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Enhancing acoustic comfort for earplug users: objective and subjective evaluation of bone-conducted sound with meta-earplugs incorporating Helmholtz resonators

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ABSTRACT

Passive earplugs are commonly used to protect workers from excessive noise exposure, but they often result in discomfort. The occlusion effect (OE) is a major discomfort that corresponds to an increased perception of bone-conducted sound at low frequencies. Objectively, the OE is associated with an increase in the sound pressure level generated in the earcanal under bone-conducted stimulation. Inspired by metamaterials, "*meta*-earplugs" incorporating Helmholtz resonators have been developed to minimize this phenomenon, and their effectiveness has been validated using artificial ears in the authors' prior work. In this study, 34 participants evaluated the effectiveness of *meta*-earplugs in reducing the OE. Three configurations of the *meta*-earplug were tested alongside a commercial foam earplug. Objective measurements of both OE and sound attenuation were conducted. Participants also completed a questionnaire evaluating their perception of low-frequency sound amplification and the judgement of the naturalness of their own voice while speaking with the earplugs. On average, the results demonstrate that *meta*-earplugs reduced the objective OE by up to 20 dB below 1 kHz. Additionally, the perception of low-frequency sound amplification decreased by 2 points, while voice naturalness judgement increased by 2 points, both assessed on a 7-point Likert scale. Using linear mixed-effects models, it was found that the perception of low-frequency sound amplification was primarily driven by the objective OE at 125 Hz, while voice naturalness was also significantly influenced by the objective OE at 4 kHz and the psychosocial characteristic of familiarity with the experimenter. Overall, *meta*-earplugs were preferred by 85 % of the participants.

1. Introduction

Prolonged exposure to high noise levels is a leading cause of noise-induced hearing loss (NIHL), and it has also been linked to non-auditory health effects, including stress, disturbed sleep, and an increased risk of hypertension and cardiovascular disease [1]. Previous studies have shown that workers in industries such as construction, manufacturing, mining, agriculture, utilities, and transportation, as well as military personnel and musicians, are at the highest risk for occupational NIHL [2,3]. Moreover, NIHL among these workers has been significantly associated with a greater likelihood of work-related injuries [4]. According to best practices for noise control, the primary strategy is to implement engineering control solutions to reduce noise at the source, followed by administrative measures such as rotating workers between quiet and noisy tasks. When these interventions cannot be implemented, hearing protection devices, like earplugs, are frequently used as the final defense against harmful noise exposure [5,6].

The discomfort of earplugs can lead to improper use or nonuse, diminishing their effectiveness in preventing NIHL [7]. Comfort is a multidimensional construct, which in the context of earplug usage can be understood through four dimensions [5]. Firstly, the "physical" dimension is tied to the user's perception of biomechanical and thermal interactions between the earplug and the earcanal. Secondly, the "acoustical" dimension relates to how noise perception is altered by the earplug. Thirdly, the "functional" dimension addresses the practical acceptability of earplugs. Finally, the "psychological" dimension involves the user's well-being and satisfaction. Discomfort arises from the complex interactions between the work environment, the user, and the

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earplug, referred to as the "triad." This triad (person-environment-earplug) encompasses a range of physical and psychological characteristics that significantly affect the perceived comfort or discomfort of hearing protectors [7]. Adapted from Ref. [7], Fig. 1 illustrates how individual characteristics and interactions between the person, earplug, and environment contribute to (dis)comfort.

Among the factors contributing to acoustic discomfort, the occlusion effect (OE) stands out as a significant issue [8]. The OE arises from the interaction (phase "I" in Fig. 1) between individuals and earplugs, which is objectively measured as an increase in low-frequency acoustic pressure generated by the vibrating earcanal wall when the earcanal is occluded, compared to when it is open, during bone-conducted (BC) stimulation [9,10]. This objective OE is denoted OE_{obj} and results at low frequencies from the shift in the earcanal's acoustic impedance (seen by its wall) from a mass-controlled behavior (open earcanal) to a compliance-controlled behavior (occluded earcanal) [11,12]. Changes in the acoustic energy reaching the inner ear, which is then converted to electrical impulses sent to the brain, can be perceived by individuals (phase "P" in Fig. 1). The perceived OE, denoted as OE_{perc}, refers to an enhanced awareness of BC sounds, such as one's own voice, chewing, or breathing [6]. Finally, these perceptions are typically evaluated as discomfort by individuals (phase "D" in Fig. 1), leading to the experienced OE, denoted as OE_{exp}. Combined with the attenuation of air-conducted (AC) sound above 1 kHz caused by the occlusion device, the OE is often experienced as one's voice sounding "louder", "resonant", "hollow", or "boomy" [13,14]. The OE_{exp} is a primary reasons why workers and musicians may avoid using earplugs [6,15–17] and is also a significant discomfort for users of earphones and hearing aids [18,19].

The OE_{obj} is usually measured using in-ear microphones both with and without the occlusion device under BC stimulation (e.g., Refs. [9,10,20]). The OE_{exp} can be assessed through BC audiometry tests by measuring hearing thresholds with and without the occlusion device (e.g., Refs. [9,10,21]). Both OE_{perc} and OE_{exp} can be evaluated using questionnaires and interviews (e.g., Refs. [8,14,17,18,22–25]). These evaluations often involve self-assessments of one's own voice, typically by reading sentences or pronouncing vowels, or listening tests with external voices [14,18,19]. For musicians, OE_{perc} can be gauged by how different their instrument sounds when wearing earplugs [17]. It is important to note that asking participants directly about the degree of perceived "occlusion" can be problematic, as this term is often misunderstood or confused with the high sound attenuation of conventional hearing protectors at mid-to-high frequencies [17] that can lead to the sensation of isolation from the external environment. Regarding the OE_{exp}, questions such as "When wearing these earplugs, are you annoyed by the sound of your own voice when speaking?" or "Are you annoyed by internal sounds, like chewing or breathing?" can provide valuable insights [8].

Deep-insertion can significantly reduce the OE_{obj} by covering a larger portion of the vibrating earcanal wall [26]. However, it is often associated with physical discomfort due to the mechanical pressure exerted on the bony part of the earcanal by the occlusion device [22,27]. Various active devices, including earplugs, hearing aids, and earbuds, have been developed to mitigate the OE_{obj} based on the principle of destructive interference [19,28]. In addition to mitigating the OE_{obj} at low frequencies, the hear-through function in active devices is also employed at medium frequencies to ensure that own voice experience remains as natural as possible [18,19]. More recently, inspired by passive metamaterials, the authors proposed modifying the acoustic impedance of the medial surface of *meta*-earplugs including Helmholtz resonators (HRs) to reduce the OE_{obj} [29,30]. Experiments using an artificial ear (detailed in Ref. [31]) have demonstrated that *meta*-earplugs can significantly reduce the OE_{obj}, achieving reductions of up to 20 dB below 500 Hz when compared to foam and silicone earplugs. However, it remains unknown whether this reduction in OE_{obj} would be replicated on human participants. Moreover, since few correlations between OE_{obj} and both OE_{perc} and OE_{exp} and mostly found with hearing aids [22,25,32], it is unknown whether the reduction of the OE_{obj} would be perceived (i.e., reduced OE_{perc}) and appreciated (i.e., reduced OE_{exp}) by earplug users. To the authors' knowledge, no study has evaluated the potential relationship between explanatory variables, including OE_{obj} and triad characteristics, and both OE_{exp} and OE_{exp}.

In this study, we evaluate OE_{obj}, OE_{perc}, and OE_{exp}, focusing on the ability of *meta*-earplugs to reduce these effects in a cohort of participants within a laboratory setting. The base configuration of the *meta*-earplug is specifically designed to fit the human outer ear and optimized to achieve a null OE_{obj} below 1.5 kHz. This optimization strategy aims to create an earplug that tends to be acoustically transparent with respect to low-frequency BC sounds [30], taking inspiration of active hearing aids [33,34], earplugs [28], and earbuds [19] that target zero OE_{obj}. A questionnaire is used to assess both OE_{perc} and OE_{exp}, aiming to determine whether *meta*-earplugs can reduce these effects and enhance acoustic comfort during earplug use. In our study, OE_{perc} is measured through the perception of low-frequency sound amplification, while OE_{exp} is assessed through the judgement of one's own voice naturalness. Additionally, we seek to correlate both OE_{perc} and OE_{exp} with explanatory variables such as OE_{obj}, sound attenuation, and triad characteristics to better understand the factors influencing the perception and the discomfort associated with the phenomenon, using linear mixed-effect models (LMMs).

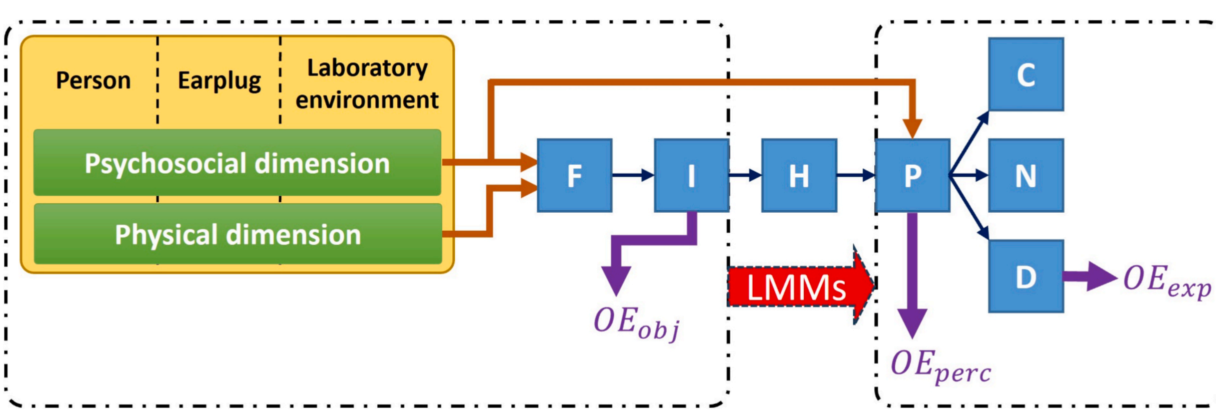

Fig. 1. Earplug comfort model adapted from Ref. [7]. Acronyms used in this figure: "Fitting/Positioning" phase (F), the "Interaction" phase (I), the "internal Human body effects" phase (H) and the "Perception" phase (P); Comfort (C), Discomfort (D) or feel Neutral (N). Linear mixed-effects models (LMMs) to quantify the relationship between subjective ratings and both participant characteristics and earplug's influence.

Overall, this paper aims to answer the following questions:

1. Does the *meta*-earplug effectively reduce the OE_{obj} measured on participants?
2. Is this reduction of the OE_{obj} perceived and preferred by participants?
3. Can OE_{perc} and OE_{exp} be explained by objective measurements and triad characteristics?

This paper is organized as follows: Section 2 outlines the experimental procedure, the design of the *meta*-earplug adapted to the human outer ear and the statistical post-processing methods. Section 3 presents the results of the objective measurements (i.e., sound attenuation and OE_{obj}), subjective evaluations of perceptions, and their statistical analyses. It also discusses the findings, limitations and future perspectives of the study. The conclusion is provided in Section 4.

2. Material and methods

2.1. Participant selection

Thirty-four participants were recruited through various means, including announcements within the laboratory, participation calls from the Acoustics Research Group in Montreal (GRAM in French), university bulletin board postings at ÉTS (École de Technologie Supérieure), and by word of mouth. Eligibility criteria required participants to have: (i) AC hearing thresholds of 20 dB hearing level (HL) or better across the frequency range of 125 Hz to 8 kHz; and (ii) no ear anomalies or history of ear surgeries, confirmed by otoscopic inspection. Hearing thresholds were measured using an Interacoustics AT 235 impedance audiometer (Interacoustics, Middelfart, Denmark) along with audiometric earphones TDH-39P (Telephonics, Farmingdale, NY). The experimenter, trained by a registered audiologist, conducted all evaluations. Prior to participation, individuals read the project information and signed a consent form, as approved by the ÉTS Research Ethics Committee (Certificate #H20231112).

2.2. Experimental setup

All measurements were conducted in a $3.6 \times 2.8 \times 2$ m^3 audiometric booth (Industrial Acoustics Company Inc., Naperville, IL) at the ICAR laboratory (ÉTS, Montreal, Canada), as shown in Fig. 2(a). The room was equipped with four decorrelated Klipsch™ speakers (Klipsch LLC., Indianapolis, IN), positioned in each corner. Participants were seated in a chair while wearing earplugs fitted with a probe tube connected to a dual microphone system to measure sound pressure levels both inside the earcanal and in the environment near the ear (see Fig. 2(b)). This method enables safe measurements for participants while minimizing the risk of uncontrolled acoustic leakage, which can occur when a microphone is positioned at the earplug/skin interface. A ¼ in. B&K (Brüel & Kjær, Nærum, Denmark) type 4961 multi-field microphone served as the reference for calibrating the dual microphone system in the audiometric booth. Both microphones and the speakers were interfaced with two NI PXI 4461 cards, housed in an NI PXI 1033 chassis located outside the booth and linked to the experimenter's computer for control and data processing.

2.3. Tested earplugs

Four earplugs were tested. (i) The *meta*-earplug in its base configuration (see Fig. 2(c) and Section 2.3.1). (ii) The *meta*-earplug with leakage to provide lower sound attenuation (see Section 2.3.2). (iii) The *meta*-earplug with a blocked entrance (i.e., filled with resin), which prevents it from reducing the OE_{obj}. (iv) A widely used commercial foam earplug (3 M™ E-A-R™ Classic regular, 3 M, Saint Paul, MN) serving as a reference for comparison (see Fig. 2(d)). Including three versions of the *meta*-earplug with identical geometry, mass, and external shape—but different acoustic properties for OE_{obj} and sound attenuation—helps minimize potential participant bias. The consistency in physical characteristics among the three versions of the *meta*-earplug prevents participants from associating specific geometries or designs with certain acoustic effects, especially in comparison with the commercial earplug, which differs significantly in shape, mass, and design. The *meta*-earplug samples were 3D printed using stereo-lithography (Form 2 printer, Formlabs®, MA) with Grey Pro V1 resin. Additionally, the *meta*-earplugs were paired with Comply® foam eartips (Oakdale, MN), available in three sizes (small, medium, and large) to ensure a proper fit within participants' earcanals. The following subsections provide detailed descriptions of the *meta*-earplug design and the acoustic leakage configuration.

2.3.1. Design of the meta-earplug

Fig. 3(a) illustrates the schematics of the *meta*-earplug, which consists of three HRs connected in series, as based on Ref. [30]. In this study, we found that three HRs were sufficient to cover the frequency range of interest up to 1.5 kHz. Unlike a single HR, which cannot achieve a near-

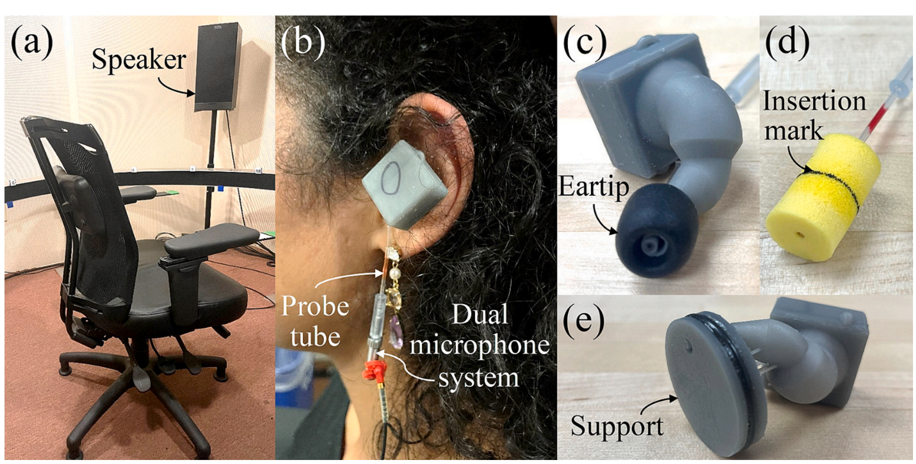

Fig. 2. (a) Audiometric booth with participant's chair and four decorrelated speakers (only one shown). (b) Participant wearing one of the three *meta*-earplugs, equipped with a probe tube connected to a dual microphone system for sound pressure level measurements. (c) Base configuration of the 3D printed *meta*-earplug including the Comply® foam eartip. (d) Commercial foam earplug from 3M™ (e) Meta-earplug with built-in support adapted to impedance tube measurement.

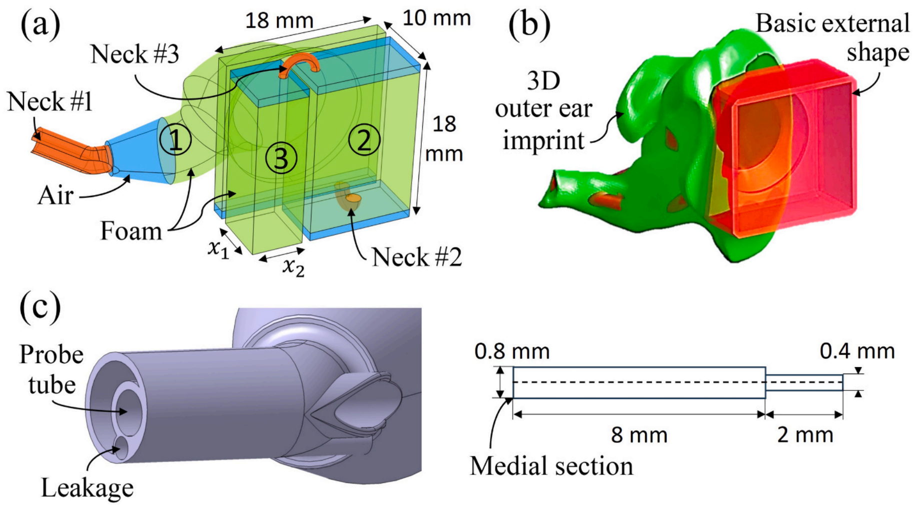

Fig. 3. (a) Geometry of the *meta*-earplug, featuring three HRs connected in series (numbers 1–3 identify the cavities of each HR that are partially filled with melamine foam). (b) Fitting of the geometry within an outer ear imprint, representing the small earcanal cluster [35]. (c) Acoustic leakage modeled as a narrow duct with varying cross-sections.

zero OE_{obj} across a broad range, multiple HRs provides additional degrees of freedom to more effectively shape the OE_{obj} curve [30]. Unlike the previous design, the current *meta*-earplug is tailored to fit a real human outer ear. To achieve this, the geometry of the *meta*-earplug was constructed using basic shapes—cylindrical, conical, and rectangular or square sections—that approximately fit into an imprint of a human outer ear (see Fig. 3(b)), representative of a cluster of "small" earcanals established in a study performed on 170 workers in Quebec [35]. The small earcanal cluster was chosen, rather than the medium or large [35], to ensure that the structure of the *meta*-earplug was compact enough to fit in all participants' ears.

In the proposed *meta*-earplug, each HR consists of a neck with a circular cross-section and a cavity. The cavities are almost completely filled by melamine foam, which lowers the acoustic resonant frequencies of the *meta*-earplug and further reduces the input impedance of its medial surface below the first resonance [30], with 1 mm of space left in front of the neck aperture to avoid damping the acoustic resonances. The total available volume for the HRs' cavities is 6.18 cm3, partially fitting in the concha. Two geometric parameters (x_1 and x_2, see Fig. 3(a)), defining the topology of the three resonators, as well as the radius ($r_{neck}^{[n]}$) and length ($l_{neck}^{[n]}$), $n \in [2,3]$, of the necks for resonators #2 and #3, were optimized. The rest of the geometry, including that of neck #1, remains fixed. Notably, the cross-section of HR1′s neck is shaped like a crescent to accommodate a probe tube for measuring sound pressure level in the earcanal (see Section 2.2).

Following the approach in Ref. [30], the optimization process uses a differential evolution algorithm [36]. The goal is to optimize the geometry of the *meta*-earplug to create an acoustically transparent device with respect to BC sound, specifically aiming for zero OE_{obj} from 100 Hz to 1.5 kHz. In the associated electro-acoustic (EA) model detailed in Appendix A, the OE_{obj} is defined as the difference in sound pressure level at the eardrum between occluded and open earcanal configurations and depends on the specific acoustic impedance $Z_{s,EP}$ of the meta-earplug's medial surface.

The transfer matrix method (TMM) is applied to calculate the specific acoustic impedance $Z_{s,EP}$ at the medial surface of the *meta*-earplug. Assuming normal incidence plane wave propagation, the transfer matrix **T** of the system describes the relationship between the acoustic pressure p and the normal velocity v, spanning from the entrance of the neck of HR#1 to the back of the cavity of HR#3, and is expressed as:

$$\mathbf{T} = \prod_{n=1}^{3} \mathbf{T}_{up}^{[n]} \mathbf{T}_{neck}^{[n]} \mathbf{T}_{down}^{[n]} \mathbf{T}_{cav,up}^{[n]} \mathbf{T}_{foam}^{[n]} \mathbf{T}_{cav,down}^{[n]} \tag{1}$$

where $[n]$ refers to the HR index.

$\mathbf{T}_{up}^{[n]}$ and $\mathbf{T}_{down}^{[n]}$ account for the continuity of acoustic pressure and volume flow as well as the effects of evanescent higher-order mode caused by the changes in the cross-section at both the entrance and the back of each neck. These matrices are defined as follows [37]:

$$\mathbf{T}_{up}^{[1]} = \begin{bmatrix} 1 & j\omega\rho_0 \frac{8r_{neck}^{[1]}}{3\pi}\left(1 - 1.25\frac{S_{neck}^{[1]}}{S_{EC}}\right) \\ 0 & S_{neck}^{[1]}/S_{EC} \end{bmatrix} \text{ and } \mathbf{T}_{up}^{[n]} = \begin{bmatrix} 1 & j\omega\rho_0 \frac{8r_{neck}^{[n]}}{3\pi}\left(1 - 1.25\frac{S_{neck}^{[n]}}{S_{cav}^{[n-1]}}\right) \\ 0 & S_{neck}^{[n]}/S_{cav}^{[n-1]} \end{bmatrix} \mathit{for}\, n \in [2,\ 3], \tag{2}$$

$$\mathbf{T}_{down}^{[n]} = \begin{bmatrix} 1 & j\omega\rho_0 \frac{8r_{neck}^{[n]}}{3\pi}\left(\frac{S_{cav}^{[n]}}{S_{neck}^{[n]}} - 1.25\right) \\ 0 & S_{cav}^{[n]}/S_{neck}^{[n]} \end{bmatrix} \text{for}\, n \in [1,3] \tag{3}$$

where $S_{neck}^{[n]} = \pi\left(r_{neck}^{[n]}\right)^2$ and $S_{cav}^{[n]} = e_{cav}^{[n]} h_{cav}^{[n]}$ are cross-section areas of necks and cavities, and j is the imaginary number.

For constant cross-sections, the transfer matrices of the necks, cavities and foam layers (respectively referred to as $\mathbf{T}_{neck}^{[n]}$, $\mathbf{T}_{cav,up}^{[n]}$, $\mathbf{T}_{cav,down}^{[n]}$ and $\mathbf{T}_{foam}^{[n]}$) are defined by:

$$\mathbf{T}_i^{[n]} = \begin{bmatrix} \cos\left(k_{eq,i}^{[n]} l_i^{[n]}\right) & jZ_{eq,i}^{[n]} \sin\left(k_{eq,i}^{[n]} l_i^{[n]}\right) \\ \frac{-1}{jZ_{eq,i}^{[n]}} \sin\left(k_{eq,i}^{[n]} l_i^{[n]}\right) & \cos\left(k_{eq,i}^{[n]} l_i^{[n]}\right) \end{bmatrix}, \tag{4}$$

For conical sections, the transfer matrices are defined as follows [38]:

$$\mathbf{T}_i^{[n]} = \begin{bmatrix} \left(cos\left(k_{eq,i}^{[n]} l_i^{[n]}\right) - \frac{1}{k_{eq,i}^{[n]}\left(l_i^{[n]} L_i^{[n]}\right)} sin\left(k_{eq,i}^{[n]} l_i^{[n]}\right)\right)\sqrt{\frac{S_f}{S_i}} & \frac{jZ_{eq,i}^{[n]}}{\sqrt{S_i S_f}} sin\left(k_{eq,i}^{[n]} l_i^{[n]}\right) S_f \\ \frac{j\sqrt{S_i S_f}}{Z_{eq,i}^{[n]}} sin\left(k_{eq,i}^{[n]} l_i^{[n]}\right) & cos\left(k_{eq,i}^{[n]} l_i^{[n]}\right) \end{bmatrix}, \tag{5}$$

where $i \in \{neck; cavity; foam\}$, $l_i^{[n]}$ represents the length of the necks, the cavity sections without foam, or the foam layers, while $Z_{eq,i}^{[n]}$ and $k_{eq,i}^{[n]}$ denote the equivalent characteristic impedance and wavenumber, respectively, accounting for visco-thermal effects. For the neck and cavity sections, $Z_{eq,i}^{[n]}$ and $k_{eq,i}^{[n]}$ are determined using a low reduced frequency model [39]. In the case of foam layers, $Z_{eq,foam}$ and $k_{eq,foam}$ are computed using the Johnson-Champoux-Allard equivalent fluid model [40]. The macroscopic properties of the melamine foam are provided in Table I of Ref. [30].

Finally, the input impedance $Z_{s,EP}$ of the *meta*-earplug is derived from the system's transfer matrix $\mathbf{T}$ (see Eq. (1)) as follows:

$$Z_{s,EP} = \frac{T_{11}}{T_{21}} \tag{6}$$

Following the approach used in Ref. [30], a numerical model of the *meta*-earplug was developed using the finite element (FE) method in COMSOL Multiphysics 6.1 (Burlington, MA) to verify the theoretical predictions of the meta-earplug's medial surface acoustic properties. Additionally, impedance tube measurement was conducted to experimentally confirm the acoustic impedance of the 3D printed *meta*-earplug. To facilitate this measurement, the *meta*-earplug was designed with a built-in support (see Fig. 2(e)) that fits into a 29 mm inner diameter impedance tube, manufactured by Mecanum (Sherbrooke, Canada).

2.3.2. Design of the acoustic leakage

As previously mentioned, the presence of HRs increases the sound attenuation of *meta*-earplugs, as demonstrated in prior studies [29,30]. However, increasing the attenuation of the AC pathway can further modify the balance of one's own voice experience. This balance typically depends on the relative contributions of AC and BC pathways when the earcanal is open [41]. To investigate how this AC-BC balance, represented by NR and OE_{obj}, influences users' acoustic perception, an acoustic leakage was introduced in one configuration of the *meta*-earplug. This design modification aims to approximate the sound attenuation profile of conventional earplugs. In addition to the base configuration of the *meta*-earplug, which reduces the OE_{obj} while increasing the noise reduction (NR), this configuration with leakage—designed to reduce the OE_{obj} without increasing the NR compared to conventional earplugs—is essential for isolating the effects of OE_{obj} or NR, if any, on acoustic perception (OE_{perc}) and comfort (OE_{exp}).

The acoustic leakage, depicted in Fig. 3(c), consists of a small duct with a length $l_{leak} = 10$ mm length and a radius r_{leak} that tapers from 0.2 mm to 0.4 mm at the *meta*-earplug medial surface. To estimate the sound attenuation provided by the *meta*-earplug including the acoustic leakage (with visco-thermal losses), we developed an analytical model of the NR provided by the acoustic leakage, assuming that most of the acoustic energy would pass through the leakage. The NR was calculated as the difference between the sound pressure levels outside and inside the earcanal:

$$NR = L_{p,out} - L_{p,in} = 20\log_{10}\left(\left|\frac{p_{out}}{p_{in}}\right|\right). \tag{7}$$

On the outside, the acoustic pressure near the earcanal entrance is assumed to be $p_{out} = 2P_0$, where P_0 is the amplitude of the incident plane wave. On the inside, the acoustic pressure at the medial surface can be computed using wavefield decomposition theory, following the approach outlined in Eq. (3) of Ref. [42], which describes the acoustic pressure in a straight, cylindrical, occluded earcanal, such that:

$$p_{in} = \frac{\tau_{EP} P_0 \left(e^{-jk_{eq}^{EC} l_{ID}} + R_{TM} e^{-2jk_{eq}^{EC} l_{EC}} e^{jk_{eq}^{EC} l_{ID}}\right)}{1 - R_{EP} R_{TM} e^{-2jk_{eq}^{EC}(l_{EC} - l_{ID})}}. \tag{8}$$

In Eq. (8), $l_{EC} = 24$ mm represents the earcanal length, matching that of the acoustical test fixture (ATF) G.R.A.S. 45CB (G.R.A.S. Sound and Vibration SA, Holte, Denmark), which was used during the experimental evaluation of the leakage design. l_{ID} refers to the earplug insertion depth, τ_{EP} denotes the transmission coefficient of the acoustic leakage in a semi-infinite space calculated using the TMM approach (e.g., see Section 2.3.1), R_{EP} is the reflection coefficient of the meta-earplug's medial surface, R_{TM} is the reflection coefficient of the coupler mimicking the eardrum in the ATF [43], and k_{eq}^{EC} is the equivalent wavenumber accounting for visco-thermal effects in the earcanal using a low reduced frequency model [39]. It will be shown that for small enough leakage, the acoustic impedance of the meta-earplug's medial surface remains relatively unchanged (see Section 3.1.1). Measurement of the NR of the *meta*-earplug with leakage was performed in the experimental setup detailed in Section 2.2.

2.4. Measurement procedure

At the beginning of the experiment, each participant was introduced to the study's subject matter. To experience the OE firsthand, participants were asked to either wear a commercial earmuff (3 M™ PELTOR™ Optime™ 98) while speaking or use their fingers to occlude their earcanals, noting the changes in the experience of their own voice and their perception of the amplification of low frequencies. They spent approximately 5 min familiarizing themselves with the phenomenon as well as the questionnaire used for the subjective evaluation (see Section 2.5). During this time, the appropriate eartip size (e.g., small, medium or large) was selected for the participant's ears to ensure both comfort and a minimum of 10 dB NR, which was tested later.

For each earplug, the measurement procedure was as follows:

1. The experimenter fitted a randomly selected pair of earplugs in the participant's ears. The random selection of earplug pairs minimized the risk of order bias in the study. All earplugs were inserted approximately 10 mm into the cartilaginous portion of the earcanal by the experimenter. This insertion depth is typical for earplug users, generally reducing the risk of mechanical discomfort compared to

deeper insertions [22,27], though it generates more OE_{obj} [9]. For *meta*-earplugs, this insertion depth corresponds to the length of the eartip. For the foam earplugs, an insertion mark was drawn on each sample to assist with consistent insertion (see Fig. 2(d)). To prevent influencing participants during the subjective evaluations, the earplugs being tested were not shown to the participants, and both insertion and removal of the earplugs were carried out by the experimenter.

2. An objective sound attenuation measurement using NR indicator defined by Eq. (7) was conducted. During this measurement, the participant remained still and silent while white noise at 90 dB(A) in the frequency range of interest (10 Hz to 10 kHz) was generated by the speakers in the audiometric booth.
3. Next, a measurement of the OE_{obj} was performed. The participant was asked to read a predefined text at a normal vocal effort, simulating regular speech. The difference between the sound pressure levels measured inside and outside the earcanal provided the NR-based OE_{obj} indicator [10]:

$$OE_{obj} = L_{p,in} - L_{p,out}, \tag{9}$$

4. The participant was then asked to provide ratings on different items related to their acoustic perceptions (see Section 2.5).

The process was repeated for all four pairs of earplugs. Participants were asked to focus on their acoustic perceptions to compare each pair with the next. They had the option to request a retest of any pair, in which case objective measurements were conducted again. At the end, participants ranked the four pairs of earplugs based on their speaking experience. A discussion followed between the participant and the experimenter, during which overall impressions were shared, and the experimenter collected feedback on the participant's experience.

2.5. Questionnaire and measured variables

To investigate the perception (OE_{perc}) and discomfort (OE_{exp}) of the OE, particularly during speech production, participants were asked three specific questions. To evaluate OE_{perc}, we avoided using the term "occlusion effect," as it is unfamiliar to most people. Instead, we asked to rate their perception of low-frequency sound amplification during speech on a 7-point Likert scale, ranging from 1 = "no amplification" to 7 = "strong amplification". For OE_{exp}, given that the OE induces voice distortion, which can negatively affect the acoustic comfort of earplug users, we asked participants to rate how natural or different their own voice sounded while wearing each earplug pair. Voice naturalness was also rated on a 7-point Likert scale, from 1 = "very natural" to 7 = "very different". Finally, participants ranked the four earplug pairs (from 1 = "the best" to 4 = "the worst") based on their preference for speaking with them.

As the study was conducted in French, the questions are translated as follows:

- Item 1: To what extent do you perceive an amplification of low-pitched sound when you speak?
- Item 2: To what extent do you experience your voice as being natural?
- Item 3: How would you rank the four earplug pairs in order of preference?

As the study aims to identify variables that could explain differences in low-frequency amplification, voice naturalness, and earplug preference, several characteristics from the triad were collected. For physical characteristics of the person, we assessed the participant's sex at birth and the AC hearing thresholds from 250 Hz to 8 kHz, averaged between the right and left ears. For psychosocial characteristics of the person, participants were asked about their age, their familiarity with the experimenter (Yes/No) to control for potential bias, and their earplug usage habits in professional or recreational activities (Yes/No). For the earplug characteristics, we assessed only the size of the eartip, which is part of the earplug rather than the person, even though it was adapted to the size of each participant's earcanal. In addition, the earplug's influence was evaluated through its interaction with the individual in the laboratory environment, as measured by NR^{freq} and OE_{obj}^{freq} values across octave band frequencies (referred to as *freq*) from 125 Hz to 8 kHz, averaged for the right and left ears. Table 1 summarizes all relevant characteristics from the triad and the interactions between the person, earplug and environment.

2.6. Statistical postprocessing

Descriptive statistics were first conducted using StatGraphics 19 (Statgraphics Technologies, Inc., The Plains, VA) to examine population characteristics and responses to the questionnaire items. Custom Matlab (MATLAB 2023a, MathWorks, Inc., Natick, MA) routines were developed to generate visualizations for the 3 items (i.e., low-frequency amplification, voice naturalness, and preference order), including boxplots and distribution plots.

Then, LMMs were developed using the R programming language [44] to quantify the relationship between subjective ratings and both participant characteristics and earplug's influence, represented by OE_{obj} and NR measurements (see Fig. 1), for the first 2 items: low-frequency amplification and voice naturalness. LMMs include both fixed effects, which are consistent across all participants, and random effects, which account for variations within participants. LMMs can be described as follows [45]:

$$y_{ij} = \boldsymbol{X}_{ij}^{T}\boldsymbol{\beta} + u_j + \epsilon_{ij}, \tag{10}$$

where y_{ij} is the response variable (scalar) for the i-th observation within the j-th participant. $\boldsymbol{X}_{ij}^{T}\beta$ represents the fixed effects, where $\boldsymbol{X}_{ij}^{T}$ is a $1 \times p$ row vector of the p predictor values (i.e., objective measurements and participant characteristics), and $\boldsymbol{\beta}$ is a $p \times 1$ vector of fixed-effect coefficients. The random effect u_j represents the variation in the intercept across participants and captures individual differences that cannot be explained by the fixed effects. The term ϵ_{ij} is a scalar representing the

Table 1
Collected characteristics from the triad, as well as from the interaction among the earplug, person, and laboratory environment.

	Characteristic name	Variable name	Variable type
Physical characteristics of the person	–Sex at birth	*Sex*	Categorical: Male; Female; Other
	–AC hearing thresholds from *freq* = 250 Hz to 8 kHz	AC^{freq}	Continuous: dB (HL)
Psychosocial characteristics of the person	–Age	*Age*	Continuous: Years
	–Earplug usage habits in professional or recreational activities	$Earplug_{usage}$	Dichotomous: Yes/No
	–Participant knows the experimenter	*Familiarity*	Dichotomous: Yes/No
Physical characteristic of the earplug	–Eartip size	$Eartip_{size}$	Categorical: Small, Medium, Large
Person-environment-earplug interaction characteristics	–NR across octave band frequencies from *freq* = 125 Hz to 8 kHz	NR^{freq}	Continuous: dB
	–OE across octave band frequencies from *freq* = 125 Hz to 8 kHz	OE_{obj}^{freq}	Continuous: dB

residual error terms and capturing the variation in the response variable y_{ij} that is not explained by the predictor variables (fixed effects) or the random intercepts.

Before fitting the LMMs, all variables from Table I were normalized using z-transformation, preventing variables with larger scales from exerting disproportionate influence on the model and ensuring that the model's coefficients are comparable across different variables [46]. Then, for each item, repeated measures correlations [47], denoted rm_{corr}, were computed between the item ratings and the continuous variables representing the objective measurements (i.e., octave bands OE_{obj} and NR, as well as AC hearing thresholds) to pre-select potential predictors. Variables with statistically significant correlations ($p < 0.05$) were subsequently assessed for multicollinearity by calculating the Variance Inflation Factor (VIF) using a linear model. When high VIF values (with a threshold of 10) were detected, the variable with the strongest correlation with the item was retained, while others were discarded to prevent multicollinearity from affecting the LMMs.

Interaction terms between the retained continuous variables and participant characteristics (both physical and psychosocial) were then constructed. All possible combinations of fixed effects were systematically explored in the LMM, resulting in 2^n potential models, where n is the total number of predictors. The candidate models were fitted using Maximum Likelihood (ML) estimation, which allows for unbiased comparison of models with different fixed effects structures by maximizing the likelihood L of the observed data given all parameters, in contrast to Restricted Maximum Likelihood (REML) [48]. Model selection was based on the lowest Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) values. AIC and BIC assess model goodness-of-fit while penalizing model complexity. AIC tends to favor more complex models that may better fit the data, whereas BIC applies a stronger penalty for additional parameters, encouraging the selection of simpler models [49]. AIC and BIC are computed using the following formulas:

$$AIC = 2k - 2\ln(L), \tag{11}$$

$$BIC = \ln(n)k - 2\ln(L), \tag{12}$$

where $n = 136$ is the number of observations in the dataset, k is the number of estimated parameters in the model, and L is the maximized value of the likelihood function of the model.

3. Results

3.1. Objective measurements

3.1.1. Objective occlusion effect

We first examine the frequency-dependent NR-based OE_{obj} induced by three versions of the *meta*-earplug (base configuration (A), with leakage (B), and closed (C)), compared to a foam earplug (D), as shown in octave bands in Fig. 4(a). As detailed in Section 2, measurements were conducted on 34 participants, with each earplug inserted to an approximate depth of 10 mm from the earcanal entrance. Participants were asked to read a predefined text at a normal vocal effort, simulating regular speech, to induce OE_{obj}. For each participant, measurements were averaged across the right and left ears. The vertical-colored lines indicate the acoustic resonant frequencies of *meta*-earplug (A). As a complement to Fig. 4(a), Fig. 7(a) in Appendix B presents the statistically significant differences in OE_{obj} octave band measurements across each pair of earplugs. Notably, these differences in OE_{obj} arise from internal microphone measurements (i.e., within the earcanal), while the sound pressure levels recorded at the external microphone (i.e., in the surrounding environment) exhibit no statistically significant differences across all earplugs in any octave band. This suggests that participants maintained consistent speech across the tested earplugs.

According to Fig. 4(a), *meta*-earplugs (A) and (B) induce a similar OE_{obj} across the entire frequency range (i.e., 125 Hz–8 kHz), with statistically significant differences observed only in the 2 kHz octave frequency band (see Fig. 7(a) in Appendix B). In addition, the OE_{obj} induced by *meta*-earplugs (A) and (B) is significantly lower than the OE_{obj} induced by earplugs (C) and (D) below 1 kHz, with reduction reaching up to 15–20 dB around 250 Hz. This reduction aligns with the predicted OE_{obj} resulting from the optimization process (see Appendix C). In previous work, the ability of *meta*-earplugs incorporating HRs to reduce the OE_{obj} was demonstrated using a dedicated artificial ear tester [29,30]. The present study extends this demonstration to human participants. Regarding the closed *meta*-earplugs (C) and the foam earplug (D), they exhibit similar OE_{obj}, with a statistically significant 4 dB difference observed only in the 250 Hz octave frequency band, despite differences in design and material properties (see Fig. 7(a) in Appendix B). This finding is consistent with previous studies showing that very different commercial earplugs produce a similar OE_{obj} when inserted to the same depth, both in human participants [20] and on the dedicated artificial ear tester [31]. For example, differences in earplugs Poisson's

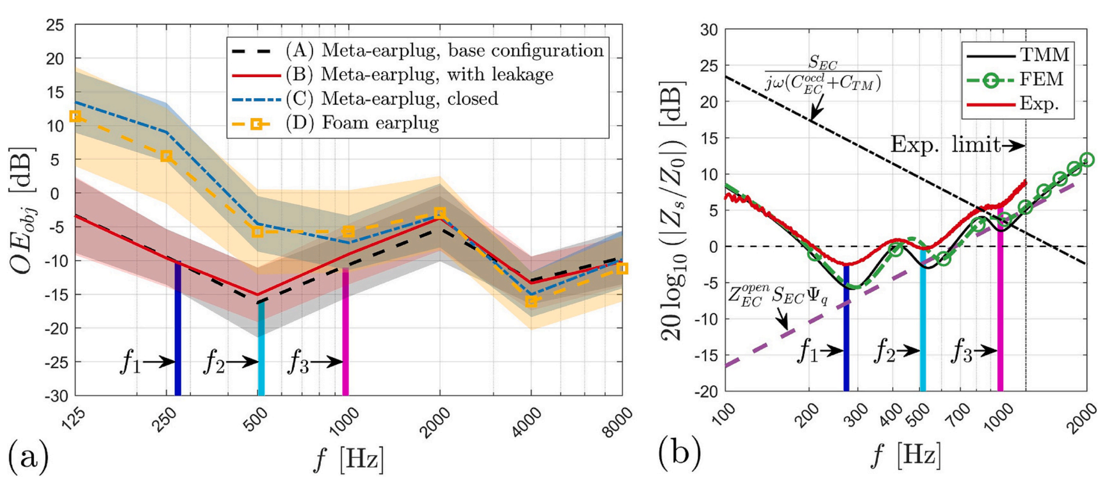

Fig. 4. (a) Experimental NR-based OE_{obj} (mean ± standard deviation, octave bands) induced by three versions of the *meta*-earplug (base configuration, with leakage, and closed) compared to a foam earplug, all inserted approximately 10 mm from the earcanal entrance. Vertical-colored lines indicate the resonant frequencies of the *meta*-earplug in the base configuration, specifically $f_1 = 273$ Hz, $f_2 = 515$ Hz and $f_3 = 976$ Hz. (b) Magnitude in dB (narrow bands) of the normalized input impedance of the *meta*-earplug medial surface (base configuration) calculated analytically (TMM), numerically (FEM), and measured experimentally using an impedance tube method [51].

ratio can influence the OE they induce but only by few dBs [50].

Fig. 4(b) displays the acoustic impedance of the medial surface of *meta*-earplug (A) that supports the reduction of the OE_{obj}. Specifically, it presents the magnitude of the normalized specific acoustic impedance (i.e., pressure to normal velocity) calculated (i) analytically using the TMM approach, (ii) numerically using the FE method, and (iii) experimentally measured using a classical impedance tube (see Section 2.3.1). According to Fig. 4(b), the analytical and numerical results are in good agreement (differences lower than 1.5 dB), verifying the accuracy of the TMM approach. In addition, the experimental measurement aligns with the models, although some discrepancies (up to 3 dB around 125 Hz) are observed. These discrepancies are likely due to geometric inaccuracies introduced by the 3D printing process and foam cutting, given the system's complex geometry. For comparison, Fig. 4(b) also shows the specific acoustic impedance $1/j\omega(C_{EC}^{occl}+C_{TM})$ of the residual occluded earcanal coupled to the eardrum, as computed using the EA model of the OE_{obj} (see Appendix A). We can see that the acoustic impedance at the medial surface of the *meta*-earplug (A) is significantly lower than that of the residual volume of the occluded earcanal, thereby driving the reduction in the OE_{obj}. The following paragraph details how this reduction in acoustic impedance is achieved using HRs.

According to Fig. 4(b), below the first resonance f_1, the acoustic impedance of the *meta*-earplug (A) is governed by the compliance effect of the cavities filled with melamine foam and decreases with frequency by −40 dB/decade. Since the optimization process was designed to achieve a zero OE_{obj} (see Appendix C), the successive resonances of the HRs help to maintain the acoustic impedance of the meta-earplug's medial surface close to the acoustic impedance Z_{EC}^{open} of the open earcanal (governed by its inertia effect, +40 dB/decade) weighted by the volume velocity ratio Ψ_q between open and occluded cases, that accounts for the effect of the insertion depth [30] (more details are given in Appendix A). It is important to note that the acoustic impedance of *meta*-earplug (B) is not significantly affected by the acoustic leakage compared to *meta*-earplug (A), due to the small size of the leakage (see Fig. 8(b) in Appendix C).

Below the first acoustic resonance of *meta*-earplugs (A) and (B) that occurs around 250 Hz (see Fig. 4(b)), the reduction of the OE_{obj} is primarily governed by the equivalent acoustic compliance $C_{eq} = V_{cav}/\left[\Re\left(\rho_{eq,foam}c_{eq,foam}^2\right)\right]$ of the cavities of volume V_{cav} filled with melamine foam and can be calculated as follows from Eq. (14) in Appendix A:

$$\Delta_{OE} = -20\log_{10}\left(\left|1+\frac{C_{eq}}{C_{EC}+C_{TM}}\right|\right), \tag{13}$$

where C_{EC} and C_{TM} are the acoustic compliances of the earcanal and the eardrum/middle-ear at low-frequencies, respectively. In *meta*-earplugs (A) and (B), C_{eq} is 11 times larger than C_{EC}, resulting in a reduction of the OE_{obj} by approximately 17 dB below the first resonance f_1 (see Fig. 4(a)). To achieve this level of compliance, the total volume of *meta*-earplugs (A) and (B) is not 11 times larger than that of the earcanal, but only 8 times larger, due to the use of melamine foam, which fills the cavities and increases the acoustic compliance of a given volume. One might seek to reduce the total volume of the *meta*-earplug, particularly for aesthetic reasons. As shown in Eq. (13), the reduction in the OE_{obj} does not decrease linearly with each halving of the meta-earplug's volume (accounted for in the equivalent acoustic compliance C_{eq}). Nonetheless, in the present configuration, the reduction typically diminishes by approximately 4 dB for every halving of the meta-earplug's volume. To achieve a more compact design without compromising OE_{obj} performance, a possible approach would be to replace the melamine foam with a material offering greater compliance for the same volume—an avenue to be explored in future work.

3.1.2. Sound attenuation

We now investigate the frequency-dependent NR induced by the three versions of the *meta*-earplug (base configuration (A), with leakage (B), and closed (C)), compared to a foam earplug (D), as shown in octave bands in Fig. 5(a). The acoustic excitation consisted of white noise at 90 dB(A) in the frequency range of interest (10 Hz to 10 kHz), generated by speakers in the audiometric booth. Again, measurements were averaged across the right and left ears for each of the 34 participants. The vertical-colored lines indicate the acoustic resonant frequencies of the *meta*-earplug in the base configuration. As a complement to Fig. 5(a), Fig. 7(b) in Appendix B presents the statistically significant differences in objective OE octave band measurements across each pair of earplugs.

According to Fig. 5(a), the *meta*-earplug in the base configuration (A) provides significantly higher NR compared to the closed *meta*-earplug (C) and the foam earplug (D) at frequencies below 1 kHz, with an average increase of approximately 10 dB and up to 15 dB around 250 Hz. This increase in NR provided by the *meta*-earplug (A) occurs within the frequency range of its acoustic resonances, f_1, f_2 and f_3, which lower the acoustic impedance of its medial surface compared to earplugs (C) and (D). At frequencies below 1 kHz, sound attenuation in conventional earplugs is typically decreased by acoustic reflections in the occluded

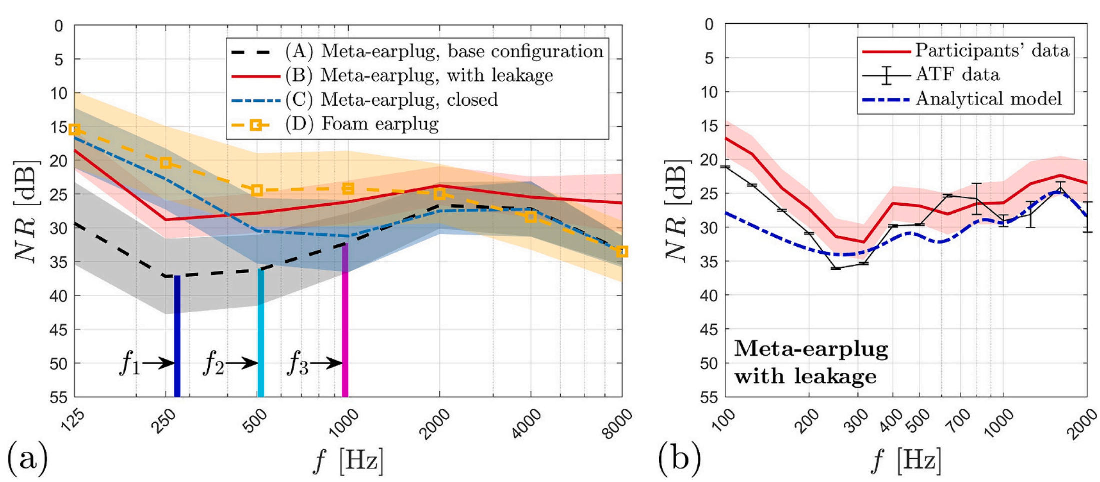

Fig. 5. (a) Experimental NR (mean ± standard deviation, octave bands) induced by three versions of the *meta*-earplug (base configuration, with leakage, and closed) compared to a foam earplug, all inserted approximately 10 mm from the earcanal entrance. Vertical-colored lines indicate the resonant frequencies of the *meta*-earplug (for both the base configuration and with leakage), specifically $f_1 = 273$ Hz, $f_2 = 515$ Hz and $f_3 = 976$ Hz. (b) NR of the *meta*-earplug with leakage, measured on participants and on ATF, and simulated using the analytical model from ref. [42].

earcanal, where the medial surface acts as an acoustically rigid surface [42]. However, in configuration (A), the lower acoustic impedance of the medial surface results in less energy being reflected back into the earcanal cavity [30], thereby reducing the sound pressure level in the occluded earcanal and increasing the NR. This effect has been used in semi-insert hearing protectors to increase low-frequency sound attenuation [52].

As described in Section 2.3.2, to counterbalance the increase in NR provided by the HRs, a small tube was incorporated into the *meta*-earplug (B), acting as an acoustic leakage which allows sound from the surrounding environment to enter the earcanal cavity, thereby reducing the NR. Since preliminary tests performed on a single human subject showed that the NR of the *meta*-earplug (A) could reach up to 45 dB at low frequencies (as shown in Fig. 5(a)), we aimed for a NR lower than approximately 30 dB for the *meta*-earplug (B) to get closer to conventional earplugs. For this purpose, we developed an analytical model of the NR provided by the acoustic leakage based on the assumption that most of the acoustic energy would flow through the leakage (see Section 2.3.2). Then, we adjusted the size of the leakage to obtain the targeted NR.

Fig. 5(b) displays the NR of the *meta*-earplug (B) simulated using the analytical model and measured on both ATF and participants. Aside from a deviation around 100 Hz, model and measurements align closely across the frequency range of interest, despite the model's assumption and the differences between the ATF and human participants. This consistency is primarily due to the dominant role of the air-conduction pathway in determining the NR of the *meta*-earplug with leakage, with minimal influence from the mechanical behavior of the system. According to Fig. 5(a), the acoustic leakage decreases the NR of the *meta*-earplug (B) by approximately 10 dB compared to *meta*-earplug (A) below 1 kHz. As a result, the NR provided by *meta*-earplug (B) become closer to earplugs (C) and (D), except around 250 Hz, where the NR of *meta*-earplug (B) remains, on average, 8 dB higher than that of earplugs (C) and (D), due to the acoustic resonance f_1 of the *meta*-earplug. Hence, *meta*-earplug (B) significantly reduces the OE_{obj} compared to earplugs (C) and (D) while achieving a NR comparable to both. However, "comparable" does not imply "equal", as statistically significant differences in NR are observed between *meta*-earplug (B) and earplugs (C) and (D) in specific octave frequency bands (see Fig. 7(b) in Appendix B).

3.2. Subjective evaluations

3.2.1. Triad characteristics

We begin by summarizing the characteristics of the triad evaluated in this study. A total of 34 participants were recruited for this study, consisting of 20 males (59 %) and 14 females (41 %). The average age was 29.7 ± 5.2 years. Of the participants, 9 out of 34 (26 %) did not know the experimenter, enabling control for any bias arising from familiarity. Additionally, 12 participants (35 %) did not regularly use earplugs. Only 3 participants reported using earplugs at work, while the remaining used them for recreational activities. In terms of eartip sizes, 15 participants (44 %) used small tips, 15 (44 %) used medium tips, and 4 (12 %) used large tips. Due to the low number of large eartip users, they were grouped with the medium size category for analysis.

3.2.2. Descriptive analyses

We now examine the subjective ratings of the four tested earplug pairs in terms of low-frequency sound amplification (i.e., OE_{perc}), voice naturalness (i.e., OE_{exp}) and earplugs preference. For this purpose, Fig. 6 displays the corresponding boxplots that allow for a visual comparison of the rating distributions across the earplugs for these 3 items. Each boxplot shows the median, mean, first and third quartiles, whiskers, and potential outliers for each earplug pair, providing a clear overview of the central tendency and variability in ratings. For additional details, Fig. 9 in Appendix D displays the frequency distributions of the raw ratings from which the boxplots were generated. Since the subjective ratings did

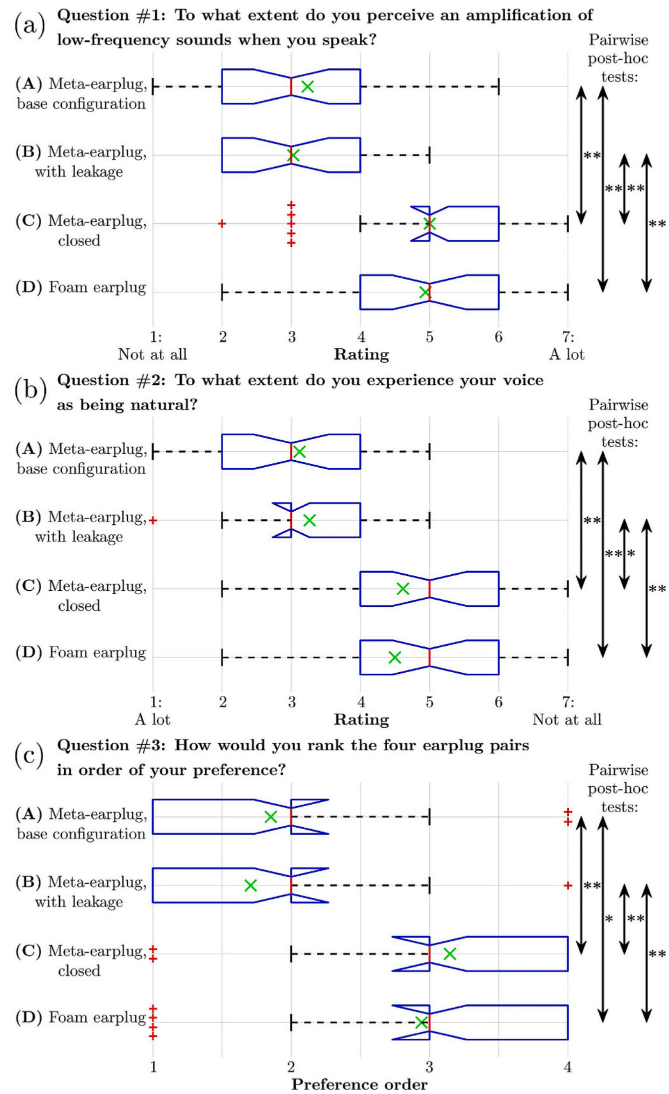

Fig. 6. Boxplots representing rating distributions for the 4 earplugs regarding (a) low-frequency sound amplification (i.e., OE_{perc}), (b) voice naturalness (i.e., OE_{exp}) and (c) earplug preference order. Each boxplot shows the mean "**x**", median "|", interquartile range (IQR, blue box), and potential outliers "+". The blue boxes span from the first (left end) to the third (right end) quartile (Q_1 to Q_3), with $Q_3 - Q_1$ defining the IQR. An inverted box shape may appear when the median coincides with either the first or third quartile. Dotted horizontal lines indicate the whiskers, representing the most extreme data points within 1.5 times the IQR. Results of pairwise comparisons using Wilcoxon signed-rank tests are also displayed. A single "*" denotes a significant pairwise post-hoc test at the 0.001 level, while a double "**" indicates significance at the 0.0001 level. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

not meet the normality assumption required for ANOVA repeated measures, the non-parametric Friedman test was employed. The Friedman test revealed overall significant differences between the earplugs in the rating distributions of low-frequency sound amplification ($p = 1.1 \times 10^{-10}$), voice naturalness ($p = 7.8 \times 10^{-8}$) and earplugs preference ($p = 4.8 \times 10^{-8}$). For all 3 items, pairwise comparisons using Wilcoxon signed-rank tests highlight significant differences between *meta*-earplugs (A)-(B) (forming a homogeneous group) and earplugs (C)-(D) (forming another homogeneous group), as shown in Fig. 6. This distinct clustering underscores that *meta*-earplugs (A) and (B) provide a noticeably different experience in terms of perceived sound amplification, voice naturalness judgement, and overall preference compared to conventional earplugs (C) and (D), suggesting that design differences lead to perceptually distinct user experiences.

According to Fig. 6(a), the median low-frequency amplification rating for *meta*-earplugs (A) and (B) is 3, which is 2 points lower than for earplugs (C) and (D) on the 7-point Likert scale, where 1 corresponds to “no amplification” and 7 corresponds to “a lot of amplification.” This indicates that *meta*-earplugs (A) and (B) generally induce less low-frequency sound amplification compared to earplugs (C) and (D). Similarly, the median voice naturalness ratings (see Fig. 6(b)) are 3 for *meta*-earplugs (A) and (B), compared to 5 for earplugs (C) and (D), where 1 corresponds to a “very natural voice” and 7 corresponds to a “very unnatural voice.” Thus, *meta*-earplugs (A) and (B) generally provide a more natural voice experience compared to earplugs (C) and (D). Finally, as shown in Fig. 6(c), the median rank for earplug preference is 2 for *meta*-earplugs (A) and (B) and 3 for earplugs (C) and (D). According to Fig. 9(c) in Appendix D, approximately 85 % of the participants ranked either *meta*-earplug (A) or (B) as their preferred choice.

As shown in Fig. 6, there are several outliers, particularly in Fig. 6c regarding the low-frequency amplification induced by the closed *meta*-earplug (C). The individual data for the corresponding participants were reviewed to check for any issues during the measurements, but no specific problems were identified. Therefore, the outlier data were retained in the study, as there is no justification for excluding them. These data will be included in the linear mixed models (LMM), contributing to the objectification of the subjective ratings with objective measurements and participant characteristics for the 3 items (i.e., low-frequency amplification, voice naturalness, and preference order). These 3 items are significantly correlated, with repeated measures correlation scores [47] of 0.85 between low-frequency amplification and voice naturalness, 0.85 between low-frequency amplification and preference order and 0.89 between voice naturalness and preference order. In the next section, we will explore in detail the relationship between explanatory variables and both low-frequency sound amplification and voice naturalness using LMMs.

Table 2
Relationship between OE_{perc} (here the perceived low-frequency sound amplification) and the predictors using LMMs minimizing (a) BIC and (b) AIC values. For the variable *Sex*, “male” is coded as 0 and “female” as 1. For $Eartip_{size}$, “small” is coded as 0 and “medium/large” as 1.

(a)		
Fixed effects	Estimate (β coeff.) $\pm$ SD	p
(Intercept)	4.05 ± 0.14	$< 2 \times 10^{-16}$
OE_{obj}^{125}	1.01 ± 0.1	$< 2 \times 10^{-16}$
Variance	(Intercept): 0.43 ± 0.65 Residual: 1.1 ± 1.05	
R^2	Marginal: $R_m^2 = 0.40$ Conditional: $R_c^2 = 0.57$	

(b)		
Fixed effects	Estimate (β coeff.) $\pm$ SD	p
(Intercept)	3.95 ± 0.1	$< 2 \times 10^{-16}$
OE_{obj}^{125}	0.9 ± 0.1	2.9×10^{-16}
OE_{obj}^{4000}	-0.35 ± 0.1	0.003
OE_{obj}^{4000} : *Sex*	0.29 ± 0.1	0.01
$Eartip_{size}$	0.28 ± 0.1	0.03
OE_{obj}^{125} : $Eartip_{size}$	0.19 ± 0.09	0.045
Variance	(Intercept): 0.21 ± 0.46 Residual: 1.05 ± 1.02	
R^2	Marginal: $R_m^2 = 0.49$ Conditional: $R_c^2 = 0.57$	

3.2.3. Objectification of subjective evaluations

3.2.3.1. Low-frequency amplification. To explore the relationship between OE_{perc}, evaluated through the perceived low-frequency sound amplification (see Section 2.5), and the predictors, including both objective measurements and participant characteristics, Table 2 presents the results of the LMMs that yielded the lowest BIC and AIC values. As detailed in Section 2.6, these models were fitted using ML estimation and include a random intercept for participants to account for individual variability. Since BIC applies a stronger penalty for the number of predictors, it identifies a model with a single predictor, whereas the model minimizing AIC includes 5 predictors. In the BIC model (see Table 2(a)), the sole predictor OE_{obj}^{125} is highly significant ($p < 2 \times 10^{-16}$) with an estimated coefficient of 1.01. The marginal R_m^2 value indicates that 40 % of the variance in OE_{perc} is explained by OE_{obj}^{125}. The random effect for participants has a variance of 0.430, indicating variability in OE_{perc} across individuals. The conditional R_c^2 value indicates that both fixed and random effects explain 57 % of the variance, while the residual variance of 1.1 reflects the unexplained variability within individuals.

In the AIC model (see Table 2(b)), OE_{obj}^{125} remains the primary predictor, consistent with the BIC model. However, additional predictors emerge, including OE_{obj}^{4000}, $Eartip_{size}$, and the interactions OE_{obj}^{125} : $Eartip_{size}$ and OE_{obj}^{4000} : *Sex*, which enhance the model’s fit to the data. With standardization applied to normalize the scale of predictors, the influence of each predictor’s coefficient can be directly compared through their estimated values (i.e., β coefficients). Notably, OE_{obj}^{4000} shows a significant negative association ($\beta = -0.350$, $p = 0.003$), suggesting that higher values of the OE_{obj} at 4 kHz reduce the OE_{perc}. According to the interaction term OE_{obj}^{4000} : *Sex*, which has a positive and significant effect ($\beta = 0.29$, $p = 0.01$), the influence of OE_{obj}^{4000} is moderated by the participant’s sex, where males experience a stronger reduction in OE_{perc}

Table 3
Relationship between OE_{exp} (here the experienced voice naturalness) and the predictors using LMMs minimizing (a) BIC and (b) AIC values. For the variable *Familiarity*, “yes” is coded as 0 and “no” as 1. For *Sex*, “male” is coded as 0 and “female” as 1. For $Eartip_{size}$, “small” is coded as 0 and “medium/large” as 1.

(a)		
Fixed effects	Estimate (β coeff.) $\pm$ SD	p
(Intercept)	3.9 ± 0.1	$< 2 \times 10^{-16}$
OE_{obj}^{125}	0.67 ± 0.1	4.6×10^{-10}
Familiarity	-0.32 ± 0.1	0.01
OE_{obj}^{4000}	-0.28 ± 0.1	0.01
Variance	(Intercept): 0.2 ± 0.45 Residual: 1.12 ± 1.06	
R^2	Marginal: $R_m^2 = 0.32$ Conditional: $R_c^2 = 0.43$	

(b)		
Fixed effects	Estimate (β coeff.) $\pm$ SD	p
(Intercept)	3.7 ± 0.1	$< 2 \times 10^{-16}$
OE_{obj}^{125}	0.68 ± 0.09	4.7×10^{-16}
Familiarity	-0.35 ± 0.1	0.005
OE_{obj}^{4000}	-0.31 ± 0.1	0.005
OE_{obj}^{125} : *Sex*	-0.24 ± 0.1	0.01
$Eartip_{size}$	0.27 ± 0.1	0.03
OE_{obj}^{4000} : *Sex*	0.2 ± 0.1	0.06
Variance	(Intercept): 0.2270 ± 0.4765 Residual: 0.9836 ± 0.9918	
R^2	Marginal: $R_m^2 = 0.4$ Conditional: $R_c^2 = 0.51$	

with increasing OE_{obj}^{4000} values than females. The variable $Eartip_{size}$ has a positive and significant effect ($\beta = 0.280$, $p = 0.029$), indicating that larger eartip size is associated with higher OE_{perc}. In addition, the variable $Eartip_{size}$ moderates the effect of OE_{obj}^{125} according to the interaction term $OE_{obj}^{125} : Eartip_{size}$, which has a positive and significant effect ($\beta = 0.19$, $p = 0.045$) and suggests that the effect of OE_{obj}^{125} on OE_{perc} is stronger for participants using medium/large eartips. Since the size of the eartip was tailored to each participant's earcanal, the influence of the variable $Eartip_{size}$ suggests that the morphological characteristics of the earcanal contribute to shaping the OE_{perc}. The random intercept variance for participants (i.e., variability across participants) is reduced to 0.212 compared to BIC model, while the residual variance is still 1.049, reflecting variability within participants. Compared to BIC model, the marginal R_m^2 value increases to 48.7 % while the conditional R_c^2 remains stable around 57 %.

For both the BIC and AIC models, a Shapiro-Wilk test was performed on the residuals to assess their normality. The test yielded a W statistic of 0.99 with a p-value of 0.39 for both models. Since the p-value exceeds 0.05, the tests assess that the residuals do not significantly deviate from a normal distribution, supporting the model's assumption of normality and further validating the models.

3.2.3.2. Voice naturalness. We now explore the relationship between OE_{exp}, evaluated through the experienced voice naturalness (see Section 2.5), and the predictors using LMMs minimizing either BIC (see Table 3(a)) or AIC (see Table 3(b)). These models were fitted using ML estimation, with a random intercept included for participants (see Section 2.6). According to Table 3(a), the BIC model reveals a significant positive association between OE_{obj}^{125} and OE_{exp} ($\beta = 0.67$, $p < 0.0001$), indicating that lower OE_{obj} at 125 Hz decreases the OE_{exp} (i.e., enhances voice naturalness judgement). In contrast, OE_{obj}^{4000} shows a significant negative association with the OE_{exp} ($\beta = -0.28$, $p = 0.01$), suggesting that higher OE_{obj} at 4 kHz increases the OE_{exp}. Additionally, *Familiarity* ($\beta = -0.32$, $p = 0.01$) shows that participants who know the experimenter tend to rate their voice as farther from natural compared to those who do not know the experimenter. In this model, 32 % of the variance in the OE_{exp} is explained by the predictors. The random effect for participants shows a variance of 0.2, indicating variability in the OE_{exp} across individuals. The combination of both fixed and random effects explains 43 % of the variance, while the residual variance of 1.12 corresponds to the unexplained variability within individuals.

In the AIC model (see Table 3(b)), the main predictors with the highest estimates are consistent with those in the BIC model. The AIC model, however, includes additional predictors, including $OE_{obj}^{125} : Sex$ ($\beta = -0.24, p = 0.01$), $Eartip_{size}$ ($\beta = 0.27, p = 0.03$) and $OE_{obj}^{4000} : Sex$ ($\beta = 0.2$, $p = 0.06$). Through interaction terms, the variable *Sex* is shown to moderate the effect of both OE_{obj}^{125} and OE_{obj}^{4000}. As OE_{obj}^{125} increases, males tend to experience their voice as farther from natural (increased OE_{exp}) compared to females. Conversely, with increasing OE_{obj}^{4000} values, males rate their voice as closer to natural than females. The positive and significant effect of $Eartip_{size}$ suggests that participants with larger earcanal sizes tend to experience their voice as less natural (i.e., increased OE_{exp}). The random intercept variance for participants, representing variability across individuals, is similar to that of the BIC model, while the residual variance slightly decreases to 0.98. Compared to the BIC model, both the marginal and conditional R^2 values increase by approximately 8 % to 40 % and 51 %, respectively, indicating an improved fit for both the fixed effects and the overall model.

Again, a Shapiro-Wilk test was performed on the residuals to assess their normality, yielding a W statistic of 0.99 with a p-value of 0.19 for the BIC model and a W statistic of 0.99 with a p-value of 0.66 for the AIC model. In both cases, the p-values are greater than 0.05, indicating that the residuals do not significantly deviate from a normal distribution.

3.3. Overview of findings

The analysis provided in Section 3.2.3 reveals that the OE_{obj} at 125 Hz is the most influential factor for both low-frequency amplification and voice naturalness. However, the repeated measures correlation indicates a high degree of correlation between OE_{obj}^{125}, OE_{obj}^{250} and OE_{obj}^{500} (see Fig. 10 in Appendix E). To mitigate the issue of multicollinearity in LMMs, variables exhibiting high VIF were excluded from the models (see Section 2.6). Nonetheless, it is essential to consider these excluded variables when analyzing LMMs, as they still hold significant relevance in understanding the overall dynamics. Therefore, the low-frequency OE_{obj} up to 500 Hz plays the most important role in shaping perceived low-pitch sound amplification (i.e., OE_{perc}), experienced voice naturalness (i.e., OE_{exp}), and earplug preference among the four earplug pairs tested.

Interestingly, the perception of low-frequency sound amplification is also influenced by the OE_{obj} in the 4 kHz octave band, which diminishes the perception of amplification as it increases. The OE_{obj} at 4 kHz plays an even more significant role in shaping experiences of voice naturalness. This was also emphasized in research on the experience of one's own voice naturalness when using active devices [18,19], where the hear-through function is crucial in medium frequencies for achieving voice naturalness. Therefore, to enhance acoustic comfort, earplugs must significantly reduce the OE_{obj} at low frequencies and increase the phenomenon around 4 kHz to adequately balance the experience of voice naturalness. In this study, however, the *meta*-earplug was not optimized for the 4 kHz frequency region. Both *meta*-earplugs (A) and (B) exhibit a 2 to 3 dB higher OE_{obj} in the 4 kHz octave band compared to earplugs (C) and (D) (see Fig. 4(a) in Section 3.1.1), with these differences being statistically significant (see Appendix B). However, the underlying cause of this phenomenon remains unclear, as does the method for increasing OE_{obj} in this 4 kHz frequency band using *meta*-earplugs. Further investigations were conducted: additional impedance tube measurements were performed in this frequency range for both *meta*-earplugs open (A) and closed (C). The resulting impedances were incorporated into a TMM implementation of the OE_{obj} model to extend the frequency range beyond that of the model presented in Appendix A. However, no differences were observed (not shown here) around 4 kHz in the resulting OE_{obj}.

The influence of the familiarity of participants with the experimenter on the OE_{exp} is evident in the findings. Participants familiar with the experimenter experienced their own voice as sounding less natural compared to the other participants. One possible explanation is that participants familiar with the research setting may possess prior knowledge about the study's objectives or procedures, leading to heightened sensitivity to change in their acoustic perceptions. Importantly, since familiarity does not interact with other variables, it seems to influence all results consistently, suggesting that the differences in perception ratings may remain constant regardless of the earplug pair evaluated. It is worth noting that this psychosocial characteristic (familiarity) was significant only in the comfort-related question (i.e., voice naturalness experience), but not in the perception-related question (i.e., low-frequency amplification perception), highlighting the psychological influence on the (dis)comfort experience.

Additionally, eartip size and sex can modulate the primary effects of OE_{obj}^{125} and OE_{obj}^{4000}. Males tend to experience their voice as less natural than females when OE_{obj}^{125} increases and when OE_{obj}^{4000} decreases. The participants that used larger eartip sizes tend to perceive greater low-frequency amplification and are more likely to experience their voice as less natural. This suggests that individual anatomical differences influence the perception of low-frequency amplification and the judgment of voice naturalness when using earplugs.

On the other hand, several factors did not show significant influence. Notably, the NR, although strongly correlated with OE_{obj} at low frequencies (see Fig. 10 in Appendix E) due to the role of HRs in reducing OE_{obj} and increasing NR, did not exert a marked effect. Specifically, the leakage in *meta*-earplug (B) did not have much influence, which may offer flexibility in adapting NR to varying needs, independent of acoustic perception (i.e., OE_{perc}) and comfort (i.e., OE_{exp}). Additionally, several participant characteristics, such as age, earplug usage, and hearing thresholds, did not affect perception or comfort. The lack of influence from hearing thresholds could be attributed to the homogeneity of participants' hearing abilities, as all were normo-hearing.

3.4. Main limitations and perspectives

In this study, only four earplug pairs were compared under a single condition (speech production in a silent room) to prioritize the quality and accuracy of the results, though this limited the amount of data collected. Despite this effort, several participants requested to retest the earplug pair they tested first, as it was challenging to recall their perceptions across all pairs, especially when the differences between earplugs were subtle. Additionally, the process of switching between earplugs took several minutes, particularly when achieving a proper fit proved difficult (i.e., insufficient sound attenuation), potentially introducing variability into the results. Unfortunately, there are no ideal alternatives to mitigate this issue.

Additionally, only a few questions were asked after testing each earplug pair to minimize the time commitment for participants and maximize their concentration. The focus was therefore placed on comparing earplug pairs on two specific attributes: one related to OE_{perc}, assessed through low-frequency sound amplification perception, and one related to the OE_{exp}, assessed through the judgement of one's own voice naturalness. Unlike in previous studies (e.g., Refs. [8,17]), annoyance from low-frequency amplification or voice distortion was not assessed here, as each earplug pair was tested for only a few minutes, whereas annoyance may require prolonged use to manifest. As a result, while the *meta*-earplugs were preferred by most participants and demonstrated significant reduction in low-frequency amplification along with improved voice naturalness, it remains uncertain whether they offer sufficient acoustic comfort for extended use.

Moreover, as previously noted, the tests were conducted in a controlled silent environment, which eliminates variations in vocal effort that might naturally occur in real-world situations. Furthermore, the speech material was predefined, consisting of standardized text for all participants. While this approach ensures consistency, it might not fully capture the variability in speech production that could arise during spontaneous conversation. Utilizing a more contextually relevant text that mimics natural dialogue could yield a more accurate reflection of everyday experiences with earplugs.

While the LMMs optimized using the AIC criterion explain between 51 % and 57 % of the variance—an encouraging outcome given the inherent complexity of modeling human perception and comfort—a substantial portion of variance remains unexplained. The explanatory power of the models could potentially be enhanced by incorporating additional physical and psychosocial characteristics of the person, such as detailed morphological features of the earcanal [35], prior experience with hearing protection devices, work history, and awareness of noise exposure related risks for examples. For instance, while eartip size has shown some influence in this study and may correlate with earcanal morphology, more specific features [35] might better capture individual differences in perception and comfort. Additionally, we attempted to gauge participants' awareness of hearing protection from noise exposure by asking if they had received training on hearing protection. However, this question did not accurately capture their understanding of the risks associated with noise exposure.

Finally, the results observed in this study might differ for individuals who rely heavily on vocal performance, such as singers, or musicians who play brass instruments, as their acoustic needs and challenges related to the OE may be unique. Expanding the study to include these populations would offer valuable insights into how earplugs, particularly *meta*-earplugs, perform in a broader range of acoustic environments and could help tailor earplug designs specifically for musicians.

4. Conclusion

In this paper, we evaluated the effectiveness of *meta*-earplugs in reducing the OE_{exp} in 34 participants. The meta-earplug's geometry was tailored to the human outer ear and optimized using an analytical model to achieve minimal OE_{obj}, with the goal of creating an acoustically transparent earplug regarding BC sound. Three configurations of the *meta*-earplug with varying levels of OE_{obj} reduction and sound attenuation were tested, along with a commercial foam earplug. Measurements of OE_{obj} and sound attenuation were performed, and participants rated their perception of low-frequency amplification (i.e., OE_{perc}) and their judgement of voice naturalness (i.e., OE_{exp}) when speaking with the earplugs. On average, the results demonstrated that *meta*-earplugs reduced the OE_{obj} by up to 20 dB below 1 kHz. Additionally, the perception of low-frequency amplification decreased by 2 points, while voice naturalness judgement increased by 2 points, both on a 7-point Likert scale. Using LMMs, we explored the relationship between explanatory variables and both low-frequency amplification and voice naturalness. The OE_{obj} between 125 Hz and 500 Hz was the primary driver of the perception of low-frequency amplification, while voice naturalness judgement was also significantly impacted by the OE_{obj} at 4 kHz. Additionally, eartip size and sex modulated these primary effects, suggesting that individual anatomical differences play a role in the subjective evaluation of both OE_{perc} and OE_{exp} when using earplugs. These factors may need to be considered in the design and optimization of future earplugs to improve user comfort and acoustic experience. Overall, the study confirmed the effectiveness of *meta*-earplugs in reducing the OE_{obj} and improving users' acoustic perception (i.e., OE_{perc}) and comfort (i.e., OE_{exp}). These findings provide valuable insights for designing next-generation earplugs and hearing aids that could enhance auditory comfort by addressing OE-related discomfort.

Author statement

The authors confirm that our work is in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki) for experiments involving humans.

Author contributions

K.C. conducted modelling and experimental work and drafted the manuscript. All authors contributed in the analysis and interpretation of data and in the revision of the manuscript.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used ChatGPT-4 to help improve the text's readability and clarity. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

CRediT authorship contribution statement

Kévin Carillo: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Franck Sgard:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Olivier Dazel:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Olivier Doutres:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Olivier Doutres reports financial support was provided by Natural Sciences and Engineering Research Council of Canada. Kevin Carillo, Olivier Doutres, Olivier Dazel, Franck Sgard have pending patent #PCT/CA2023/050504 assigned to École de technologie supérieure (ÉTS), Institut de recherche Robert-Sauvé en santé et sécurité du travail (IRSST), and Le Mans Université. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Objective occlusion effect model

The OE_{obj} induced by the *meta*-earplug is derived from a simple EA model, as detailed in Ref. [30]. The temporal dependency is expressed as $e^{j\omega t}$, where j is the imaginary unit. The earcanal is modeled as a cylindrical tube with a length $l_{EC} = 29$ mm and a radius $r_{EC} = 3.75$ mm. An ideal volume velocity source represents the vibration of the earcanal wall induced by BC stimulation. In this model, the OE_{obj} is defined as the difference in sound pressure level at the eardrum between occluded and open configurations, and is computed as follows:

$$OE_{obj} = 20\log_{10}\left(\left|\frac{Z_{EC}^{occl}}{Z_{EC}^{open}}\Psi_q\right|\right), \tag{14}$$

where Z_{EC}^{open} and Z_{EC}^{occl} are the acoustic impedances seen by the volume velocity source in the open and occluded configurations, respectively, and Ψ_q represents the ratio of volume velocity between the occluded and open configurations, accounting for the insertion depth of the occlusion device. For an insertion depth of 10 mm, this ratio is adjusted to $\Psi_q = 1/10$, as described in Ref. [30]. This adjustment was made based on a comparison between simulation and measurements of the OE_{obj} conducted on an artificial ear tester, which provides OE_{obj} measurements comparable to those observed in human participants for the same insertion depth [31].

When the earcanal is open, the acoustic impedance (i.e., the pressure-to-volume velocity ratio) seen by the source is approximated at low frequencies by [12]

$$Z_{EC}^{open} = j\omega\left(L_{EC}^{open} + L_{rad}^{open}\right), \tag{15}$$

where $L_{EC}^{open} = \rho_0 l_c / S_{EC}$ represents the acoustic mass of the open earcanal, defined between the earcanal entrance and the centroid position l_c of the earcanal wall normal velocity. The earcanal cross-sectional area is given by $S_{EC} = \pi r_{EC}^2$, and ρ_0 is the air density. Under BC stimulation, the cartilaginous part of the earcanal is assumed to vibrate the most [9,12,50] so the centroid position is taken in this region, with $l_c = 5$ mm from the earcanal entrance. The term $L_{rad}^{open} = 8\rho_0/\left(3\pi^2 r_{EC}\right)$ represents the acoustic radiation at the earcanal entrance, idealized as a baffled circular piston.

When the earcanal is occluded by the *meta*-earplug, the acoustic impedance seen by the source is approximated at low frequencies by

$$Z_{EC}^{occl} = \frac{\left(Z_{s,EP}/S_{EC}\right) \times \left(1/j\omega\left(C_{EC}^{occl} + C_{TM}\right)\right)}{\left(Z_{s,EP}/S_{EC}\right) + \left(1/j\omega\left(C_{EC}^{occl} + C_{TM}\right)\right)}, \tag{16}$$

where $Z_{s,EP}$ is the specific acoustic impedance (i.e., pressure-to-normal velocity ratio) of the medial surface of the *meta*-earplug, computed using the TMM approach detailed in Section 2.3.1. The acoustic compliance of the occluded volume of the earcanal is given by $C_{EC}^{occl} = (l_{EC} - l_{ID})S_{EC}/\left(\rho_0 c_0^2\right)$, taking a shallow insertion depth of $l_{ID} = 10$ mm. Here, c_0 and ρ_0 represent the speed of sound in air and the air density, respectively, and C_{TM} denotes the acoustic compliance of the eardrum/middle ear at low frequencies. Note that the influence of the earcanal motion on the acoustic impedance conditions applied at the open earcanal entrance, the earplug medial surface and the eardrum surface is not accounted for [53].

Appendix B. Statistical analysis of objective measurements

Since the residuals of both OE_{obj} and NR octave band measurements violate the normality assumption required for repeated measures ANOVA, the non-parametric Friedman test is employed to determine whether the type of earplug influenced the measurements. Additionally, pairwise comparisons using Wilcoxon signed-rank tests are conducted to assess whether statistically significant differences exist between each pair of earplugs at the 0.05 level. The results are presented in Fig. 7.

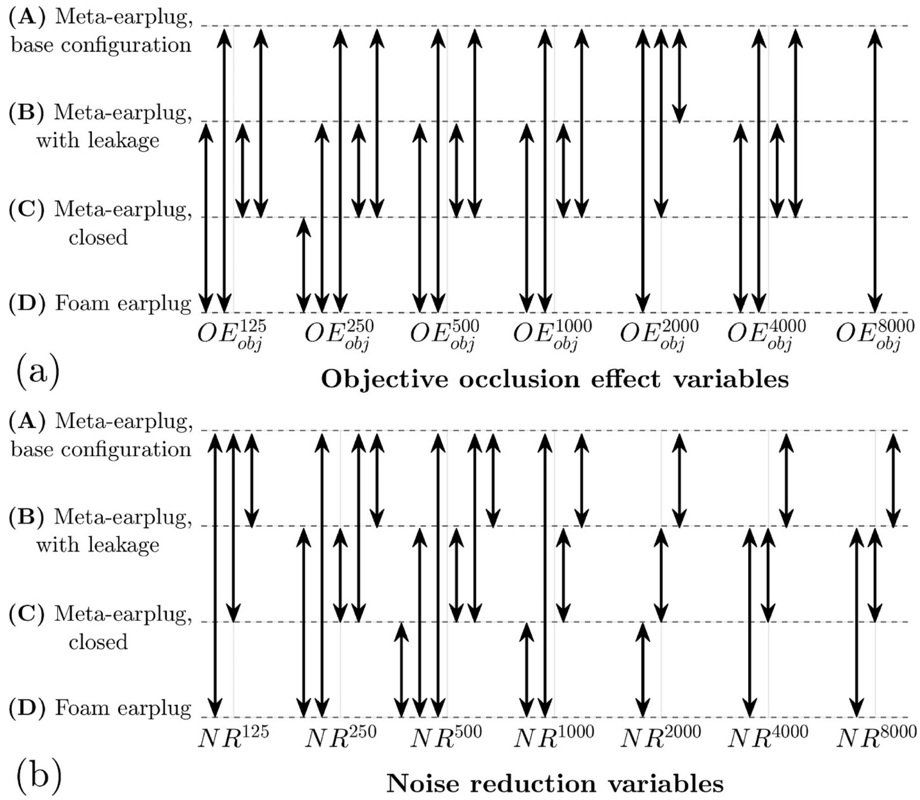

Fig. 7. Results of pairwise comparisons using Wilcoxon signed-rank post-hoc tests at the 0.05 significance level for (a) OEobj and (b) NR octave band measurements.

Appendix C. Optimization results and leakage influence

Table 4 summarizes the geometrical values of the *meta*-earplug, which consists of 3 HRs arranged in series and optimized to minimize the OE_{obj}. The table also provides the lower and upper limits of the geometrical parameters. Note that the length and cross-section of neck #1, as well as the thickness of the melamine foam in the cavities, are fixed (see Section 2.3.1).

Table 4
Lower limit, upper limit and optimized value (in mm) of the geometrical parameters of the *meta*-earplug. Superscripts $[n]$, $n \in [2, 3]$, refer to HRs #2 and #3. Geometric parameters x_1 and x_2 (see Fig. 3(a)) define the topology of the three resonators while $r^{[n]}_{neck}$ and $l^{[n]}_{neck}$ corresponds to the radius and length of the HRs necks.

	x_1	x_2	$r^{[2]}_{neck}$	$r^{[3]}_{neck}$	$l^{[2]}_{neck}$	$l^{[3]}_{neck}$
Lower limit	2	2	0.5	0.5	4.5	4.5
Optimized value	**7**	**6.2**	**0.9**	**0.5**	**6.2**	**7.1**
Upper limit	7	17	0.9	0.9	15	15

Fig. 8(a) shows the simulations of the OE_{obj} induced by the acoustically rigid configuration and the optimized *meta*-earplug from 100 Hz to 2 kHz. For the acoustically rigid configuration, the OE_{obj} decreases with frequency by approximately 40 dB/decade, consistent with literature data for conventional earplugs [9,10,20]. This decrease is explained by the change in the acoustic impedance of the earcanal seen by its wall between the mass-controlled open state and the compliance-controlled occluded state [12]. In contrast, the *meta*-earplug significantly reduces the OE_{obj} at low frequencies, achieving nearly 20 dB reduction below 300 Hz. From 300 Hz to 2 kHz, the successive acoustic resonances of the *meta*-earplug (see vertical-colored lines) maintain the OE_{obj} close to zero.

Fig. 8(b) shows the magnitude in dB (narrow bands) of the normalized input impedance at the medial surface of the *meta*-earplug both with and without leakage, calculated analytically (TMM). The results show that the acoustic leakage has little influence on the meta-earplug's acoustic impedance. This is due to the leakage being sufficiently narrow, leading to an acoustic impedance much larger than that of the HRs in series, allowing the HRs to dominate the overall acoustic impedance of the system.

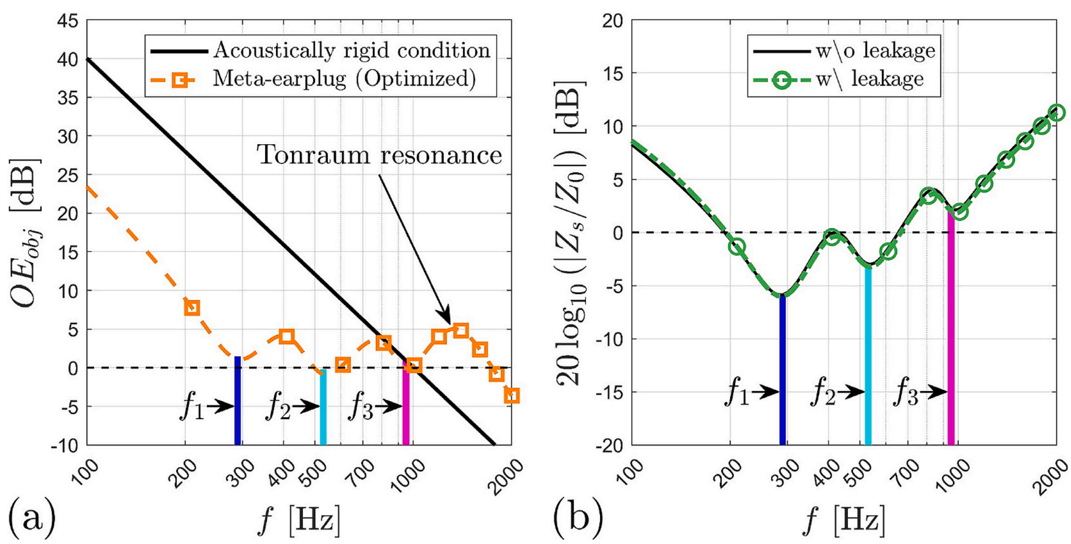

Fig. 8. (a) Simulations of the OEobj induced by the acoustically rigid configuration and the optimized meta-earplug. Vertical-colored lines represent the resonant frequencies of the meta-earplug. (b) Magnitude in dB (narrow bands) of the normalized input impedance at the medial surface of the meta-earplug with and without leakage, calculated analytically (TMM).

Appendix D. Raw ratings data

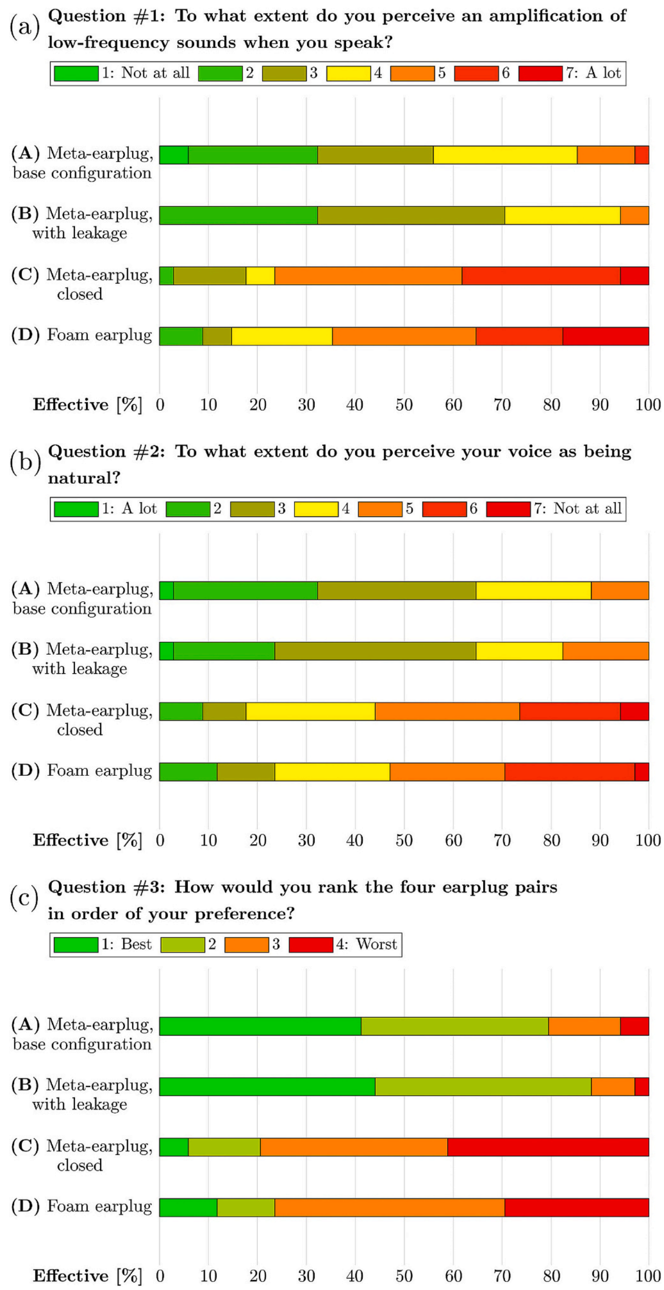

Fig. 9. Frequency distributions of the subjective ratings of the four tested earplug pairs in terms of (a) low-frequency sound amplification (i.e., OEperc), (b) voice naturalness (i.e., OEexp) and (c) earplugs preference.

Appendix E. Repeated measures correlation

Fig. 10 presents the repeated measures correlation matrix for both OE_{obj} and NR measurements across octave frequency bands from 125 Hz to 8 kHz. Each cell represents the repeated measures correlation rm_{corr} between two variables, calculated while accounting for within-subject dependencies and comprised between -1 and 1. Strong positive correlations (highlighted in darker red) indicate that as one variable increases, the other tends to increase across repeated measurements for the same participant. Conversely, strong negative correlations (highlighted in darker blue) indicate an inverse relationship.

Notably, the low-frequency OE_{obj} variables exhibit high positive correlations between 125 Hz and 500 Hz ($rm_{corr} > 0.9$). Similarly, low-frequency NR variables are significantly correlated across the same frequency range ($rm_{corr} > 0.8$). Additionally, low-frequency OE_{obj} variables are moderately negatively correlated with low-frequency NR variables between 125 Hz and 250 Hz ($rm_{corr} > 0.65$). This aligns with the observations from Fig. 4(a) and Fig. 5(a), where we see that the reduction in OE_{obj} by the *meta*-earplug tends to increase NR, driven by the effect of the HRs at low frequencies. These relationships are crucial to consider when discussing the LMM results, as highly correlated variables were excluded to prevent multicollinearity and improve model quality.

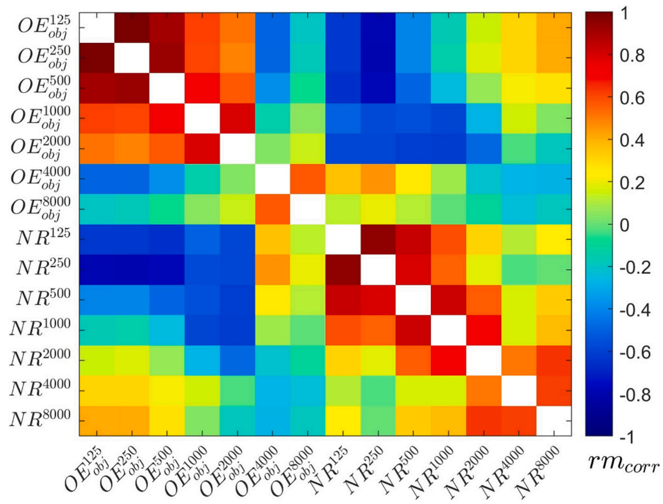

Fig. 10. Repeated measures correlation matrix for the OEobj and NR measurements.

Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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