with enough precision was assessed during the first task of the experiment. During this task, the participant was asked to balance several frequencies on four separated trials. At each frequency, four values were therefore collected (the collected value was the voltage output difference between the two channels) and the inter-trial standard deviation was calculated to evaluate the intra-subject repeatability. Four subjects, who had an average standard deviation across all frequencies of more than 3dB, were not retained for the rest of the experiment.

2.3 Procedure

The loudness balance was done in a bilateral way. Thus, when the subject increased the input level by +X dB in one ear, the level decreased by –X dB in the opposite ear. This is to prevent the participant to focus his attention on one ear, which could be a source of bias. The mouse wheel was used to balance noise from one ear to the other, with a resolution of 1 dB SPL and a range of ±15 dB SPL in each ear. The subject was asked to click the left mouse button whenever he was finished balancing and ready to switch to the next frequency. Every time a new track/frequency was started, the initial audio balance was randomly chosen among the 30 positions available to ensure the participant remained active during the exercise. The initial input gains were pre-calibrated on a dummy head at each frequency so that, where the two input channels meet at the same level, the SPL generated at the eardrum should correspond to a value of approximately 4 sones.

Each retained subject was asked to balance narrowband noise with a bandwidth of one-third of an octave centered on nine frequencies: 125, 250, 500, 1000, 2000, 3150, 4000, 6300, and 8000 Hz. This was done in three separated tasks, with several trials per task (each trial contained 10 tracks as the frequency 1000 Hz was assessed twice and averaged in each trial). In the first task, both ears were open and the intra-subject repeatability was assessed as well as the initial difference of sensitivity between the subject's left and right ears. This open-ear correction was defined as the mean transfer function between the two in-ear microphones at equal loudness, across four trials. In the second task, the participant had to balance noise in the open vs. occluded condition. An earplug was first inserted inside the subject's left ear and its insertion loss was estimated as the transfer

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function between the two in-ear microphones when white noise was being played on four speakers (one in every corner of the sound booth). The insertion loss was used to correct the level in the left ear channel so that the balance can be done approximately at the same levels as in the first task. The occluded-ear correction was then computed as the mean equal loudness level difference between the occluded ear and the open ear, across two trials, and corrected with the open-ear correction. The third task consisted only in repeating the second task with the right ear occluded.

3 Results

Figure 1 shows the distribution of the twelve resulting occluded-ear corrections measured on the six retained subjects. Each subject's individual mean correction (arithmetic average of the occluded-ear corrections obtained on both ears) was then computed and used to calculate the intersubject standard deviation σ (Table I).

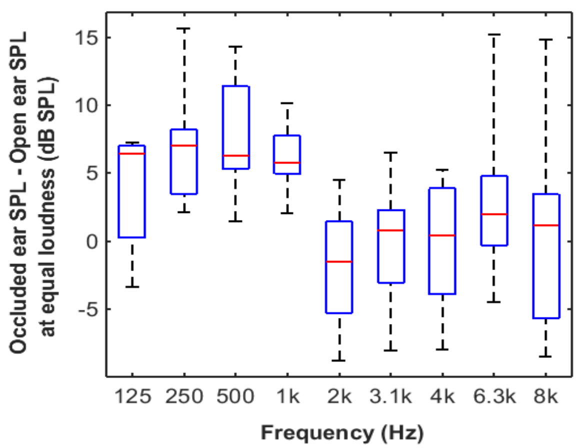

Figure 1: Distribution of the differences in equal loudness levels measured on six subjects (two results per subject, i.e. twelve values) at nine frequencies in the open vs. occluded ear. The boxes show the 2nd and 3rd quartiles separated by the median (in red), while the dashed whiskers show the 1st and 4th quartiles.

Frequency (Hz)	125	250	500	1k	2k	3.1k	4k	6.3k	8k
Difference (dB)	*4.1*	*6.7*	*7.8*	*6.1*	*-1.7*	*0.0*	*-0.2*	*3.0*	*0.4*
σ (dB)	*3.1*	*2.7*	*3.1*	*0.9*	*3.5*	*3.1*	*3.6*	*3.1*	*3.4*

Table I: Average difference (N = 6) in equal loudness levels measured at nine frequencies in the open vs. occluded ear. σ is the intersubject standard deviation.

4 Discussion

For safety purposes, the microphones were never closer than 1 cm to the eardrum, and the results for frequencies ranging from 3.1 to 8 kHz should be carefully interpreted as they might be influenced by some resonance in the open ear. Nevertheless, it clearly appears that up to 1 kHz sounds were selected at much higher levels in the occluded ear than in the open ear, until this difference drops at 2 kHz.

To our knowledge, this is the first time loudness in the open-ear and occluded-ear conditions were compared using the same transducer on both sides, which is extremely important when discussing the factors that may cause such discrepancies. Indeed, one of the main potential factors given by Keidser et al. to explain the difference was the source location effect described in Rudmose's experiments [5]: "the near source is regarded as having a "smaller acoustic size" and consequently must produce more sound pressure in the ear canal to equal the loudness of the distant and "larger" loudspeaker". Having used headphones on both sides in our experiment, this factor should be discounted with regard to the results seen in Fig. 1, just like any factor that is to do with the use of a loudspeaker (e.g. mechanical vibration through the subject's chair).

As stated by Keidser et al. [2], "one possibility is that occlusion of the canal changes the relationship between SPL near the eardrum and the power entering the middle ear". We have been studying many ways of modeling this effect, but none has given entire satisfaction so far.

The acoustic reflex explanation, also mentioned in Keidser's work, is not relevant here as the occluded ear and the open ear were stimulated simultaneously during the loudness balance, while a stapedial muscle contraction occurs bilaterally in normal ears.

Eventually, the observed difference in equal loudness levels may only result from a psychological process, during which the presence of an earplug leads some subjects to feel their occluded ear is more protected than it actually is. We have not yet investigated such possibility.

5 Conclusions

These results raise important questions as regards to the determination of noise exposure received by people wearing earplugs, and perhaps other types of HPDs. In the long term, such data may even have an impact on the standards that define the free-field corrections to be used for the determination of sound immission from communication equipment (ISO 11904, CSA Z107.56). Finally, they are a key point to consider for in-ear dosimetry applications, as future systems may need to include acoustic corrections to account for a change of sensitivity due to occlusion of the ear canal.

Acknowledgments

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References

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