Effects of ear canal occlusion on hearing sensitivity: A loudness experiment

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Over the last century, hearing research has repeatedly reported differences in loudness perception when different types of transducers are being used. One of the effects of using different transducers is that listening may be performed via an open ear (loudspeaker), a cushioned ear (headphones), or an occluded ear (hearing aid receivers, insert earphones). The question of whether varying the acoustic load applied to the ear canal might impact hearing sensitivity has therefore become essential given the need to establish realistic noise damage risk criteria in an attempt to prevent noise-induced hearing loss for any given listening condition. Although such loudness discrepancies in the cushioned ear have been recently proven to be caused by loudness measurement artifacts, currently available data do not exclude a possible impact of ear canal occlusion on loudness perception. This paper presents the results of a loudness balance test carried out on 18 normal-hearing listeners. Using an earplug to occlude the canal, in-ear sound pressure levels were compared between the occluded ear and the cushioned ear at equal loudness. The results show agreement within 1 dB between the two listening conditions, and support the conclusion that loudness does not depend on the type of acoustic load applied to the ear canal.

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I. INTRODUCTION

Loudness is usually defined as the subjective intensity of a sound. It has been extensively used by acousticians and hearing scientists to describe the potential effects of noise on human hearing. In 1933, Fletcher and Munson published their set of equal loudness contours (Fletcher and Munson, 1933), which served as the basis for the first standardization of *A* and *B* weighting filters. Today, the *A*-weighting filter remains the universal standard for sound exposure measurements whenever results relevant for hearing conservation are needed (ISO, 2013). Also, although auditory fatigue is detected primarily as an increase in hearing thresholds, it may as well be revealed by a decrease in loudness (Botte and Mönikheim, 1994; Florentine *et al.*, 2011). The measurement of loudness therefore appears as a valuable method for testing the dangerousness of noise. However, such measurements of loudness are subject to many artifacts, some of which relate to the "missing 6 dB" issue reported 70 years ago.

The so-called "missing 6 dB" case originates in the differences observed between the loudness induced by headphones (HPs) and that induced by a loudspeaker (LS). In 1949, Beranek stated that supra-aural HPs require that the sound level be 6–10 dB louder at the eardrum to elicit the same loudness perception as in a free sound field (Beranek, 1949) at low frequencies. Although largely unexplained at the time, these discrepancies were found to occur at thresholds (Sivian and White, 1933), as well as for supra-threshold loudness adjustments (Munson and Wiener, 1952; Robinson and Dadson, 1956). While the differences at the threshold point were then proved to be largely due to the masking effect of physiological noise (Killion, 1978; Rudmose, 1982), the effect for levels above threshold was more complex. According to Rudmose (1982), this was caused by (i) mechanical coupling of the subject's chair; (ii) source location; (iii) transducer distortion; (iv) the formal procedure performed to balance the loudness, or (v) the monaural case problem (for monaural measurements, the non-tested ear should be properly occluded when performing the tests in a free-field to ensure only monaural data are compared and not binaural data). Rudmose accompanied this list of factors with strongly supportive data suggesting that if the procedures used in his experiments were followed there should be no missing 6 dB, and that the most influential factor was, in fact, the effect of the source's location. Indeed, it was shown that when matching a 100-Hz tone for loudness, a lower sound pressure level (SPL) at the eardrum was required for a distant LS rather than for a nearby LS. To explain this effect, which reached about 4 dB on three out of four listeners, Rudmose (1982) referred to the so-called "acoustic size." This suggests that some subjects perceive a nearby source as much "smaller," causing it to need more in-ear sound pressure to equal the loudness of a more distant—and thus, "larger"—source. Also, not only was this psychological effect reported as subject dependent, but also, it was reported

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that people could be trained to eliminate it. Later, Keidser *et al.* (2000) published a broad literature review regarding the equal loudness contours obtained with three types of transducers: LS, HPs, and in-ear monitors. This review, along with a new set of contours obtained on human subjects, suggests that an average of 10 dB higher of eardrum SPLs are required at 500 Hz for the occluded ear to perceive the same loudness as the open ear. Most importantly, the "open ear" here represents the ear excited by a free-field LS, while the term "occluded" refers to an ear excited either with insert earphones or hearing aid receivers. Well aware of the previous observations made about LS location (Rudmose, 1982), Keidser *et al.* (2000) mention that "acoustic size" is a factor that could possibly explain their results, though they also stated that there were no other data but Rudmose's to support the "source location effect" theory. Nevertheless, the effects of source positioning on loudness are currently well documented in the literature (Florentine *et al.*, 2011; Völk and Fastl, 2011; Zahorik and Wightman, 2001) and it now seems evident that loudness cannot be solely described by the SPL and frequency at the eardrum. The source location effect is particularly important for binaural testing as it was shown that the perceived apparent source width decreases with increasing interaural cross correlation (Kasbach *et al.*, 2013; Potard and Burnett, 2004). This may explain why the effect can reach as much as 20 dB in reverberant sound fields (Zahorik and Wightman, 2001), where interaural cross correlation decreases sharply with increasing source distance (Hartmann *et al.*, 2005). Additionally, the fact that most anechoic chambers will not effectively absorb long wavelength sounds perhaps explains why the missing 6 dB issue was primarily reported for low frequencies. In the end, the only known way to guarantee the same loudness using two different transducers is to assure the same ear signals (time dependent sound pressure signals at the eardrums) in both situations, which can effectively be achieved by individual binaural synthesis (Völk and Fastl, 2011). Finally, because the results reported by Keidser *et al.* (2000) include both monaural data and binaural data, they may also have been affected by two recently observed factors: the differences in binaural-to-monaural loudness ratios between HP and LS playback (Epstein and Florentine, 2009) and the frequency dependence of binaural loudness summation (Charbonneau, 2017). However, it is difficult to speculate as to which specific factors had an impact on the reported discrepancies as some of the above-listed factors are subject dependent or might depend on the acoustic properties of the room used for free-field listening (Florentine *et al.*, 2011). Also, although Völk and Fastl showed that "*the same sound-pressure time-functions in the auditory canal ensure the same loudness in LS and HP reproduction*" (Völk and Fastl, 2011), they did not verify whether this statement also applied to insert earphones. Therefore, some doubts remain with regard to the factors that caused the discrepancies observed with in-ear monitors, such as a potential influence from the acoustic load applied to the ear canal when the latter is occluded.

While some of the effects of closed hearing-aid fittings have been widely covered in the literature (Winkler *et al.*, 2016), the question of whether occluding the human ear canal can have an impact on hearing sensitivity is only a recent concern. Recently, Theis *et al.* (2012) released the results from a study for which a more extensive report is also available (Gallagher *et al.*, 2014). In this study, 20 human subjects were exposed to high levels of noise, and their effective noise dose was estimated by measuring their temporary threshold shifts (TTS). This was done for open ear exposure as well as for occluded ear exposure. In the latter case, the subjects wore earplugs, but steps in the experiment were taken to achieve the same in-ear SPLs as in the open ear configuration. The results, although currently unexplained, revealed that "*94 dB SPL inside the ear under a hearing protection does not produce an equivalent auditory response to 94 dB in the free-field*" (Gallagher *et al.*, 2014). Quantitatively, the TTS-based noise dose calculations showed that the occluded ear received an average of 11 dB less noise exposure than the open ear. In other words, the estimation of the effective *A*-weighted SPLs when hearing protectors are worn such as described in ANSI S12.68 (ANSI, 2007), that is, by simply subtracting the attenuation from the protector, would tend to overestimate the effective noise dose by an average of 11 dB. Such findings, if confirmed, could obviously have a dramatic impact on current occupational noise exposure legislation, and are particularly important considering the new emergence of in-ear dosimeters (Bonnet *et al.*, 2015). Indeed, in-ear noise dosimetry is oftentimes integrated into hearing protection devices (Bessette and Michael, 2012; Mazur and Voix, 2013; Theis *et al.*, 2012), and new calibration factors would be needed in the case of so-called "dosimetric earplugs" to account for such a shift in the sensitivity of the hearing system due to occlusion of the ear canal.

This section has presented some known artifacts related to loudness measurements, which are essentially due to the use of unlike receivers (Epstein and Florentine, 2009) and/or varying source distances (Rudmose, 1982; Zahorik and Wightman, 2001). Such artifacts should therefore be avoided by using identical transducers positioned at equal distance from the ear. This paper aims to investigate the effects of ear canal occlusion on hearing sensitivity by comparing the loudness elicited by circum-aural HPs between the unoccluded ear and the ear occluded by an earplug.

II. METHOD

The psychophysical loudness balance procedure used here to compare the loudness in the occluded and unoccluded (or "cushioned"; Sec. II will show that the unoccluded ear is in fact covered by HP cushions) ears consists in performing left-right loudness adjustments with HP-generated diotic noise stimuli, while having one ear occluded by an earplug. When the same loudness is achieved in both ears, the SPLs obtained in the occluded and unoccluded ears are compared by means of in-ear probe microphone measurements. The subjects, instrumentation, and loudness balance procedure are described in Secs. II A, II B, and II D, respectively. As the test-frequencies range from 125 Hz to 8 kHz, a simple acoustic model is also introduced (Sec. II C) to better understand the results (Sec. III) at high frequencies. This protocol was approved by the *Comité d'éthique pour la recherche*, École de technologie supérieure's (ÉTS's) internal review board.

A. Test-subjects

All subjects underwent a screening audiogram using Békésy's tracking method and were required to have hearing thresholds of 25 dB hearing level (HL), or less, across the frequency range of 125–8000 Hz. An otoscopic screening was also performed on both ears and the participants showed no abnormalities. The participants were asked to run a quick loudness balance (as described in Sec. II D, but with both ears unoccluded) training task that was repeated a maximum of two times until their standard deviation (STD) became 3 dB or less (a series of preliminary tests were conducted in unoccluded ears and revealed that after training, most subjects were able to perform the requested balance task with an inter-trial STD below this 3 dB value). Two subjects who were unable to reach the 3 dB criterion after three attempts were not retained for the rest of the experiment. A total of 18 subjects (11 male, 7 female) with ages ranging from 22 to 50 yr (average 31 yr) completed the full study. All of the retained subjects eventually had hearing thresholds below 20 dB HL across the frequency range of 125–1000 Hz, and only 12 of them over the full range of 125–8000 Hz. Because 25 dB HL can be considered high for normal hearing (Martin and Champlin, 2000), the data analysis described in Sec. III was repeated on these 12 subjects only, which lead to similar results and the same conclusions as presented in this paper. Overall, the retained participants seemed to have a slightly better hearing in their right ears as the measured hearing thresholds were, on average, higher on their left side by 1–2 dB at most test-frequencies (this precision will be useful to understand the results presented in Sec. III).

B. Instrumentation

The tests took place in a double-wall 10 m^2 Eckel (Eckel, Morrisburg, ON, Canada) audiometric sound booth, as shown in Fig. 1. Every participant had access to a computer mouse featuring a scroll wheel to adjust the loudness, and the mouse was connected to a laptop located outside the room. The subject's input directives via the mouse wheel were converted into audio balance commands using Pure Data software (Pure Data community, https://puredata.info/) and an 8pre Universal Serial Bus (USB) audio interface (MOTU, Cambridge, MA). Circum-aural HPs with high passive noise reduction (Fitcheck Solo™ by Michael Associates, Inc., State College, PA) were used for stimuli generation to avoid having the sounds originating from the mouse disturb the participant in any way during the balance process. Audio signal acquisition was made using a PXI-4462 DAQ acquisition module (National Instruments, Austin, TX) and MATLAB software (MathWorks, Natick, MA). SPLs were computed using MATLAB scripts.

A schematic drawing of the acquisition setup and wiring is presented in Fig. 2. The in-ear sound signals were recorded on both ears and redirected in real time to the experimenter who could check that no parasite noise (cough, throat clearing, deep breathing, etc.) was produced by the subject during the measurements. Such in-ear measurements were made using recently developed earpieces designed by the authors to perform sound measurements both in the open and occluded ears (École de Technologie Supérieure, 2018). An open type earpiece (OTE) was used to measure sound inside the unoccluded ear while a closed type earpiece (CTE) was used to measure sound at the medial end of an occluding earplug. The two earpieces, shown in Fig. 3, are each made of miniature FG Series electret microphones (Knowles, Itasca, IL) connected to probe tubes of identical length to collect data occurring at approximately 8 mm past the ear canal entrance when fully inserted. The acoustical effect of the probe tubes was assessed through preliminary calibration measurements where the microphone responses were recorded with and without the tubes under an identical sound field. The response of the probe-microphones was also compared between open-inlet and blocked-inlet (tube entrance blocked with thick, soundproof rubber material) conditions to ensure no sound leakage through the probe tube walls, revealing an overall noise reduction (NR) of the system of about 50 dB, which is much more than the moderate attenuation of the earplug used in this experiment (Fig. 4). During experimentation, daily calibrations were conducted with the two assembled earpieces to ensure that the relative sensitivity difference between the two probe microphones was precisely measured and then used to correct the interaural level differences (ILDs) presented in Sec. III.

FIG. 1. (Color online) Subject wearing the HPs (b) and adjusting the mouse wheel (a) used for loudness equalization in the audiometric sound booth. The earpieces are fitted onto the subject's ears, under the HPs, and the microphones are connected to the battery-powered signal conditioning box (c) behind the subject.

For occluded ear measurements, the probe tube passes through a double-flanged earplug and another microphone allows for sounds measurements outside the ear canal (see Fig. 3). The SPL differences between the in-ear microphone (IEM) and the outer-ear microphone (OEM) can therefore be used to estimate the attenuation (in the form of NR) provided by the earplug and ensure that the earpiece is correctly fitted inside the auditory canal. Since the present study aims to

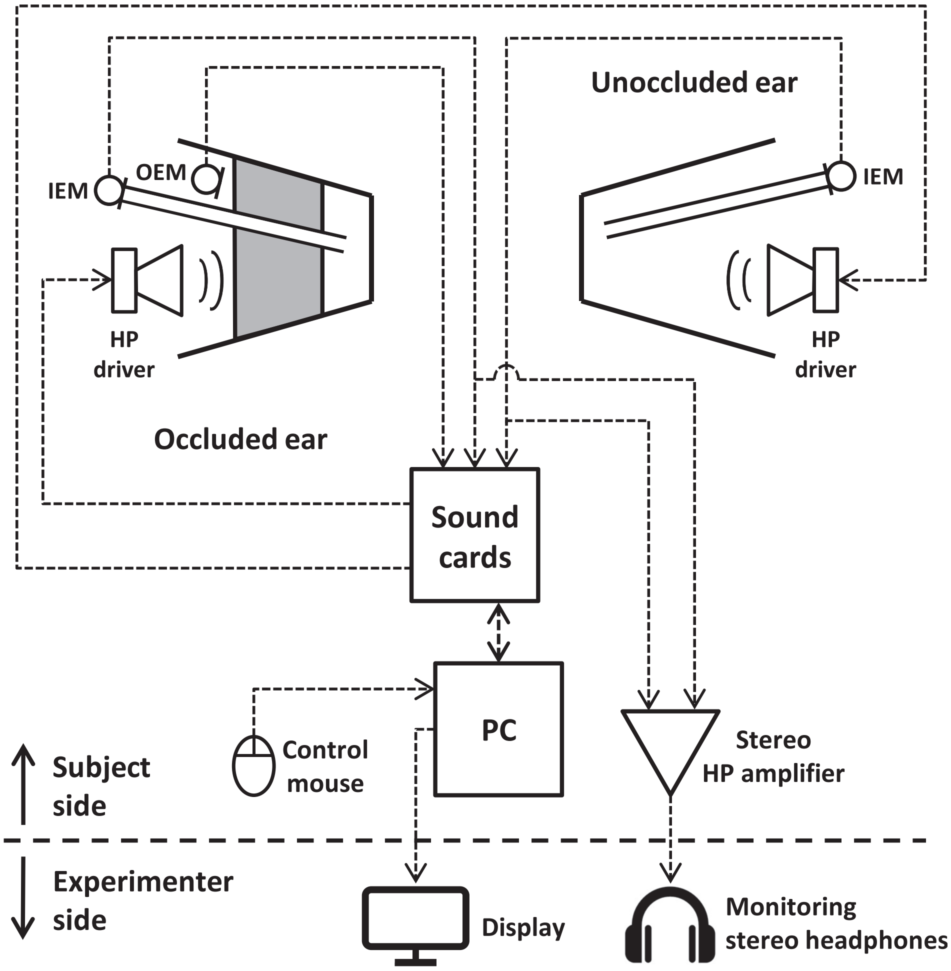

FIG. 2. Schematic drawing of the acquisition setup.

investigate the effect of ear canal occlusion on loudness perception, it is believed that maximizing the so-called "occlusion effect" (OE) increases the chances for such effect to be measured (the authors did not want to miss the opportunity to investigate potential psychological factors inherent to the increased perception of low-frequency physiological noise caused by the OE). Thus, as a deeper earplug insertion tends to decrease the OE (Berger and Kerivan, 1983; Dean and Martin, 2000; Lee, 2011), the CTE was inserted just enough (approximately 4 mm instead of the 8 mm for deep insertion) to provide a tight seal in the auditory canal. Figure 4 presents the average attenuation obtained on the 36 ears tested over the

FIG. 3. (Color online) Three-dimensional models showing the OTE (left) and the CTE (right). In-ear measurements are performed via thin probe tubes connected to miniature electret microphones. An outer-ear microphone (OEM) on the CTE makes it possible to measure earplug attenuation.

7 octave-band frequencies from 125 to 8000 Hz. The measured attenuation values are typical of this type of moderate pre-molded earplugs when shallowly inserted.

C. Canal correction acoustic modeling

Since the data were not collected directly at the eardrum, deviations from eardrum measurements are expected for high frequencies. This is caused by the presence of standing waves in the ear canal that may lead the measured in-ear

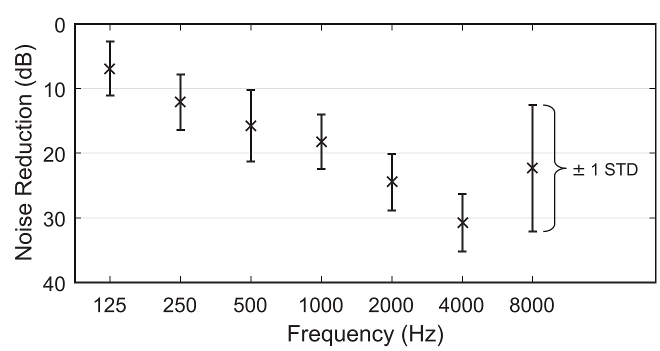

FIG. 4. NR provided by the CTE, as measured on 18 subjects (36 ears) in third-octave band values. The NR was estimated by measuring the sound pressure ratio between the in-ear microphone (IEM) and the OEM microphones under continuous white noise delivered by the HPs, and removing the effect of the tube on the IEM. The values are typical of shallowly inserted pre-molded earplugs.

SPLs to misrepresent the actual eardrum SPLs both in the occluded and unoccluded ears. To quantify this effect, a simple acoustic model of the ear canal was developed. Considering the ear canal to be a lossless cylindrical tube terminated in an impedance Z_T, the equation for the ratio of the pressure at any point at a distance d from the eardrum (P) to the pressure at the eardrum P_T, from Mapes-Riordan (1991), is

$$\frac{P}{P_T} = \cosh(kd) + \frac{1}{Z_T} jR_0 \sinh(kd), \qquad (1)$$

where R_0 and k are the wave impedance and wavenumber, and Z_T is the eardrum impedance.

Using expression (1), the difference between the measured SPL (in-ear SPL along the ear canal) and eardrum SPL was computed at various measuring positions in the auditory canal. The eardrum impedance was simulated using Shaw and Stinson (1983). The resulting curves for the four higher test-frequencies, displayed in Fig. 5, are consistent with previous results obtained both with theoretical calculations (Gilman and Dirks, 1986) and canal-replica measurements (Chan and Geisler, 1990). Additionally, such curves stand both for open ear measurements and measurements made between the eardrum and the medial end of an earmold in the occluded ear (Chan and Geisler, 1990; Gilman and Dirks, 1986).

Figure 5 shows clear dips (also called "antiresonance notches") at the two highest frequencies, 4 and 8 kHz. For instance, a probe-microphone at 22 mm from the tympanic membrane may read up to 10 dB below the eardrum SPL at 4 kHz. Such results are, though, only indicative (especially for high frequencies) given that only a rough estimate of the ear canal geometry was used (Stinson and Lawton, 1989), and the positions of the 4 and 8 kHz dips are expected to vary across individuals. This was confirmed by recent real-ear measurements (unpublished results) made by the authors, revealing high disparities in the shapes of the 4 and 8 kHz curves while the 1 and 2 kHz curves remained globally the same for all subjects.

Since the same deviations from eardrum SPLs are expected in the occluded and unoccluded ears at one given position in the ear canal, such deviations may be ignored when comparing eardrum SPLs between the two listening conditions provided that all measurements were taken at equal distance from the eardrum. In this experiment, the distance from probe to eardrum was not assessed. Since the human ear canal may present length variations reaching more than 10 mm between individuals (Ballachanda, 2013; Stinson and Lawton, 1989), it is difficult to speculate on the resulting differences between measured SPLs and eardrum SPLs. The insertion depth is, however, relatively well known with the designed earpieces. As mentioned in Sec. II B, the CTE was only shallowly inserted to maximize the OE. On the other hand, the OTE was fully inserted to avoid earpiece displacements during experimentation. Hence, the probe tip rested around 4 mm past the ear canal entrance in the occluded ear, rather than 8 mm in the unoccluded ear. Since this study is to compare SPLs in the occluded and unoccluded ears, such a shift in measurement position may significantly affect the results above 1 kHz. Because of the expected intersubject variability in the shapes of the 4 and 8 kHz curves and the lack of data regarding probe-to-eardrum distances, the impact of this 4-mm shift on the results is hard to predict at these frequencies. Nonetheless, the impact at 1 and 2 kHz can be reasonably estimated using Fig. 5. Taking 26 mm as the average length of the ear canal, the probe-to-eardrum distance can be assumed to be 22 mm in the occluded ear and 18 mm in the unoccluded ear. Thus, using the slopes of Fig. 5 at 20 mm from the eardrum, it is thought that the 4-mm shift between the two earpieces caused the occluded ear's SPLs to be underestimated by about 1.1 dB at 2 kHz and 0.3 dB at 1 kHz, as compared to the unoccluded ear.

D. Procedure

The subjects remained seated during the experiment and were to perform left-right loudness adjustments using the provided HPs and computer mouse (see Fig. 1), while having one ear occluded by an earplug. As each test stimulus was presented diotically, the aim was for the subject to obtain the same loudness in the occluded and unoccluded ears. The

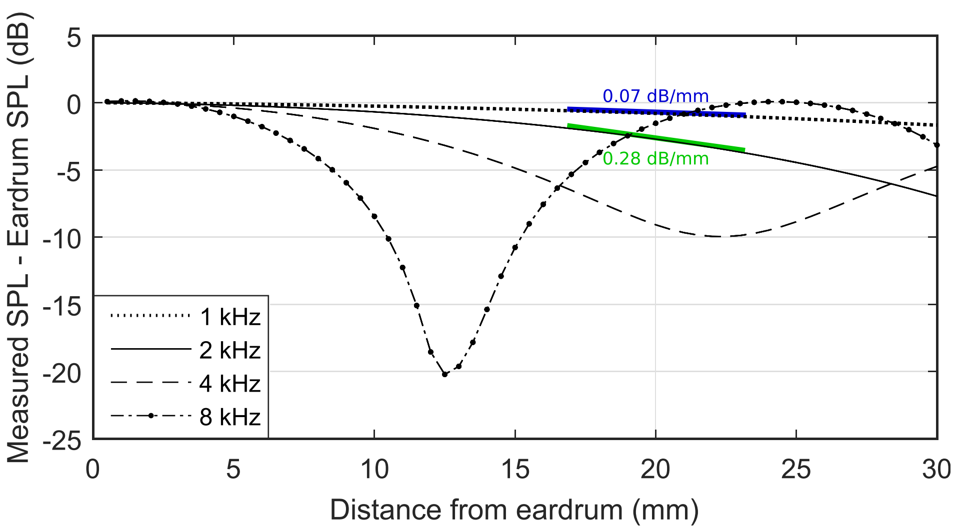

FIG. 5. (Color online) Simulated difference between measured and eardrum SPLs at various measuring locations along the occluded or unoccluded ear canal, computed in third-octave band values at 1, 2, 4, and 8 kHz. The slopes of the 1 and 2 kHz curves are indicated at 20 mm from the eardrum.

balance approach and test stimuli used for loudness equalization are detailed in Secs. II D 1 and 2.

1. Loudness balance approach

Each subject was tested for all octave band center frequencies from 125 to 8000 Hz in two mirror tasks. In the first task (further referred to as "task L") the participant's left ear was occluded, whereas in the second task (further referred to as "task R") the right ear was occluded. Before each task, the two earpieces were carefully fitted into the subject's ears and the HPs properly adjusted over them. Binaural white noise was then played through the HPs for 20 s, allowing for the CTE's attenuation to be measured (see Fig. 4), as well as the sound pressure ratio between the two in-ear probe tube microphones. To compensate for the attenuation provided by the earplug, the latter ratio was then used to correct the signal gain to be sent to the occluded ear during the loudness adjustments. Each task could last between 10 and 25 min depending on the participant's speed, and was started only about 1 min after the end of white noise presentation to avoid confusion. Within each task, the following sequence was presented three times (more details about the noise stimuli are given in Sec. II D 2): 1 kHz, 2 kHz, 4 kHz, 8 kHz, 125 Hz, 250 Hz, 500 Hz, 1 kHz. Thus, the subject was to balance every test-frequency three times, except for the 1000-Hz stimulus, which was adjusted six times for increased accuracy. This number of iterations was carefully determined so that the total test duration for one subject (70 min, on average) did not exceed 90 min to maintain a good balance between results quantity and results quality (Schatz *et al.*, 2012). Since the within-subject STD was measured to be on average 3 dB at all frequencies, which equals the maximum variability observed on most subjects when no apparent tiredness was involved (see Sec. II A), it is believed that the performed number of iterations was quite appropriate for the designed leveling task.

To prevent the participants from focusing their attention on one ear, the loudness balance was done in a binaural manner. That is, if the subject increased the stimulation level by x dB in one ear, it would cause the level to decrease by x dB in the opposite ear at the same time. The mouse wheel was used to balance noise from one ear to the other, with a resolution of 1 dB (preliminary testing revealed this value to be the most appropriate for the designed leveling task) and a range of 30 dB in both ears (i.e., the smallest and largest interaural level variations available were 2 dB and 30 dB, respectively). The subjects were asked to click the left mouse button whenever they were finished balancing and satisfied that they were meeting the left-right equal loudness target. Following the click, the noise levels were kept constant on both sides for 3 s and the in-ear SPLs were automatically measured and computed over a 2-s period (period during which the participants were informed that they should remain as quiet as possible). The noise stimuli were then automatically switched to the next octave-band test-frequency and the audio balance was randomly reset to one of the 31 positions available to ensure that the participant remained active during the exercise. In addition, the direction of the mouse's scrolling wheel used to increase the SPL on a given ear was randomly reset after each adjustment. Figure 6 shows an example of what the measured in-ear SPLs looked like over time during loudness equalization.

2. Test-stimuli

Because loudness is frequency dependent, particular attention must be paid to avoid balancing loudness between spectrally different signals. Narrow band noise stimuli with a bandwidth of one-eighth of an octave were therefore used to produce almost identical frequency content on both ears despite the non-uniform attenuation of the earplug. The stimuli were calibrated on a 45CB acoustical test fixture (GRAS Sound and Vibration A/S, Holte, Denmark) so that when the participants selected the same SPLs in both ears, the elicited loudness should correspond to a value of approximately 50 phons (which is considered moderately loud) at all frequencies. The left and right stimuli were phase-uncorrelated to avoid any impact from a potential interaural time difference (ITD) caused by the earplug. This latter point is critical, as it was recently found by the authors that the phase delay introduced by the earplug with coherent (phase-correlated) stimuli had had a great impact on previous tests results (Bonnet *et al.*, 2016) for frequencies below 2 kHz. Indeed, with diotic stimulation, the requested loudness equalization exercise resembles a lateralization task where the subject aims to center a sound image in one's head. For frequencies up to 1500 Hz, the apparent lateral position of the auditory image indeed depends both on ILDs and ITDs (Yost, 1981).

III. RESULTS

The average interaural level difference at equal loudness (further referred to as "AILDEL value") was computed for each subject and each test-frequency for the two tasks described in Sec. II D. Each AILDEL value was calculated as follows:

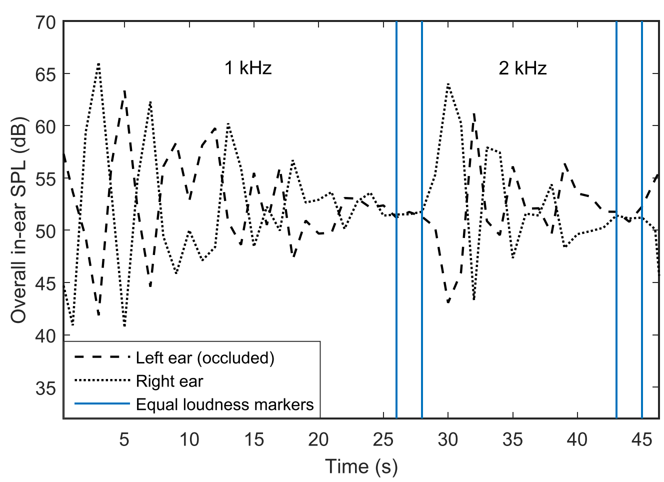

FIG. 6. (Color online) 1-s in-ear equivalent continuous SPLs ($L_{eq,1s}$) as a function of time during loudness equalization measured on one subject at 1 and 2 kHz (the participant's left ear was occluded by the CTE). The values shown during the 2-s periods delimited by the markers correspond to the equal loudness levels captured after the mouse click. In this example, the levels selected for equal loudness are very close between the two ears.

$$\mathrm{AILDEL} = \frac{1}{n}\sum_{i=1}^{n}[Lp_{\mathrm{left}} - Lp_{\mathrm{right}}]_i, \tag{2}$$

where Lp_{left} and Lp_{right} are the equal loudness SPLs in the left and right ears, respectively, and n is the number of loudness adjustments performed at the selected frequency ($n = 3$ for all frequencies except 1 kHz where $n = 6$).

If ear canal occlusion does not affect loudness perception, such AILDEL values should be the same regardless of the ear wearing the earplug. Thus, to investigate the effect of an earplug occluding the canal, the calculated AILDEL values were compared between task L and task R. Figure 7 compares the ILDs measured inside the subjects' ears between task L (left ear occluded) and task R (right ear occluded). As a mean to control the results presented in this study, the subjects were also asked to perform a quick third task at the end of the experiment with both ears unoccluded and only two iterations per frequency. The results from this control task (not shown) were very similar to the two tasks shown in Fig. 7.

Wilcoxon signed-rank tests were run to compare the AILDEL values of task L and task R at each of the seven test-frequencies. Except for the 2 kHz frequency ($Z = -2.94$, $p = 0.003$), no statistical differences were found at the 5% significance level. This trend appears unchanged even if a Bonferroni correction is applied ($\alpha = 0.007$). However, because of the standing waves forming in the ear canal and the deviations in microphone positioning (the microphone in the CTE was further away from the eardrum than in the OTE), the SPL differences between the occluded ear and the unoccluded ear are believed to be significantly underestimated at 2 kHz. Repeating the same statistical tests with adjusted values using the acoustical corrections presented in Sec. II C revealed similar distributions ($p > 0.05$) at all of the test-frequencies. Overall, Fig. 7 shows that similar SPLs were selected in the occluded and unoccluded ears for equal loudness. This comparison between task L and task R avoids biased conclusions due to initial hearing sensitivity differences between the participants' left and right ears. By looking at task L's results only, from 125 to 1000 Hz, one could indeed think that the earplug caused higher SPLs to be selected in the left ear for equal loudness. The similarity of the results obtained in task R suggests that such a difference is, in fact, not caused by the earplug, but more likely, it is due to the trend by which more subjects selected higher SPLs in their left ear at these frequencies. Besides, such a trend to select higher SPLs in the left ear is not surprising as a slight overall hearing asymmetry has already been found in the subjects' audiograms (see Sec. II A). The AILDEL values of task L and task R may, in fact, be written as follows:

$$\mathrm{AILDEL}_L = \Delta_{\mathrm{earplug},L} + \Delta_{\mathrm{subject}}, \tag{3}$$

$$\mathrm{AILDEL}_R = -\Delta_{\mathrm{earplug},R} + \Delta_{\mathrm{subject}}, \tag{4}$$

where $\Delta_{\mathrm{earplug},L}$ and $\Delta_{\mathrm{earplug},R}$ are the effects of the earplug on the equal loudness level difference in task L and task R, respectively, and $\Delta_{\mathrm{subject}}$ is the initial hearing sensitivity difference that exists between the participant's left and right ears.

The expression that follows calculates the average (both tasks included) effect of the earplug:

$$\Delta_{\mathrm{earplug}} = \frac{\Delta_{\mathrm{earplug},L} + \Delta_{\mathrm{earplug},R}}{2} = \frac{\mathrm{AILDEL}_L - \mathrm{AILDEL}_R}{2}. \tag{5}$$

Using expression (5), the average effect of the earplug was calculated for each of the 18 tested participants, and the mean values are shown in Table I. The 1 and 2 kHz values were adjusted using the canal corrections presented in Sec. II C.

Table I confirms earlier observations, namely, that the earplug (and therefore, canal occlusion) had no impact on the equal loudness values. An increased dispersion of the results is visible at 4 and 8 kHz.

IV. DISCUSSION

Figure 7 shows no statistical difference between the AILDEL values of task L and task R at all frequencies,

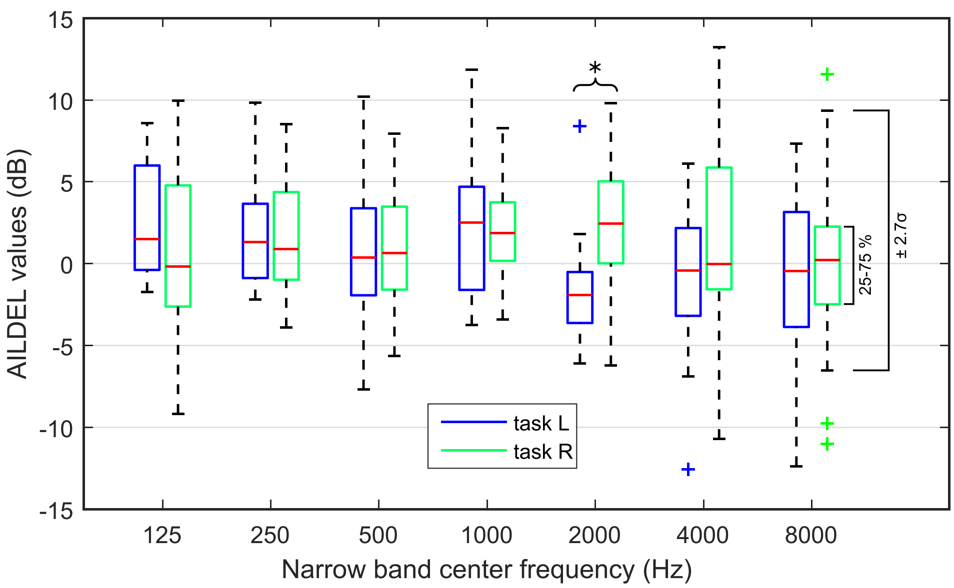

FIG. 7. (Color online) Box and whisker plot ($N = 18$) comparing the AILDEL values of task L and task R at the different test-frequencies. The red lines represent the median, while the crosses represent the outliers. Statistically significant differences are marked with an asterisk (∗). When higher SPLs are selected in the occluded ear, positive and negative results should be observed in task L and task R, respectively (the opposite trend accounts for higher SPLs selected in the unoccluded ear).

TABLE I. Intersubject mean and STD ($N = 18$) of the average effect of the earplug ($\Delta_{earplug}$) at the different test-frequencies. A positive effect accounts for higher SPLs selected in the occluded ear. Correction factors of +0.3 dB and +1.1 dB were applied at 1 and 2 kHz, respectively (values in bold below).

Frequency (Hz)	125	250	500	1000	2000	4000	8000
Mean (dB)	0.7	0.2	−0.1	**0.4**	**−0.9**	−1.1	−0.6
STD (dB)	2.0	2.0	2.5	2.0	2.2	3.5	4.1

except for 2 kHz. The effect at 2 kHz is, however, believed to be due to the discrepancies in microphone positioning between the occluded ear and the unoccluded ear as repeating the analysis using corrected values according to Sec. II C revealed no differences. Such discrepancies, combined with a high intersubject standing-wave pattern variability at higher frequencies (see Sec. II C), had the direct effect of increasing the dispersion of the results above 2 kHz. Depending on the positions of the antiresonance notches shown in Fig. 5, placing a microphone further away from the eardrum can result either in a loss or a gain of measured sound pressure, which contributes to the higher STDs observed at 4 and 8 kHz in Table I. Thus, the authors wish to inform the reader that the results at these two frequencies are rather uncertain and should be considered with caution.

Several potential explanations were proposed to account for the differences observed in the auditory response between the open ear and the occluded ear (Gallagher *et al.*, 2014): changes in the acoustic impedance of the tympanic membrane due to occlusion of the auditory canal, changes in the acoustic reflex and ossicular chain dynamics when the ear is occluded, or reduction in the stress reaction as a result of the increased perceived safety by the individual when wearing a hearing protector. This last possibility is, however, regarded as unlikely by the authors as previous studies have shown a negative relationship between physiological arousal and the magnitude of TTS (Muchnik *et al.*, 1992; Thompson *et al.*, 1987). When discussing the discrepancies observed in the loudness contours between free-field and hearing aid stimulation, Keidser *et al.* wrote that "*one possibility is that occlusion of the canal changes the relationship between SPL near the eardrum and the power entering the middle ear system*" (Keidser *et al.*, 2000). If such a change were to exist, or if a change should occur in the impedance of the acoustic membrane, it is expected that the present study would show significant effects caused by the earplug on loudness balance results. However, this is not the case as all differences reported in Fig. 7 and Table I are minor and not statistically significant. Indeed, after removing all known artifacts related to loudness measurements (see Secs. I and II), it is believed that there should be no difference in the loudness perception between the cushioned ear and the occluded ear. This is also supported by the fact that, to the authors' knowledge, no significant differences have ever been reported in the reference audiometry thresholds between insert earphones and supra-aural HPs. In other words, threshold occurs at a constant eardrum pressure (Killion, 1978; Wilber *et al.*, 1988).

The intriguing data (Gallagher *et al.*, 2014; Theis *et al.*, 2012) originating from TTS measurements (see Sec. I) remain, however, unexplained in the light of these results. The present study was conducted using shallowly inserted earplugs to maximize the OE, but could be repeated with deeply inserted earplugs for confirmation. Also, the supra-threshold stimulation levels were set at 50 phons as the experiment was limited by the inability of the HPs and audio interface to deliver the same SPL and sound quality in both the protected and unprotected ears at higher levels. The use of higher stimulation levels would help to investigate the acoustic reflex explanation (Gallagher *et al.*, 2014; Keidser *et al.*, 2000) since such a reflex is usually associated with higher level sounds above 85 dB SPL. Finally, the loudness balance procedure used by Völk and Fastl (2011) could be repeated with insert earphones to confirm the present findings. Such a procedure, which uses individual binaural synthesis so that the eardrum signal generated by receivers at the ear and that coming from free-field stimulation are strictly identical during loudness equalization, showed no differences between the open ear and cushioned ear when comparing the loudness induced by HPs to that of a LS. Hence, results are consistent with recent studies suggesting loudness does not depend on the type of acoustic load applied to the ear canal.

This outcome is of particular relevance for in-ear noise dosimetry where measurements of the sound exposure levels are often performed in the occluded ear. Since the authors have no other data but those from Theis *et al.* (Gallagher *et al.*, 2014; Theis *et al.*, 2012) to support the theory of a change in hearing sensitivity when the ear canal is occluded, the use of correction factors to account for such a change is not recommended as it would likely lead to the underestimation of the actual noise exposure received by individuals wearing earplugs or in-ear monitors. Similarly, these results could serve as evidence for the validity of fit-check systems, used to estimate the effectiveness of hearing protection devices (Voix *et al.*, 2018). Such systems either make use of objective or subjective measurements, the latter being performed either at threshold or supra-threshold levels. As this study suggests that a relationship between loudness and SPL at the eardrum exists regardless of the acoustic load applied to the ear, it implies that such objective and subjective methods should be equivalent as long as the right experimental procedures are used. Besides, future or current systems that rely on the loudness balance method could perhaps benefit from the experimental design presented in this paper.

V. CONCLUSIONS

The aim of this paper was to investigate the effect of ear canal occlusion on loudness perception. Using an earplug to occlude the ear canal, the in-ear SPLs were compared between the occluded ear and the unoccluded ear at equal loudness. The results support the conclusions that such an effect does not exist and that, if the right experimental procedures are used, there should be no difference in loudness perception among the occluded, cushioned, or open ear. The factors put forward many years ago to explain the "missing 6 dB" issue are believed to be responsible for the loudness discrepancies observed between in-ear receivers and free-field stimulations.

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