Loudness In The Occluded Ear Canal: Are We Again Missing 6 dB?

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1 Introduction

Over the last century, Auditory Research has been repeatedly reporting differences between earphone/earbud and free-field loudness perception. Although it is still unclear today what causes these differences, many possible explanations have been given; one of them being that ear occlusion modifies the subject's perception of loudness. In this paper, we shall try to give the full picture on this issue and identify the factors most likely to explain those discrepancies.

2 Origins

To the authors' knowledge, the so called "missing 6-dB" problem started with a paper from Sivian & White [1] stating that pressure thresholds observed at low frequencies using conventional earphones mounted in flat cushions were approximately 6 dB higher than thresholds measured on the same subjects when a loudspeaker was the sound source and the subject's ears were uncovered. There was no acceptable explanation given as to why the minimum audible pressure (MAP) differed significantly from the minimum audible field (MAF). This was later confirmed by Munson & Wiener [2] who found that for loudness balancing the reported differences still existed. The fact that those differences were about the same for threshold and supra-threshold levels made it quite tempting to think there could be a generalized explanation for both situations. However, as stated by Rudmose [3], it is quite likely that "there are truly two problems, each with its own solutions". This is something anyone should keep in mind when comparing loudness data, as specific precautions should be taken for each of the scenarios.

3 The "end"

Regarding noise levels at threshold, Killion [4] came to the conclusion that the 6 dB difference at minimum audible pressure (MAP) between a loudspeaker and an earphone could be attributed to four methodological shortcomings: i) inadequate determination of actual stimulus levels; ii) physiological noise; iii) transducer distortion, and iv) mechanical vibration coupled to the subject. This was later confirmed through direct measurements by Rudmose [3], who identified masking from physiological noise as the main reason to explain threshold differences at low frequencies for noise generated by earphones mounted in flat cushions.

As for loudness balance tests, Rudmose found a very specific list of factors that may provoke those differences. He also added that if the procedures used in his experiments were followed there should be no missing 6 dB. Those factors are: i) mechanical coupling of the subject's chair (the subject's chair needs to be isolated from the floor); ii) source location; iii) transducer distortion; iv) the formal procedure for performing the balancing, and v) the monaural case problem (for monaural measurements, it must be ensured that the non-tested ear is sufficiently occluded when performing the tests in free-field to avoid comparing monaural data with binaural data). One essential factor is in fact the source location problem. According to Rudmose, "when performing loudness balances between sounds generated by a loudspeaker located across the room with that generated by a loudspeaker near the ear (ear or ears open), some subjects require more sound pressure from the near source than from the distant source for equal loudness". This phenomenon can be explained by the so-called "acoustic size". In other words, some listeners perceive a more distant source as having a "larger acoustic size" and consequently, the smaller source (e.g. earphones) must be "stronger" to equal the loudness of the larger source. From Rudmose's data, this effect is subject dependent and can reach up to 4 dB in the case of supra-aural headphones compared to free-field stimulation. Also, once a subject becomes aware of this phenomenon, he can be trained to eliminate it.

Lastly, Völk & Fastl [5] used binaural synthesis to show that "the same sound-pressure time-functions in the auditory canals ensure the same loudness in loudspeaker and headphone reproduction" and possibly gave a final end to this issue. Their explanation is that "the same loudness perception (and the overall auditory impression) can only be elicited if the auditory event position is comparable in both cases", which confirms the observations made by Rudmose about the importance of source location.

Having said that, one could easily consider "the case of the missing 6 dB" closed. And yet the debate was re-opened as scientists started to question the effects of listening with an obstructed ear canal.

4 Return of the jedi

Keidser *et al.* [6] studied the "relative perception of low and high frequency sounds in the open and occluded ear". Their findings revealed that for balancing tests "normal-hearing listeners tend to select an average 10 dB higher level for low-frequency sounds at 500 Hz when listening with the ear occluded than when listening with the ear open". It should

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be noted that the “open ear” was excited by a loudspeaker while sound in the “occluded ear” was delivered by hearing aid receivers. Hence, it is difficult to determine whether ear occlusion actually had an impact on the reported differences as the “acoustic size” parameter may also have influenced the results.

Recently, the present authors undertook a loudness balance experiment [7] where circum-aural headphones were used to present sounds diotically in the open (meaning “no earplug”) and occluded (by an earplug) ear. The results suggested the occluded ear needs more sound power for the same achieved loudness, but further investigations showed that these data may have been impacted by some inter-aural time difference (ITD) introduced by the earplug. Additional tests shall be performed shortly and new results should be presented at the conference.

Using a totally different experiment, Theis *et al*. [8] found that in-ear dosimetry tends to overestimate the noise dose when performed in the occluded ear. Their protocol is based on the assumption that TTS (Temporary Threshold Shift) is a good indicator of the noise dose received by the auditory system. These interesting results should, however, be considered with caution as very few details about the experimental procedure were provided.

5 Discussion

Three main changing parameters were identified to describe the large amount of data represented by the above-cited studies: nature of the source (loudspeaker, headphones, in-ear monitors), characteristics of the sound stimuli (spectral and temporal features, excitation level), and the mechanical load applied to the external ear (ear covered with earcups, occluded ear, fully open ear). The discrepancies referred as the original “missing 6 dB problem”, that is when comparing the loudness obtained with a loudspeaker to that with circum- or supra-aural headphones, are regarded by the authors as a solved issue as they have now received several valuable and experiment based explanations [3]–[5]. On the other hand, the differences observed when studying the impact of ear canal occlusion on loudness perception have not been explained, but a few possible explanations are proposed below.

One explanation is that ear occlusion can change the relationship between sound pressure level at the eardrum and the acoustic power entering the middle ear. Various modeling strategies were exercised by the present authors but none seems to be able to support such theory, unless it is provoked by some modification of middle ear impedance when the ear canal is occluded. Moreover, if this effect were to exist, one would expect it to occur at threshold levels as well as supra-threshold levels. Yet, the fact that threshold detection occurs at a constant eardrum pressure has been generally accepted in the scientific community [4] and no differences have been reported at threshold levels despite the use of both in-ear and supra-aural earphones for audiometric testing. Besides, a change of middle ear impedance is unlikely to be the answer as neither the acoustic reflex or added static pressure could explain our latest results [7].

Another possibility is that the factors causing the discrepancies observed for the occluded ear canal are the same involved in the original “missing 6 dB problem”, although the data from Theis *et al*. [8] remain unexplained by such considerations. Regarding the results from Keidser *et al*. [6], the source location could easily have affected the results. The amplitude of the effect (10 dB instead of 4 dB as mentioned by Rudmose [3]) could be due to the increased source proximity inherent to the use of in-ear receivers. As for the recent findings from Bonnet *et al*. [7], it is known that earplugs can affect our ability to localize sounds [9]. Therefore, the earplug might affect the lateralization task even once the ITD issue is solved in future experiments.

6 Conclusions

Based on our own experimental measurements and those from other inquisitive studies, focus was made on the factors that should be considered when studying the effect of ear canal occlusion on loudness perception and/or risks of hearing damage. A list of studies was provided, but we believe additional data are needed to draw more specific conclusions on this issue. Hopefully, upcoming tests will help resolve the problem.

Acknowledgments

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