Safety Science 196 (2026) 107098

Contents lists available at ScienceDirect

Safety Science

journal homepage: www.elsevier.com/locate/safety

Analysis of the functional and acoustical comfort of earplugs experienced by a group of workers in Canadian companies and identification of the influencing variables

Bastien Poissenot-Arrigoni [a], Olivier Doutres [a,*], Alessia Negrini [b], Djamal Berbiche [c], Franck Sgard [b]

[a] Department of Mechanical Engineering, École de Technologie Supérieure, 1100 Rue Notre-Dame Ouest, Montréal, Québec H3C 1K3, Canada
[b] Institut de recherche Robert-Sauvé en santé et sécurité du travail, 505 Boulevard de Maisonneuve Ouest, Montréal, Québec H3A 3C2, Canada
[c] Département des Sciences de la Santé Communautaire. Faculté de Médecine et des Sciences de la Santé, Université de Sherbrooke. Centre intégré de santé et de services sociaux de la Montérégie-Centre, Centre de recherche Charles-Le Moyne (CRCLM), Campus de Longueuil, 150 Place Charles-Le Moyne, bureau 200, C.P. 11, Longueuil J4K 0A, Canada

ARTICLE INFO

Keywords:
Earplugs
Functional comfort
Acoustical comfort
Hearing protectors
Earcanal morphology
User experience

ABSTRACT

Earplugs are essential for hearing protection in noisy workplaces, but their effectiveness depends heavily on user comfort, which influences proper and consistent use. This study explores functional and acoustical comfort experienced by 173 workers across Canadian companies, each testing different 'disposable or reusable' earplug models over seven weeks. Comfort is assessed using detailed questionnaires covering six subdimensions: ease of insertion and removal, noise protection, impact on work, and discomfort related to internal and external noise perception. Linear mixed-effects models are applied within a triad framework encompassing person-, earplug-, and environment-related characteristics in order to identify those with a significant influence on functional and acoustical comfort. Results show that person-related variables are the most influential. Handedness, hearing loss, and prior HPD experience significantly impact comfort, with left-handed participants reporting greater insertion and removal discomfort—possibly due to earcanal asymmetry and dexterity differences. Several earcanal morphological features also play a role, including isoperimetric ratios, circumference at multiple cross-sections, conicity, and length. Only a few earplug-specific characteristics influence comfort outcomes. Foam expansion time is linked to reduced acoustical discomfort associated with the perception of internal sounds, while stem presence improves insertion ease. Environmental factors do not have significant effects. In the longer term, these findings call for a rethinking of the design and selection of 'disposable or reusable' earplugs, primarily based on earcanal morphology and users' past experience. The study also underscores the need for improved objective metrics to assess comfort and supports the development of more personalized hearing protection solutions.

1. Introduction

Noise-induced hearing loss globally stands as a prevalent and financially burdensome occupational disease. To address this concern, employers commonly provide 'disposable or reusable' earplugs. These devices are primarily intended to reduce the intensity of noise reaching the tympanic membrane, thereby protecting workers from hearing damage. However, their effectiveness depends largely on comfort-related factors, as earplugs may be worn incorrectly, intermittently, or not at all if they cause discomforts (Berger, 2013; Berger and Voix, 2022; Bockstael et al., 2011; Canadian Standards Association, 2014; Doutres et al., 2019, 2020, 2022). Although the barriers to hearing protector use often outweigh the perceived benefits for users, hearing protection devices (HPDs) can also be a source of comfort, for example, by fostering a sense of being protected from noise, improving communication in noisy environments, or positively influencing concentration, productivity, and task performance. Comfort is therefore not merely the absence of discomfort. Nevertheless, for the sake of simplicity, the term 'comfort' is used hereafter to refer to both facets of the concept, namely its negative (discomfort) and positive (comfort) dimensions.

Comfort, in the context of earplug usage, comprises four dimensions (Doutres et al., 2019, 2022): physical, functional, acoustical, and

* Corresponding author.
E-mail address: olivier.doutres@etsmtl.ca (O. Doutres).

https://doi.org/10.1016/j.ssci.2025.107098
Received 28 August 2025; Received in revised form 23 October 2025; Accepted 16 December 2025
Available online 23 December 2025

psychological. The physical dimension involves the user's perception arising from biomechanical and thermal interactions between the earplug and the earcanal. The functional dimension encompasses concepts like usability, efficiency, and usefulness. The acoustical dimension pertains to alterations in perception of external and/or internal sounds. Lastly, the psychological dimension relates to the user's well-being and satisfaction. All attribute of comfort pertaining to these 4 dimensions stems from intricate interactions among the work environment, the user, and the earplug itself, forming a concept known as the "triad" (Doutres et al., 2022). The triad components (person/earplug/environment) can be described by many physical and psychosocial characteristics (Doutres et al., 2022). Understanding all the characteristics of the triad that affect comfort, and their relative contribution, would allow for more effective protection of noise-exposed individuals. Indeed, knowing the influences of the psychosocial characteristics of the triad (e.g., past behavior, experience with HPD use) on comfort would allow for effective consideration of comfort in the earplug selection phase. Similarly, knowledge of the relationship between physical characteristics of earplugs (e.g., shape or softness) and comfort could aid in the design of more comfortable earplugs.

A recent study from the research team aimed at enhancing our understanding of the physical discomfort associated with earplugs by identifying key triad characteristics that significantly impact the primary attributes of this comfort dimension (Poissenot-Arrigoni et al., 2023). The multidimensional comfort of earplugs was evaluated in a field study involving 173 participants (Negrini et al., 2025), who tested seven different earplug models over a seven-week period and completed detailed comfort questionnaires. Triad characteristics were assessed through both self-reported questionnaires and laboratory measurements using comfort testers. Statistical analyses identified key triad characteristics influencing physical discomfort attributes, such as the earplug's radial force, extraction force, and friction coefficient. Additionally, aspects of the work environment (e.g., work duration) and individual characteristics (e.g., ear morphology, prior experience with earplugs) were found to play a role in physical discomfort. The present study shares the same objective, namely identifying the physical and psychosocial characteristics of the triad that significantly influence comfort. However, this time, the focus is put on the functional and acoustical dimensions of comfort, as assessed during the same field test campaign.

Unlike physical comfort, the literature is sparser regarding functional and acoustical comfort for earplugs and the potential characteristics that influence these dimensions of comfort. According to the definition of earplugs' comfort proposed by (Doutres et al., 2019), the functional dimension covers the practical aspects of earplugs, including ease of use, effectiveness, and utility. Previous studies (summarized in (Doutres et al., 2020), see for example sec. 3.3) have demonstrated that earplug type significantly influences key attributes of functional comfort. For instance, premolded earplugs are generally perceived as easier to insert compared to other types, while roll-down foam earplugs, although often considered more challenging to insert, are recognized for their superior ability to maintain a stable position once fitted. More recently, Valentin et al. (2024) investigated the multidimensional comfort of various commercial earplugs in a laboratory setting by exposing participants to two distinct industrial noise environments, that primarily differed in overall sound level (by 2.1 dB), stationarity, and spectral content. They observed that the earplug type (i.e., roll-down foam, premolded, and push-to-fit foam earplugs) significantly influenced the perception of earplug functionality. Functionality, evaluated in their comfort questionnaire based on ease of insertion, stability, and fit, was rated highest for push-to-fit foam earplugs compared to roll-down foam and premolded earplugs. However, they found no impact of the sound environment (a characteristic of the "environment" component of the triad) on comfort judgment, regardless of the comfort dimension assessed. Regarding the "person" component of the triad, Park and Casali identified experience with hearing protection as an influential factor affecting their physical-functional comfort index (Park and Casali, 1991; Doutres et al., 2020). Their findings indicate that novice users tend to perceive HPDs as more comfortable compared to experienced users.

The triad characteristics influencing the acoustical dimension of comfort are now examined. This comfort dimension includes challenges in perceiving and accurately localizing useful sounds (e.g., alarm signals, machine noises), as well as the occlusion effect, which causes discomfort due to amplified physiological noises such as one's own voice or chewing sounds. Regarding acoustic comfort related to the perception of useful environmental sounds, Sweetland (1983) demonstrated that a participant's experience with wearing HPDs, a psychosocial characteristic of the "person" component of the triad, can have a significant impact. He observed the effect of long-term habituation: the greater the experience, the lower the associated discomfort. He also noted a medium-term habituation effect, where participants' discomfort decreased as the eight-week test campaign progressed. Still focusing on the influence of the "person" component of the triad, Gonçalves et al. (2015) found that workers with impaired audiograms were more likely to negatively assess HPD use in terms of "ease of auditory communication." Now considering the influence of the "environment" component of the triad, Sweetland (1983) also showed an effect of external noise levels on acoustic discomfort related to the perception of useful sounds: quieter environments resulted in greater acoustic discomfort. Laboratory studies focusing more on environmental sound perception (rather than acoustic comfort) have also demonstrated reduced intelligibility in low-noise environments and improved intelligibility at higher noise levels when wearing HPD (for normal hearing participants)(Acton, 1967; Doutres et al., 2020; Giguère and Berger, 2016; Kryter, 1946; Suter, 1992). As mentioned previously, Valentin et al. (2024) found that there was no effect of the sound environment on acoustic discomfort judgments. However, speech comprehension and signal detection tests conducted on the same participants revealed significant differences between the two types of industrial noise conditions. This confirms that the perception of an effect, as measured by perceptual tests, and the judgment of comfort, assessed through questionnaires, represent two distinct concepts (Doutres et al., 2022). Furthermore, this suggests that individuals' comfort judgments may not fully reflect the actual challenges and effects of wearing earplugs in a given sound environment. Finally, concerning the potential influence of the "earplug" component of the triad on the acoustic discomfort associated to the perception of useful environmental sounds, two studies have shown that roll-down foam earplugs are perceived as providing excessive attenuation (Arezes et al., 2008; Spomer et al., 2017). In their laboratory study, Valentin et al. (2024) observed that there is no significant effect of the earplug family on the comfort attribute associated with the intelligibility of alarm signals.

Regarding the occlusion effect, used here as an indicator to quantify acoustic discomfort related to the perception of internal sounds when the ears are occluded by an earplug, the influencing triad characteristics are poorly documented. The most well-known factors include insertion depth (Killion, 1988, 2012; Mueller, 2003) (which is not a characteristic of the triad but rather part of the interaction phase in the comfort model (Doutres et al., 2022)) and the presence of acoustic vents (primarily studied in the context of hearing aids rather than HPDs). The earplug itself can have a positive effect in reducing the occlusion effect, but mostly if it has been specifically designed for this purpose (Carillo et al., 2025; Denk et al., 2024). Indeed, recent laboratory studies have found no significant differences in discomfort judgments between various commercially available 'disposable or reusable' earplugs (Saint-Gaudens, 2025). This is likely because their primary purpose is to reduce noise levels at the eardrum from workplace exposure rather than to mitigate the occlusion effect. In Valentin et al.'s laboratory study (2024), roll-down foam earplugs were rated as more uncomfortable (compared to premolded and push-to-fit foam earplugs) regarding the perception of internal sounds. However, Valentin et al. rather attribute this effect to the insertion depth of these earplugs, which tends to be shallower due to their greater difficulty in insertion.

This literature review highlights the limited research on the functional and acoustical dimensions of earplug comfort. There is a lack of field studies that assess multidimensional comfort while quantifying numerous characteristics of the three triad components to determine their potential influence (Doutres et al., 2019). Regarding functional comfort, research suggests some influence of earplug characteristics, but little is known about the impact of the work environment or the user. For acoustic comfort, studies have primarily focused on the effects of the acoustic environment on the perception of external sounds and on the earplug itself regarding the perception of internal sounds. However, the influence of many physical and psychosocial characteristics of the triad remains unexplored.

This study aims at identifying the physical and psychosocial characteristics of the triad components that have a significant influence on functional and acoustical comfort induced by earplugs. This study can be considered as a continuation of the one previously published by the team on the physical comfort of earplugs (Poissenot-Arrigoni et al., 2023). It shares many methodological elements, including the comfort measurement data from (Negrini et al., 2025), as well as the techniques and "comfort testers" used (or developed) to assess various physical properties of the triad components. The paper is structured as follows: The Methodology section provides an overview of the key elements of earplug comfort measurements conducted in the field. It also presents the six subdimensions of functional and acoustical comfort identified previously using factor analyses (Negrini et al., 2025) and used here to evaluate the impact of the triad characteristics on the comfort dimensions of interest in this work. The physical and psychosocial characteristics of the triad are then briefly outlined, followed by a description of the statistical tools used to assess their impact on functional and acoustical comfort. The Results section first presents the measured triad characteristics, then provides a descriptive analysis of the functional and acoustical (dis)comfort subdimensions, and concludes with an overview of the key influential characteristics within the triad. The Discussion section provides an in-depth analysis of the observed effects on these two comfort dimensions. Finally, the paper concludes with a section dedicated to the main limitations of the study and perspectives for future research aimed at improving the understanding and modeling of earplug comfort.

2. Methodology

Various methodological tools were used to meet the main objective of the study, which is to gain a better understanding of the characteristics of the triad that influence the functional and acoustical comfort associated with wearing earplugs. Sub-section 2.1 details the field measurement campaign, which provided comfort data on wearing various earplug models (Negrini et al., 2025). The study received ethical approval from the École de Technologie Supérieure (ETS) committee (ethics certificate H20171101). The (dis)comfort subdimensions identified previously using factor analyses (Negrini et al., 2025) and used here as main outcomes to investigate functional and acoustical comfort are briefly presented (descriptive analyses of these subdimensions are provided in sec. 3.2). Sub-section 2.2 is dedicated to the assessment of the triad characteristics and allows to complete the Poissenot-Arrigoni' study (2023). Two physical characteristics are added in this study since they were considered particularly relevant to study functional and acoustical comfort: the expansion time of roll-down foam earplugs and the sound exposure level of the participants. Finally, sub-section 2.3 describes the statistical analyses used to evaluate the impact of the triad characteristics on functional and acoustical comfort.

2.1. Earplugs comfort assessment in the field

2.1.1. Earplugs

In the earplug comfort field survey (Negrini et al., 2025), used here to perform an in-depth analysis of functional and acoustical comfort, different earplug models (representing commonly used types in North America) were tested. Among these, seven were 'disposable or reusable'. Specifically, three of them belonged to the roll-down-foam earplugs family, one to the premolded earplugs family and three to the push-to-fit foam earplugs family (see Table 1). This study defines earplugs based on specific physical attributes for which test-benches (referred to as "comfort testers") have been developed.

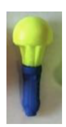
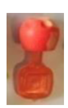
2.1.2. Test protocol and (dis)comfort subdimensions

A total of 173 individuals employed across three companies in Quebec, Canada, operating respectively in the printing, manufacturing, and agri-food sectors, participated in this study. To address the specific objective of this research, only the subsample of participants who tested 'disposable or reusable' earplug models was considered. Spanning eight weeks, the field study started during "Week 0," where the research team, comprising scientific professionals and audiologists, introduced the project and conducted eligibility interviews among interested employees of the participating companies. The inclusion criteria were strictly adhered to: participants needed to be 18 years or older, proficient in French, knowledgeable about HPDs, regularly exposed to workplace noise, without ear or neurological pathologies, and not experiencing significant earwax accumulation in their earcanals. Upon meeting these criteria, participants completed the "User Profile Questionnaire" (UPQ) (Negrini et al., 2025) measuring the numerous physical and psychosocial characteristics of the triad (see sec. 2.2). Subsequently, a custom earplug manufacturer molded the earcanals of the participants, enabling the collection of detailed data regarding earcanal morphologies.

Over the subsequent seven weeks ("Weeks 1-7″), participants tested earplugs from three distinct families: roll-down-foam, premolded, and push-to-fit-foam (see Table 1). For the roll-down foam and push-to-fit foam variants, participants wore the same model for one week and wore it another week, two weeks later. However, the premolded earplug was uniquely tested by each participant and was not reused. All participants assessed the premolded earplug. Each test week typically involved individual training sessions on earplug insertion and usage, conducted by audiologists. The field attenuation estimation system, specifically the 3M™ E-A-Rfit™ Dual-Ear Validation System, was utilized for training purposes. For earplug models incompatible with this system, a surrogate model of similar shape and material was selected. After the individual training sessions, if the earplug provided sufficient attenuation for the participant, the test week began.

At the end of each week, participants completed the "Comfort of Hearing Protection Devices – North America Questionnaire" (COPROD-NAQ; (Negrini et al., 2025)) to express their opinions regarding the four comfort dimensions for the tested earplug. To meet the main objective of this study, we consider their answers about the functional and acoustical dimensions. Following the COPROD-NAQ factor structure, the 4 distinct subdimensions measuring different facets of functional comfort were considered: "FC – Protection from noise", "FC – Impact on work", "FC – Removal", and "FC – Insertion". In the COPROD-NAQ, items related to the functional dimension were positively worded to assess comfort; consequently, the conceptual subdimensions of this dimension are referred to as comfort subdimensions. Specifically, "FC – Protection from noise" was measured using 7 items capturing multiple aspects such as effectiveness, sense of protection, ease of use, secure positioning, and utility in the work environment and activities (e.g., *These earplugs are useful considering your work activities*). It does not measure acoustical comfort but rather encompasses the perceived efficiency of earplugs for an individual within a specific work environment. "FC – Impact on work" is composed of 3 items measuring the impact of wearing earplugs on the concentration, quality of work and productivity (e.g., *When you wear these earplugs, your concentration is really better*). "FC – Removal" (3 items; e.g., *Remove these earplugs is easy*) assessed how comfortable participants felt with removing the earplugs easily, quickly, and with few gestures. Meanwhile, «FC – Insertion» (5 items; e.g., *Insert these*

Table 1
Objective characteristics of the tested earplugs.

Earplugs ↓		*Characteristic name* →		Earplug intrinsic properties						Properties of the "earcanal/earplug" coupled system measured on cylindrical comfort testers with rigid walls				
				Conical	Pod-Shaped	Stemmed	Mass (g)	Diameter (mm)		Friction coeff.	Radial force (N)		Extraction force (N)	Expansion time (s)
Earplug family	*Earplug model manufacturer's name*	*Picture*	Label used in this study (↓) / Variable symbol (→)	**Con**	**Pod**	**Stem**	**Mass**	$\mathbf{D_1}$	$\mathbf{D_2}$	$\boldsymbol{\mu_9}$	$\mathbf{RF_7}$	$\mathbf{RF_9}$	$\mathbf{EF_9}$	$\mathbf{Expan}_{\mathrm{Time75\%}}$
Roll-down-foam	3M™ E-A-R ™ Classic/ uncorded regular and small		Cylindrical foam	No	No	No	0.31	13.5	13.5	0.48	7	4.7	2.3	4.06
	3 M™ 1100 Earplug		Bullet shaped foam	Yes	No	No	0.38	12.9	12.4	0.61	6.9	4.45	2.7	4.28
	Honeywell Howard Leight Max Regular and small		Bell-shaped foam	Yes	No	No	0.63	12.3	11.7	0.55	9.9	6.5	3.6	6.14
Premolded	3 M™ E-A-R™ UltraFit™		Multi-flange elastomeric polymer	Yes	No	Yes	1	12.5	10.5	0.52	52	4	2.1	NA
Push-to-fit foam	3 M™ E-A-R™ Push-Ins		Push-to-fit foam pod 1	No	Yes	Yes	0.62	NA	12.2	0.62	10.9	3.2	3.5	NA
	Honeywell TrustFit® Pod		Push-to-fit foam pod 2	No	Yes	Yes	0.94	NA	13	1.03	20.8	5.8	6.0	NA
	3 M™ E-A-R™ Push-Ins with grip rings		Push-to-fit foam sheath	Yes	No	Yes	1.18	13.4	11.5	0.52	29	4.5	2.3	NA

earplugs is intuitive) assessed these aspects as well as how intuitive the insertion of the earplugs was and its adaptability to work pace. Regarding the acoustical dimension of comfort, items in the COPROD-NAQ were negatively worded to capture discomfort; therefore, the two conceptual subdimensions associated with this dimension are referred to as discomfort subdimensions. Specifically, "AD – External noise" (5 items; e.g., *When you wear these earplugs, your perception of the sounds of machines useful for doing your work is difficult*) allowed to assess if with the tested earplugs participants could not hear useful sounds coming from their work environment (e.g., people speaking, warning signals, company announcements). Meanwhile, "AD- Internal noise" (3 items; e.g., *When you wear these earplugs, you are annoyed by your own voice when you speak*) assessed if participants were annoyed by the sounds coming from their body (e.g., voice, chewing, heartbeat).

For each item, participants indicated their level of agreement on a five-point Likert scale varying from 1 (strongly disagree) to 5 (strongly agree), except for the items measuring the " FC – Impact on work », which ranged from 1 (really worse) to 5 (really better).

Confirmatory factor analyses were used to compute an index for each subdimension (Negrini et al., 2025). These subdimension (dis)comfort indices, hereafter referred to simply as "subdimensions" for brevity and described in more detail in Section 3.2, serve as the primary measures for characterizing participants' perceived comfort in this study. This approach differs slightly from the method used in the physical comfort study by Poissenot-Arrigoni et al. (2023), where individual general and explanatory questionnaire items were used to characterize the comfort dimension of interest, rather than relying on a composite (dis)comfort index for each subdimension.

2.2. Assessment of the triad characteristics

Various physical and psychosocial characteristics of the "Person/Environment/Earplug" triad (Doutres et al., 2022), potentially influential for earplug comfort, underwent evaluation in the field through the UPQ or objective measurements in the laboratory. Various types of variables (continuous, dichotomous, and categorical) were then computed and employed to describe the study sample and conduct statistical analyses to test the relationships between the triad characteristics and the functional and acoustical comfort induced by earplugs. The methodologies employed to assess these triad characteristics are presented in subsections 2.2.1 to 2.2.3.

2.2.1. Person (earplug user)

The variables that define the physical and psychosocial characteristics of the individual are summarized in Table 2 and elaborated upon in sections 2.2.1.1 and 2.2.1.2.

2.2.1.1. Physical characteristics. This study considered specific physical characteristics of individuals, including earcanal morphology, hearing condition, and hand dominance.

For the assessment of each participant's earcanal morphology, a comprehensive process described in (Poissenot-Arrigoni et al., 2022) was utilized. The left and right earcanal morphologies were obtained by scanning earmolds cast during "Week 0″. This method assumes that the scanned earcanal accurately represents the participant's earcanal morphology. The earcanal, an "S-shaped" duct extending from the concha to the tympanic membrane, displays varying cross-section shapes and sizes along its curvilinear axis. Three characteristic cross-sections were utilized: entrance (E), first bend (FB), and second bend (SB). These sections were positioned objectively and repeatably using Stinson and Lawton's method (Stinson and Lawton, 1989), with E located at the base of the concha and FB and SB positioned based on the curvilinear axis's curvature. Several indicators of earcanal girth were extracted from these sections for both right (R) and left (L) sides, such as circumferences of E ($C_{E(L)}$ and $C_{E(R)}$), FB ($C_{FB(L)}$ and $C_{FB(R)}$), and SB ($C_{SB(L)}$ and $C_{SB(R)}$) cross-sections.

Additionally, the ellipticity evaluated through the isoperimetric ratio (IR) of each cross-section was calculated ($IR_{E(L)}$, $IR_{E(R)}$, $IR_{FB(L)}$, $IR_{FB(R)}$, $IR_{SB(L)}$ and $IR_{SB(R)}$). This characteristic represents the circularity of the section. It varies between 0 and 1; the closer to 1, the more circular the cross-section. The lengths of the right ($L_{E\text{-}SB(R)}$) and left ($L_{E\text{-}SB(L)}$) earcanals between E and SB were computed, and the conicity was determined to measure the narrowing of the earcanal towards the medial direction ($F_{E\text{-}SB(R)}$ and $F_{E\text{-}SB(L)}$). It is computed as the ratio between the cross-section E and SB areas: A ratio close to 1 indicates that the earcanal is non-conical, whereas a higher ratio indicates that the earcanal significantly shrinks in the medial direction.

Earcanal sizes were also measured using an extended version of 3 M™ Eargage earcanal sizing tool (referred to the acronym EE in (Poissenot-Arrigoni et al., 2024)). This tool, comprising plastic spheres in different sizes, was adapted in this study to include additional larger spheres to capture the size of all participants' earcanals (Poissenot-Arrigoni et al., 2024). The earcanal sizes were categorized into multiple sizes from extra-small (XS) to extremely large (XXXL).

During "Week 0," participants underwent hearing condition assessments conducted by an audiologist using a portable audiometer. Hearing screenings occurred in a quiet room with specific frequencies tested for each participant (500, 1000, 2000, and 4000 Hz). Dichotomous variables were created ($HL_{(L)}$ and $HL_{(R)}$) to classify participants as having normal hearing or hearing impairment in each ear.

Hand dominance (or laterality) information was self-reported by participants in the UPQ (left-handed, right-handed, or ambidextrous).

2.2.1.2. Psychosocial characteristics. Biological, demographic, and

Table 2
Physical and psychosocial characteristics of the person.

	Characteristic	Variable label	Variable type / values
Physical characteristics	EE categorization	$EE_{(R)}$; $EE_{(L)}$	Categorical: XS; S; M; L; XL; XXL; XXXL
	Earcanal cross-sections circumferences (left and right)	$C_{E(L)}$; $C_{FB(L)}$ $C_{SB(L)}$; $C_{E(R)}$ $C_{FB(R)}$; $C_{SB(R)}$	Continuous (mm)
	Earcanal cross-sections isoperimetric ratios (left and right)	$IR_{E(L)}$; $IR_{FB(L)}$ $IR_{SB(L)}$; $IR_{E(R)}$; $IR_{FB(R)}$; $IR_{SB(R)}$	Continuous: [0,1]
	Earcanal length	$L_{E\text{-}SB(L)}$; $L_{E\text{-}SB(R)}$	Continuous (mm)
	Earcanal conicity	$F_{E\text{-}SB(L)}$; $F_{E\text{-}SB(R)}$	Continuous (surfaces ratio)
	Hearing loss	$HL_{(L)}$ $HL_{(R)}$	Dichotomous: Yes or no
	Hand dominance	Laterality	Categorical: Left-handed, Right-handed, or Ambidextrous
Psychosocial characteristics	Age	Age	Categorical: 21–44 y.o. or 45–65 y.o.
	Education	Edu	Categorical: No degree, Professional or collegial, or University
	Experience with HPD use (duration)	$Expe_{Time}$	Categorical: 0–5, 6–15, 16–25, or 26+ (years)
	Wearing time during day	$Wear_{Time}$	Categorical: A few minutes, A few hours, or All day
	Used to wear the earplug family	$Habit_{Fam}$	Dichotomous: Yes or no
	Test week	Time	Categorical: Week#1; Week#2; Week#3; Week#4; Week#5; Week#6; Week#7

sociocultural data regarding each participant were collected via the UPQ, encompassing age and educational degree. Participants' ages were categorized into two groups: 21 to 44 years old and 45 to 65 years old. Three categories were used to assess the educational degree: No degree, Professional or collegial, and University.

Participants' prior experiences with earplugs were evaluated through two variables. Firstly, participants reported the duration they had been using earplugs at work, categorized into four groups for the variable "$Expe_{Time}$": 0 to 5 years, 6 to 15 years, 16 to 25 years, and more than 26 years. Secondly, participants disclosed their typical duration of earplug use during a workday, choosing from options "A few minutes," "A few hours," or "All day." Participants also identified the earplug family they were accustomed to. A dichotomous variable, "$Habit_{Fam}$," categorized as "yes" if the worker tested an earplug from a familiar family or "no" if they had no prior experience with that family of earplugs.

Each worker participated in the measurement campaign for 7 weeks, and their responses were collected for each earplug at the end of every week. The categorical variable "time" was recorded and corresponds to the week number of the test. This variable could help assess mid-term habituation to wearing HPDs, a habituation that may occur during the testing campaign, during which participants mostly test earplugs they do not usually wear. It is thus included here as a psychosocial characteristic of the "person" component of the triad, in accordance with the holistic model of HPD use (see Table 5 in (Doutres et al., 2022)).

2.2.2. Environment

The variables related to the physical and psychosocial attributes of the environment are outlined in Table 3 and detailed below.

2.2.2.1. Physical characteristics. The physical aspects of the work environment include characteristics such as air quality, air temperature, humidity, noise, presence of useful acoustics signals and presence of vibrations (Doutres et al., 2022). As the study encompassed three distinct companies and lacked continuous monitoring of those physical characteristics at individual workstations, the physical attributes were represented by the categorical variable "Company" assigned values 1, 2, or 3. This variable enables statistical analyses to gauge the potential influence of the company on the perceived comfort of earplugs. However, it does not specify the particular physical or psychosocial attributes within each company that might affect functional and acoustical comfort.

Throughout the field test campaign, a "season" variable was recorded, indicating values such as "spring," "summer," "fall," and "winter." This variable approximates an atmospheric condition score by assuming that temperatures in the environment are higher in summer compared to spring and fall, and lower in winter. In Quebec, average daily temperatures fluctuate between 22 °C in July and −15 °C in January (source: climat.meteo.gc.ca).

Because continuous noise measurements were not performed at each workstation or for each worker, the daily noise exposure of participants was estimated using two distinct approaches, depending on the data made available by the participating companies. For two of the companies, public health reports conducted within the companies in 2018 provided minimum and maximum values for each job category. This information, combined with the type of job held by each participant, allowed for the assignment of a minimum "$Expo_{min}$" and maximum "$Expo_{max}$" value to each individual. For the third company, only a noise map of the shop floor was available. Rough estimates of the minimum and maximum daily noise exposure levels for each participant were derived based on their job type and the noise map, assuming time spent at each workstation and break times over an 8-hour reference period.

Table 3
Physical and psychosocial characteristics of the environment.

	Characteristic	Variable label	Variable type / values
Physical	Company	Company	Categorical: 1, 2, or 3
	Season of the completion of the UPQ	Season	Categorical: Spring, Summer, Autumn, or Winter
	Maximum daily exposure based on a 3-dB exchange rate	$Expo_{Max}$	Continuous (dB(A))
	Minimum daily exposure based on a 3-dB exchange rate	$Expo_{Min}$	Continuous (dB(A))
Psychosocial	Work duration	W_{Dur}	Continuous (hours per week)
	Exposure time	$Expo_{Time}$	Continuous (hours per week)
	% of exposure time	$Expo_{\%}$	Continuous (%)
	Team work	Team	Dichotomous: Yes or no
	Noise level perception	$Noise_{Percep}$	Likert scale
	Possibility to change department	$Change_{Dep}$	Categorical: Yes or No / Do not know
	Necessity to: Speak, move head, bend	$Must_{Speak}$	Dichotomous: Yes or no
		$Must_{MoHead}$	Dichotomous: Yes or no
		$Must_{Bend}$	Dichotomous: Yes or no
	Earplug interference	$Equip_{Inter}$	Dichotomous: Yes or no
	Work shift	Shift	Dichotomous: Day shift, or Evening and night shifts
	Work schedule	Schedule	Categorical: Week, Week-end or Both

2.2.2.2. Psychosocial characteristics. The psychosocial attributes of the environment were acquired through the UPQ, focusing on categories like "Task and usage" and "situational influences" in accordance with (Doutres et al., 2022).

Participants provided information about their weekly working hours, which was quantified with a continuous variable termed "W_{Dur}" to represent work duration. Additionally, individuals estimated their weekly noise exposure, resulting in two associated variables: "$Expo_{Time}$," indicating daily hours of noise exposure, and "$Expo_{\%}$," representing the percentage of time exposed to noise weekly.

Details regarding work schedules (weekdays, weekends, or both) and shifts (day, evening, or night shifts) were obtained. Three dichotomous variables ("$Must_{Speak}$," "$Must_{MoHead}$," and "$Must_{Bend}$") identified whether workers needed to communicate, move their heads, or bend over to execute their tasks. Participants also reported if any additional equipment interfered with their earplugs ("$Equip_{Inter}$"). Moreover, the presence of teamwork was indicated by a dichotomous variable labeled "Team".

Within the "Situational influences" category of the environment, participants rated their perception of workplace noise using a 5-point Likert scale, gauging from "quiet" to "very noisy" ($Noise_{Percep}$). Furthermore, participants indicated their capacity to switch departments or teams within the company, denoted by the variable "$Change_{Dep}$".

2.2.3. Earplug

This study solely considered the physical attributes of the earplugs, as psychosocial characteristics like attractiveness or aesthetic design (referenced in (Doutres et al., 2022)) were not surveyed in the questionnaires. The physical properties of the earplugs, outlined in Table 4, were evaluated in the laboratory using new samples of the same earplug models tested by the participants. Most of these properties and associated comfort testers are presented in (Poissenot-Arrigoni et al., 2023). The only physical characteristics added specifically for this study on the

Table 4
Physical characteristics of the earplug.

	Characteristic	Variable label	Variable type / values
Earplugs intrinsic properties	Conicity	Con	Dichotomous: Conical or not
	Pod shape	Pod	Dichotomous: Pod shaped or not
	Stemmed	Stem	Dichotomous: Stemmed or not
	Mass	Mass	Continuous (g)
	Diameter	D_1, D_2	Continuous (mm)
Coupled earcanal/ earplug properties measured on comfort testers	Friction coefficient	μ_9	Continuous ()
	Radial force	RF_7, RF_9	Continuous (N)
	Extraction force	EF_9	Continuous (N)
	Expansion time	$Expan_{Time75\%}$	Continuous (s)

functional and acoustical comfort is the expansion time.

Initially, the intrinsic attributes of uncompressed earplugs were evaluated. Earplug shape was assessed through two categorical variables: "Con," indicating conical/cylindrical shape, and "Pod," identifying pod-shaped earplugs. Mass measurement for each earplug was conducted using a scale, and two diameters were assessed on each earplug using a caliper. D_1, situated near the lateral side, and D_2, positioned on the medial side, were measured. However, for statistical analysis exploring the correlation between earplug attributes and functional comfort, only D_1 was considered, given the impracticality of using both D_1 and D_2 simultaneously.

Subsequently, four other characteristics of the coupled earplug/earcanal system were assessed using comfort testers. These properties encompassed radial force, extraction force, friction coefficient and expansion time. Comfort testers, featuring fixed dimensions and temperature control, make use of a hollow rigid cylinder to mimic a human earcanal. The tester diameters were chosen based on morphological research by (Poissenot-Arrigoni et al., 2022), conducted on a group of participants drawn from the same research project. This ensured assessment under conditions closely resembling real-world usage within the human earcanal. These characteristics are pivotal in representing key earplug attributes within the triad, encompassing softness and texture. It is important to note that these characteristics of the coupled "earcanal/earplug" system actually represent the system during the interaction phase of the comfort model (Doutres et al., 2022). However, since all earplugs are tested under the same conditions using comfort testers with rigid walls (i.e., no skin), these characteristics are considered representative of the earplug itself and therefore attributed to the earplug component of the triad. This will be discussed in more detail in the section presenting the limitations of the study (see sec. 5).

More specifically, to evaluate the physical characteristics of the earplug regarding the static mechanical pressure it might exert on earcanal walls, radial force was measured. This assessment was conducted by inserting the earplug into the rigid cylinder of the J-Crimp station operated by Blockwise (©Blockwise, Tempe, Arizona, USA) heated at 36 °C. The test aimed to assess earplug radial force at 9 mm and 7 mm compression, mimicking the diameter of the first bend (FB) section of the earcanal (Poissenot-Arrigoni et al., 2022). The J-Crimp station applied radial displacement to the earplug, measuring the resultant force over 10 min. The iris was heated to 36 °C to match earcanal temperature, allowing the earplugs to reach thermal and mechanical equilibrium during the 10-minute compression. The recorded radial force post-compression served as the earplug's radial force. Given participants' training in proper earplug insertion, it was assumed they wore the earplugs correctly during the field study. Therefore, the insertion depth within the artificial earcanal created by the J-Crimp station was set at 70 % of the earplug length for roll-down foam earplugs, the multi-flange elastomeric polymer earplug, and the push-to-fit foam earplugs. However, the two push-to-fit foam pod earplugs were fully inserted into the rigid earcanal of the comfort tester during measurements. More details about the measurement and computation of the radial force are given in (Poissenot-Arrigoni et al., 2023). In the statistical analysis, only the radial force value at 9 mm compression will be utilized. This decision stemmed from the limitations observed during the statistical analysis exploring the relationships between earplug characteristics and attributes of functional comfort, which restricted the simultaneous use of radial forces at both 9 mm and 7 mm.

The friction coefficient between the earplug and the earcanal represents another physical attribute potentially associated with maintaining in position, insertion and functional comfort caused by earplugs. This coefficient is defined as the ratio between the tangential and normal forces resulting from the interaction between the earplug and the skin. To approximate this coefficient, the normal force at 9 mm compression was obtained from the J-Crimp station (©Blockwise, Tempe, Arizona, USA). Simultaneously, the tangential force was measured using another comfort tester depicted in (Poissenot-Arrigoni et al., 2023). This tester featured a rigid cylindrical sample holder with a diameter of 9 mm, heated at 36 °C, into which an earplug was inserted. A rigid rod, affixed to a newton meter mounted on a helical slide link, was employed to gently push the earplug out of the cylinder at a manually controlled rate, measuring the force required for extraction. The maximum extraction force registered during the sliding of the earplug was considered the tangential force for calculating the friction coefficient, which is actually a static one. Each earplug model underwent testing three times, with a new earplug used for each test. Nonetheless, this setup had limitations, as the cylindrical sample holder lacked skin substitute and was dry without an earwax replica.

Finally, the expansion time ($Expan_{Time75\%}$) was specifically evaluated for this study, as it is anticipated to be a key physical characteristic of the roll-down foam earplugs relevant to understanding functional comfort. It is thus only assessed for this earplug family which needs to be pre-compressed before insertion. For the other earplug families, the expansion time is set to 0. This characteristic is also determined using a J-Crimp station (©Blockwise, Tempe, Arizona, USA) with specific parameters (Fig. 1). Each of the three roll-down-foam earplugs underwent a standardized process: initially, the earplug was placed in the machine's wide-open iris to facilitate insertion without compression. Subsequently, the earplug was swiftly compressed to 40 % of its initial diameter, held at that diameter for 20 s (simulating the rolldown before insertion), and then rapidly expanded to 60 % of its initial diameter, maintaining that for approximately 10 min (simulation the expansion of the earplug inside the earcanal). Throughout this final phase, the earplugs expanded within the rigid earcanal, reaching their maximal force. The time taken to achieve 75 % of the maximum force after the iris release was regarded as the earplug expansion time. This methodology draws inspiration from Gardner's patent (Gardner, 1992) but is notably enhanced in this study by the objective measurement of expansion time and the use of a cylindrical tester.

2.3. Statistical analyses

All statistical analyses were carried out with the software IBM® SPSS® Statistics 29 (IBM Corp., 2023). First, descriptive analyses were conducted to describe the sample via its UPQ answers, and the (dis) comfort subdimensions analysing the COPROD-NAQ answers. Subsequently, following the methodology used by Poissenot-Arrigoni et al. (2023), a series of statistical analyses was conducted to identify triad characteristics significantly impacting functional and acoustical (dis) comfort subdimensions. Linear mixed-effects modeling was chosen due to participants testing various earplugs over seven weeks, accounting for individual variations and missing measurements. Managing the extensive independent variables considered (outlined in section 2.2) involved an initial independent analysis for each triad component. The person triad component, with 27 characteristics, underwent further analysis by partitioning into morphological and non-morphological

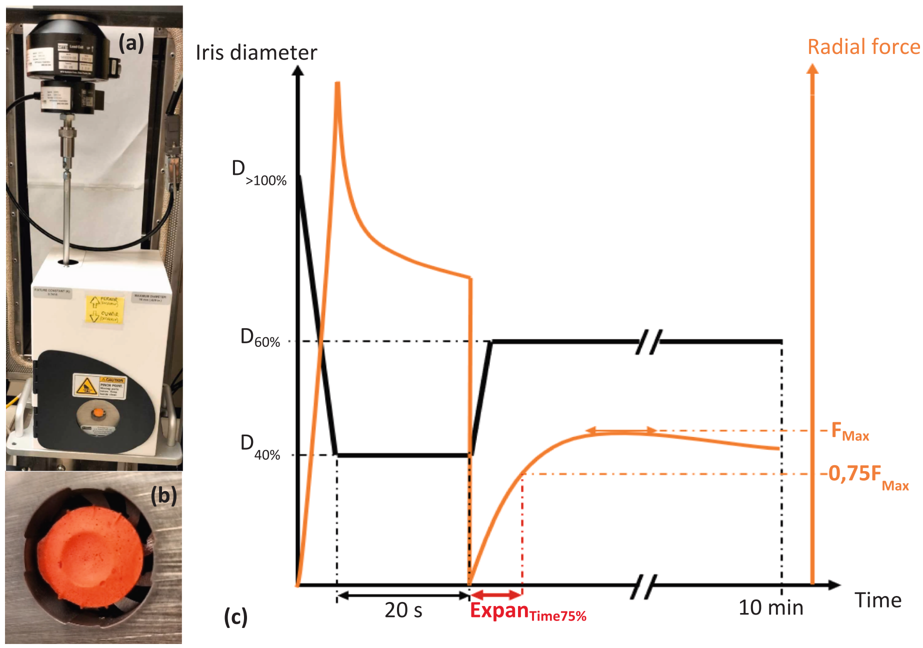


Fig. 1. Comfort tester and procedure to measure the expansion time of roll-down foam earplugs, (a) J-Crimp™ Station with crimp teeth applying displacement on a roll-down foam earplug, (b) close-up of a roll-down foam earplug being tested, (c) a representation of the imposed displacement (black curve), measured force (orange curve) and illustration of the expansion time (red double arrow). The curves are scaled for easier reading. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

subcomponents. This strategy limited variables, yielding more robust statistical outcomes and allowed individual assessment of each triad component's effect on functional and acoustical (dis)comfort subdimensions, disregarding others. Following this screening process, only the variables significantly influencing a (dis)comfort subdimension in the preliminary independent analyses were included in a global analysis. In both preliminary and global analyses, an iterative process was employed for the considered triad variables (e.g., earplug characteristics). Linear mixed-effects modeling retained variables with a p-value below 0.2 at each step, preventing the elimination of potentially influential variables. The process persisted until all remaining independent variables achieved a p-value below 0.2. A subsequent iteration with a significance threshold of 0.1 followed, continuing until all model variables attained a p-value below 0.1 (Grech and Eldawlatly, 2023; Hosmer et al., 2013). Throughout this process, the Akaike Information Criterion (AIC) determined the model with the lowest AIC, balancing quality and simplicity. All variables were normalized using z-transformation before fitting the linear mixed-effects models. In the selected linear mixed-effects model, variables with p-values below 0.05 were considered to significantly impact (dis)comfort subdimensions. Variables within the 0.05 to 0.1 range were deemed trends, suggesting potential comfort influence. For significant variables, the normalized beta-estimate's sign indicated the direction of their influence on comfort. This method facilitated the identification of the most impactful variables on (dis)comfort subdimensions.

3. Results

This section begins by presenting the triad characteristics associated with the comfort measurements conducted on the field (subsection 3.1). A comprehensive description of the characteristics of the triad evaluated in the context of this study has been done in (Poissenot-Arrigoni et al., 2023). Here, a summary of those characteristics is given together with a description of the two physical characteristics added in this study (i.e., earplug expansion time and participant daily noise exposure). Subsection 3.2 presents a descriptive analyses and internal consistency of the 6 (dis)comfort subdimensions (4 for the functional comfort and 2 for the acoustical comfort). Subsections 3.3 and 3.4 present the characteristics of the triad found to significantly influence those (dis)comfort subdimensions. Compared to our previous paper dedicated to the physical comfort (Poissenot-Arrigoni et al., 2023), only the global analysis is presented here for the sake of conciseness (i.e., the three preliminary analyses that consider the characteristics of the person, environment, and earplug components are not presented but only the global analysis which takes into account the selected characteristics of the triad components).

3.1. Physical and psychosocial characteristics of the triad

3.1.1. Person

The sample (N = 159) was mainly composed by men (85 %). The participants in this study exhibited diverse earcanal morphologies, with lengths ranging from 7.8 mm to 19.6 mm and circumferences that progressively decreased from the entrance to the second bend. Based on measurements using the 3M™ Eargage earcanal sizing tool, the majority of earcanals (83 %) were classified as medium to extra-large (M, L or XL), while 13 % were categorized as extremely large (XXL or XXXL). For each participant, the audiologist carried out a hearing screening at week 0, showing that around 63 % of them had normal hearing, while 37 % had a hearing impairment. Specifically, among them, 43 % were unilaterally hearing-impaired and 57 % bilaterally hearing-impaired. Most participants were right-handed (88 %), followed by 11 % left-handed and 1 % ambidextrous. Approximately 56 % of the sample is aged between 45 to 65 years. In terms of earplug use, 23 % had less than 5 years of experience, 27 % between 6 to 15 years, 36 % from 16 to 25 years, and 14 % had over 26 years of earplug use. Thus, half of the participants reported wearing earplugs for more than 16 years. Nearly 41 % tried earplug families they were familiar with before the study. Approximately 66 % of participants reported wearing roll-down foam earplugs.

Educationally, 75 % held a professional or collegial degree, 15 % had a university degree, and 10 % had no degree. Before the study, 74 % of participants wore earplugs throughout their workday, 23 % for a few hours, and 3 % for just a few minutes. Approximately 96 % of the participants believed that using earplugs effectively prevented hearing problems.

3.1.2. Environment

The environment was perceived as noisy or very noisy by 80 % of the participants, a perception supported by the estimated daily exposure levels. Daily exposure could be estimated for 110 participants working across the three companies included in the study. For these participants, the minimum exposure ($Expo_{Min}$) ranged from 80 dB(A) to 101 dB(A), while the maximum exposure ($Expo_{Max}$) ranged from 86 dB(A) to 101 dB (A). Specifically, the $Expo_{Min}$ was between 80 dB(A) and 85 dB(A) for 27 % of the participants, between 86 dB(A) and 90 dB(A) for 55 %, and above 91 dB(A) for 17 % of them. $Expo_{Max}$, on the other hand, was never below 85 dB(A). It was between 85 dB(A) and 90 dB(A) for 23 % of the participants and above 90 dB(A) for 77 % of them. It is worth noting that, at the time of the test campaign (conducted between 2018 and 2020), the daily exposure limit in Quebec was 90 dB(A), which was only reduced to 85 dB(A) in 2023. The significant variability in exposure levels is explained by the diversity of job categories and the acoustic environments across the companies.

In the "task and use" category, around 96 % spoke during work, 46 % frequently moved their head, and 67 % bent their bodies during shifts. Only 7 % reported earplugs interfering with their equipment before the study. Only a small portion of participants (21 %) could change the department as accommodation to reduce their noise exposure.

Participants worked an average of 41 h per week, with 39 % on evening or night shifts and 46 % with variable schedules on the weekdays and weekends. They felt exposed to workplace noise for about 32 h weekly, roughly 77 % of their work time. The majority (79 %) worked alongside colleagues or in teams.

3.1.3. Earplug

The earplugs' physical characteristics and their interaction with the earcanal are detailed in Table 1. The first three characteristics are represented by dichotomous variables, indicating conical shape, pod shape, or stem presence. Mass, medial (D2), and lateral (D1) diameters are provided, with lateral diameters set to 0 mm for the non-canonical shaped push-to-fit foam earplugs due to stem contact avoidance.

Radial forces at 7 mm and 9 mm compression (RF7 and RF9) are utilized to depict earplug stiffness. Earplugs without stems show minimal differences in radial force, while those with stems display significant disparities, confirming stem rigidity. When stemmed earplugs compress to 7 mm, substantial foam compression between the tester cylinder and stem leads to higher radial forces.

Extraction forces for earplugs within the rigid earcanal range between 2.1 and 3.6 N, with the cylindrical foam earplug exhibiting the lowest friction coefficient. Despite different materials and technologies, the multi-flange elastomeric polymer, bell-shaped foam, and push-to-fit foam sheath earplugs surprisingly show similar friction coefficients.

Regarding the expansion time of roll-down-foam earplugs, the cylindrical foam and bullet shaped foam have very similar expansion time (4.06 s and 4.28 s respectively), whereas the bell-shaped foam has a significantly longer expansion time of 6.14 s.

3.2. Descriptive analyses and internal consistency of the (dis)comfort subdimensions

The results of the descriptive analyses of the studied (dis)comfort subdimensions, along with the Alpha values are presented in Table 5. It is shown that, on average, the participants found the tested earplugs moderately comfortable for 3 functional subdimensions (i.e., "FC – Protection from noise", "FC – Removal", and "FC – Insertion"). The level of functional comfort most strongly felt by participants was related to the aspects of removal. For the subdimension "FC – Impact on work", it is important to note that the response scale ranges from 1 (really worse) to 5 (really better). A score close to 3 therefore indicates a certain neutrality from participants regarding the potential effect of earplugs on their work. Regarding the two acoustical subdimensions, participants showed, on average, low levels of discomfort.

Table 5
Descriptive analyses and internal consistency of the studied (dis)comfort subdimensions.

	M (SD)	Median	Minimum-Maximum	Cronbach's Alpha
Functional comfort subdimension				
FC – Protection from noise	3.51 (1.10)	3.71	1–5	0.92
FC – Impact on work	3.14 (0.80)	3.00	1–5	0.95
FC – Removal	4.15 (1.05)	4.67	1–5	0.93
FC – Insertion	3.55 (1.20)	3.80	1–5	0.94
Acoustical discomfort subdimension				
AD – External	2.21 (1.03)	2.00	1–5	0.88
AD – Internal	1.88 (1.04)	1.67	1–5	0.90

Note: M = mean; SD = Standard deviation

However, it is worth noting that across all subdimensions, variability remains high (SD ≈ 1), and the mean differs from the median – being lower for the functional comfort and higher for the acoustical discomfort. This suggests that, despite the overall trend toward comfort, a non-negligible portion of participants experienced and reported significant discomfort.

The questionnaires collected in this study over the seven weeks of testing (N = 727) showed that the internal consistency level (Cronbach's Alpha) is satisfactory for the 6 subdimensions. The values reported in Table 5 indicate that each set of items effectively measure a specific concept with a consistent degree of homogeneity (DeVellis and Thorpe, 2021). Thus, the reliability of the measurements allows them to be used in subsequent analyses.

3.3. Influence of the characteristics of the triad on the functional comfort subdimensions

The statistical analyses carried out to test the influence of the psychosocial and physical characteristics of the triad on the 4 functional comfort subdimensions are presented in subsections 3.3.1 to 3.3.4, respectively.

3.3.1. FC – protection from noise

The global analysis reveals that, by order of importance (based on the amplitude of the beta estimates), the following triad characteristics influence the "FC – Protection from noise" comfort subdimension (see Table 6): familiarity with specific earplug families and morphological characteristics of the earcanals. This subdimension is thus predominantly influenced by characteristics of the person component of the triad. Regarding the most influential characteristics ($Habit_{Fam}$), the model reveals that participants who regularly use earplugs from the same family as the tested ones perceive them as providing better noise protection. Regarding the characteristics of the earcanal, three appear to be predominant, in order of importance: the circumference of the second and first bends cross-sections, the conicity, and the isoperimetric ratio of the entrance and second bend cross-sections. Opposing trends are observed between the right and left earcanals.

3.3.2. FC – impact on work

The results of the global analysis presented in Table 7 reveal that only characteristics of the person triad component influence the "FC – Impact on work" subdimension: familiarity with specific earplug families, hearing loss and time spent wearing earplugs at work (in years).

Table 6
Triad characteristics influencing the "FC − Protection from noise" subdimension.

Triad characteristic	Variable name (p-value)	Beta estimate (estimated marginal means)		Effect direction (toward greater comfort)
Use to wear earplugs from the same family	$Habit_{Fam}$ (<0.001)	never used before:	−0.58 (−0.52)	People accustomed to wearing an earplug from the same family as the tested earplug
		used before:	0 (0.06)	
Circumference, second bend, right earcanal	$C_{SB(R)}$ (<0.001)	−0.43		Smaller circumference of the second bend of the right earcanal
Circumference, first bend, right earcanal	$C_{FB(R)}$ (0.001)	−0.30		Smaller circumference of the first bend of the right earcanal
Circumference, first bend, left earcanal	$C_{FB(L)}$ (<0.001)	0.30		Larger circumference of the first bend of the left earcanal
Conicity, right earcanal	$F_{E\text{-}SB(R)}$ (0.003)	−0.29		Less conical right earcanal
Isoperimetric ratio, entrance, right earcanal	$IR_{E(R)}$ (<0.001)	−0.25		More oval entrance of the right earcanal
Isoperimetric ratio, entrance, left earcanal	$IR_{E(L)}$ (0.004)	0.20		More circular entrance of the left earcanal
Isoperimetric ratio, second bend, right earcanal	$IR_{SB(R)}$ (0.047)	−0.10		More oval second bend of the right earcanal

Table 7
Triad characteristics influencing the "FC − Impact on work" subdimension.

Triad characteristic	Variable name (p-value)	Beta estimate (estimated marginal means)		Effect direction (toward greater comfort)
Use to wear earplugs from the same family	$Habit_{Fam}$ (<0.001)	never used before	−0.38 (−0.28)	Participants accustomed to wearing earplugs from the same family as the tested earplug
		used before	0 (0.11)	
Hearing loss	$HL_{(R)}$ (0.003)	normal hearing	−0.32 (−0.25)	People with hearing impairment in the right ear (including unilaterally and bilaterally hearing-impaired participants)
		hearing impairment	0 (0.77)	
Experience with HPD use (in years)	$Expe_{Time}$ (0.036)	0<-<5 years	0.33 (−0.10)	Participants having been wearing earplugs for less than 26 years find earplugs as having a less negative impact on work
		6<-<15 years	0.48 (0.05)	
		16<-<25 years	0.28 (−0.15)	
		>26 years	0 (−0.43)	

Again, participants familiar with earplugs from the same family as the tested ones report a positive impact on work. People with hearing impairment in the right ear note a positive impact on their work (marginal mean of 0.77). Another long-term effect appears with the variable "time spent wearing earplugs at work" ($Expe_{Time}$). It is found that participants having been wearing earplugs for less than 26 years find the earplugs have a less negative impact on their work (marginal means of all categories are negatives (or close to 0), but the amplitude is greater for the category "$Expe_{Time}$ > 26 years").

3.3.3. *FC − removal*

The "FC- Removal" comfort subdimension is almost solely influenced by characteristics of the person component of the triad (see Table 8). Indeed, only one characteristic belongs to the environment component, while all the others belong to the person component. In order of importance (based on the amplitude of the beta estimates), this subdimension is influenced by the participant's handedness, the size of the earcanals measured using an extended eargage (EE), the duration of protector use during the study period, and finally, numerous morphological characteristics of the earcanal, such as the circumference of the entrance section, the isoperimetric ratio of several earcanal sections, and the circumference of the FB and SB sections within the earcanal. Again, the analyses on earcanal morphology reveal opposite trends between the right and left earcanals. For example, the right earcanal (resp., the left) is associated with greater comfort during protector removal when the entrance section has a narrower (resp., wider) circumference and when this same entrance section is more oval (resp., circular) in shape. Notably, the environment shows no discernible influence, as earplug removal is generally straightforward and independent of workplace conditions. While certain earplug characteristics, such as the presence of a stem, friction coefficient or radial force, might be expected to influence earplug removal, the apparent simplicity of the gesture and/or users' familiarity with wearing earplugs likely explains the lack of significant impact of these earplug characteristics.

3.3.4. *FC − insertion*

The global analysis reveals that, by order of importance (through the amplitude of the beta estimates), the following triad characteristics influence the "FC − Insertion" comfort subdimension: laterality, daily wearing duration, number of years of earplug use, earplug familiarity, hearing loss, stem presence and earcanal entrance shape (see Table 9). Again, the person triad components predominantly influence this functional comfort subdimension, suggesting minimal influence from the environment and the earplug.

Focusing on the 'person' component of the triad, characteristics such as handedness, experience with earplug use, and hearing loss appear to influence the insertion subdimension. In particular, left-handed individuals tend to report greater discomfort during insertion. This may be linked to bilateral asymmetries in earcanal morphology observed in these participants (Poissenot-Arrigoni et al., 2024) (see Discussion, Section 4). This asymmetry could also explain the trend observed here regarding the shape of the earcanal entrance, which should be more oval on the right earcanal and more circular on the left in order to improve insertion comfort (see Table 9). The three characteristics related to earplug experience suggest a long-term habituation effect, a common and largely unavoidable bias in field studies on hearing protection (Doutres et al., 2020). The finding that people with normal hearing perceive earplugs as less comfortable to insert warrants further investigation.

Regarding earplug characteristics alone reveals that the presence of a stem significantly influences the comfort experienced during the insertion. Earplugs with stem were perceived easier to insert than Roll-down-foam ones (even if familiar to 69 % of participants before the study).

Table 8
Triad characteristics influencing the "FC − Removal" subdimension.

Triad characteristic	Variable name (p-value)	Beta estimate (estimated marginal means)		Effect direction (toward greater comfort)
Laterality	Laterality (<0.001)	Left	−2.20 (−0.56)	Ambidextrous individuals (the marginal mean of the ambidextrous category is the only one which is positive and is of the highest amplitude).
		Right	−1.70 (−0.07)	
		Ambidextrous	0 (1.63)	
EE categorization, left earcanal	$EE_{(L)}$ (0.011)	XS	1.95 (0.85)	Individuals with smaller left earcanal find earplugs more comfortable to remove ({XS, S, M, L} compared to {XL, XXL, XXXL}).
		S	1.81 (0.71)	
		M	2.09 (0.99)	
		L	1.87 (0.77)	
		XL	1.59 (0.49)	
		XXL	0.73 (−0.37)	
		XXXL	0 (−1.1)	
EE categorization, right earcanal	$EE_{(R)}$ (0.001)	XS	−0.84 (0.46)	Individuals with extra-large right earcanal find earplugs more comfortable to remove ({XXL, XXXL} compared to {XS, S, M, L, XL})
		S	−1.80 (−0.50)	
		M	−1.49 (−0.20)	
		L	−0.96 (0.34)	
		XL	−1.24 (0.06)	
		XXL	−0.42 (0.87)	
		XXXL	0 (1.30)	
Time	Time (<0.001)	Week#1	−0.50 (0.23)	Earplugs more comfortable to remove at Week#7.
		Week#2	−0.25 (0.47)	
		Week#3	−0.71 (0.01)	
		Week#4	−0.48 (0.25)	
		Week#5	−0.24 (0.48)	
		Week#6	−0.56 (0.16)	
		Week#7	0 (0.72)	
Circumference, entrance, right earcanal	$C_{E(R)}$ (<0.001)	−0.43		Smaller entrance of the right earcanal
Circumference, entrance, left earcanal	$C_{E(L)}$ (<0.001)	0.43		Larger entrance of the left earcanal
Isoperimetric ratio, entrance, right earcanal	$IR_{E(R)}$ (<0,001)	−0.43		More oval entrance of the right earcanal
Isoperimetric ratio, first bend, right earcanal	$IR_{FB(R)}$ (<0.001)	0.24		More circular first bend of the right earcanal
Isoperimetric ratio, entrance, left earcanal	$IR_{E(L)}$ (0.008)	0.22		More circular entrance of the left earcanal
Circumference, second bend, left earcanal	$C_{SB(L)}$ (0.025)	−0.16		Smaller circumference of the second bend of the left earcanal
Isoperimetric ratio, second bend, left	$IR_{SB(L)}$ (0.011)	−0.15		More oval second bend of the left earcanal
Length, left earcanal	$L_{E\text{-}SB(L)}$ (0.024)	−0.14		Shorter left earcanal

Table 9
Triad characteristics influencing the "FC − Insertion" subdimension.

Triad characteristic	Variable name (p-value)	Beta estimate (estimated marginal means)		Effect direction (toward greater comfort)
Laterality	Laterality (<0.001)	Left	−1.97 (−0.83)	Ambidextrous individuals
		Right	1.26 (−0.12)	
		Ambidextrous	0 (1.14)	
Time spent wearing earplugs in a workday	$Wear_{Time}$ (0.014)	Few minutes	−0.79 (−0.52)	Participants wearing earplugs few hours per day or all day long
		Few hours	0.18 (0.45)	
		All day	0 (0.27)	
Experience with HPD use (in years)	$Expe_{Time}$ (<0.001)	0<-<5years	0.77 (0.39)	Individuals with shorter experience wearing earplugs at work
		6<-<15 years	0.55 (0.17)	
		16<-<25 years	0.45 (0.08)	
		>26 years	0 (−0.38)	
Use to wear earplugs from the same family	$Habit_{Fam}$ (<0.001)	never used before	−0.59 (−0.23)	Individuals accustomed to wearing earplugs from the same family as the tested
		used before	0 (0.36)	
Hearing loss left ear	$HL_{(L)}$ (<0.001)	normal hearing	−0.50 (−0.18)	People with hearing impairment in the left ear (including unilaterally and bilaterally hearing-impaired participants)
		hearing impairment	0 (0.32)	
Stem	Stem (<0.001)	without stem	−0.44 (−0.15)	Earplugs with stem
		with stem	0 (0.28)	
Isoperimetric ratio, entrance, right earcanal	$IR_{E(R)}$ (<0.001)	−0.35		More oval entrance of the right earcanal
Isoperimetric ratio, entrance, left earcanal	$IR_{E(L)}$ (0.008)	0.15		More circular entrance of the left earcanal

3.4. Influence of the characteristics of the triad on the acoustical discomfort subdimensions

The statistical analyses conducted to investigate the impact of the psychosocial and physical characteristics of the triad on the 2 acoustical discomfort subdimensions are presented in subsections 3.4.1 and 3.4.2.

3.4.1. AD − external noise

The "AD − External noise" subdimension measures the acoustical discomfort caused by the potential reduction in the intelligibility of useful sounds (i.e., colleague speech, safety alarms, company announcements) when earplugs are worn. The global analysis reveals that this subdimension is primarily influenced by characteristics of the person (mainly related to the size and shape of the earcanal) (see Table 10). With respect to the characteristics of the person component in the triad, it was found that the following earcanal morphological features are associated with reduced discomfort related to the intelligibility of external sounds: a larger cross-section at the first bend of the left earcanal, a smaller cross-section at the first bend of the right earcanal, and a more circular cross-section at the second bend of the right earcanal. Table 10 also shows that participants who need hearing useful sounds for their work, experience less discomfort related to the intelligibility of external sounds.

3.4.2. AD − internal noise

The "AD − Internal noise" subdimension assesses the discomfort associated with an increased auditory perception of the bone-conducted part of physiological noises at low frequencies, and known in the literature as the "occlusion effect". The physiological noises specifically included in this subdimension are: voice, chewing, and other body sounds (e.g., swallowing, stomach, heartbeat, breathing).

The global analysis indicates that this subdimension is predominantly influenced by characteristics related to the person (see Table 11). However, one characteristic associated with the earplug itself is also identified as influential — and is, in fact, the most influential among all triad characteristics examined in this study. For roll-down foam earplugs, discomfort is observed to decrease as the earplug expansion time increases. This could be due to the fact that earplugs with longer expansion times are easier to insert more deeply into the earcanal, given that the occlusion effect is known to diminish with greater insertion depth.

Multiple morphological features of the earcanal also influence this discomfort subdimension. One notable feature is the isoperimetric ratio of the cross-section at the earcanal entrance. Again, the analysis shows opposing trends between the right and left earcanals: for the right earcanal, discomfort decreases as the cross-section becomes more oval, whereas for the left earcanal, discomfort decreases as the cross-section becomes more circular. Additionally, another geometric characteristic of the earcanal is found to impact this discomfort subdimension: earcanal conicity. Specifically, a more conical shape is linked to reduced discomfort from internal sounds.

Additionally, participants who were not accustomed to wearing earplugs from the same family as the tested model experienced greater discomfort related to internal sounds. The variable of least importance is age, with participants aged 21–44 reporting less discomfort from internal sounds compared to those aged 45–65.

Table 10
Triad characteristics influencing the "AD − External noise" subdimension.

Triad characteristic	Variable name (p-value)	Beta estimate (estimated marginal means)	Effect direction (toward reduced discomfort)
Circumference, first bend, left earcanal	$C_{FB(L)}$ (0.002)	−0.33	Larger first bend of the left earcanal
Need to hear useful sounds	$Must_{Hear\text{-}Noise}$ (<0.001)	−0.29	Individuals who need to hear useful external sounds
Circumference, first bend, right earcanal	$C_{FB(R)}$ (0.036)	0.22	Smaller first bend of the right earcanal
Isoperimetric ratio second bend, right earcanal	$IR_{SB(R)}$ (<0.001)	−0.02	More circular second bend of the left earcanal

Table 11
Triad characteristics influencing the "AD − Internal noise" subdimension.

Triad characteristic	Variable name (p-value)	Beta estimate (estimated marginal means)		Effect direction (toward reduced discomfort)
Expansion time	$Expan_{Time75\%}$ (0.024)	−0.47		Longer expansion time (for roll-down foam earplugs only)
Isoperimetric ratio, entrance, right earcanal	$IR_{E(R)}$ (0.001)	0.34		More oval entrance of the right earcanal
Earcanal conicity, left earcanal	$F_{E\text{-}SB(L)}$ (0.003)	−0.28		More conical
Use to wear earplugs from the same family	$Habit_{Fam}$ (0.032)	never used before	0.24 (0.26)	Participants accustomed to wearing earplugs from the same family as the tested earplug
		used before	0 (0.03)	
Isoperimetric ratio, entrance, left earcanal	$IR_{E(L)}$ (0.016)	−0.23		More circular entrance of the left earcanal
Age	Age (0.019)	21–44 years-old	−0.06 (0.02)	21–44-years-old participants
		45–65 years-old	0 (0.31)	

4. Discussion

The analysis of the four subdimensions of functional comfort (noise protection, impact on work, removal, and insertion) and the two subdimensions of acoustical discomfort (external noise and internal noise) reveals a clear and consistent trend. While characteristics of the environment and earplug do exert some influence, their impact appears relatively minor compared to the significant role played by individual characteristics in shaping judgments of these two functional and acoustical comfort dimensions. Specifically, of the 41 characteristics identified as influencing the six (dis)comfort subdimensions analyzed in this study (see sections 3.2 and 3.3), 92.7 % are related to individual characteristics (n = 38/41), 4.9 % to the earplug itself (n = 2/41), and 2.4 % to the environment (n = 1/41).

Regarding the person-related characteristics influencing (dis)comfort subdimensions, certain categories stand out more than others. Specifically, 65.8 % (i.e., n = 25/38) are related to the geometry of the earcanal, and 21.1 % (i.e., n = 8/38) are characteristics linked to experience with HPDs. Additionally, two personal characteristics—laterality and the presence of hearing loss—account for 10.6 % of the influential characteristics for this triad component and are often among the most significant in the models generated for the subdimensions under consideration.

We will first focus more closely on the influential characteristics related to the person-related characteristics influencing comfort aspects and related to the geometry of the earcanal. It is observed that multiple morphological characteristics of the earcanal have a significant to moderate impact on both functional and acoustical (dis)comfort subdimensions. The different influencing characteristics are: (i) the isoperimetric ratios at different cross-sections which influence almost all subdimensions (i.e., all except "FC-Impact on work"), (ii) the circumference at different cross-sections of the earcanals which influence three subdimensions "FC-Protection from noise", "FC-Removal" and "AD-External noise", (iii) the earcanal conicity which influences the "FC-Protection from noise" and "AD-Internal noise" subdimensions and (iv) the earcanal length which affects the "FC-Removal" subdimension. A general trend seems to emerge from these results across the different subdimensions of interest: greater comfort (in terms of insertion, removal, noise protection, and internal noise perception) is associated with a narrower and more oval-shaped right earcanal entrance, and simultaneously, with a wider and more circular left earcanal entrance. This opposite trend between right and left earcanals is intriguing and may reflects a general side-specific relationship between earcanal entrance shape, handedness and comfort. Interestingly, left-handed participants reported more discomfort—both for insertion and removal—than right-handed or ambidextrous participants. One possible explanation is that optimal comfort may arise when the ear's morphology aligns with the insertion dynamics of the hand used on that side. For right-handed individuals, the dominant hand may facilitate insertion into a narrower, more oval right entrance, while the non-dominant hand benefits from a wider, more circular left entrance. In contrast, this morphology–comfort alignment may not hold for left-handed individuals, potentially explaining their lower comfort ratings. Dedicated laboratory studies would be necessary to confirm these hypotheses.

Although the effects of the morphological properties of the earcanal on (dis)comfort subdimensions are complex to analyze, the fact that numerous morphological characteristics play a role suggests two important considerations: (1) the shape and size of the user's earcanal are crucial for achieving a more personalized and comfortable fit, emphasizing the need for further research on shape compatibility between existing 'disposable or reusable' earplugs (of interest in this study) and representative earcanal geometries, and (2) artificial ears, such as those used in ATF to quantify earplug attenuation (ANSI/ASA S12.42, 2014) or the occlusion effect (Doutres et al., 2025), should replicate the complexity of the earcanal's shape and its inter-individual variability as proposed for example in (Poissenot-Arrigoni et al., 2022). Regarding the first point, the importance of compatibility between the earplug and the earcanal may explain why custom-molded earplugs are associated with greater overall comfort compared to 'disposable or reusable' models (Negrini et al., 2025; Terroir et al., 2021).

Let us now analyze the person-related psychosocial characteristics that influence functional and acoustical comfort, specifically those linked to experience with HPDs. The two most prominent characteristics are: "Use to wear earplugs from the same family" (variable $Habit_{Fam}$) and "Experience with HPD use (in years)" (variable $Expe_{Time}$). Regarding the former, this study shows that individuals accustomed to wearing earplugs from the same family as the tested model report that it (i) provides better noise protection ("FC-Protection from noise"), (ii) has a more positive impact on their work ("FC-Impact on work"), (iii) is more comfortable to insert ("FC-Insertion"), and (iv) causes less discomfort related to the perception of internal sounds ("AD-Internal noise"). This bias, linked to long-term habituation to wearing earplugs, is well known and partly motivates researchers to conduct their studies in laboratory settings on populations that are less experienced—or even completely unfamiliar—with HPDs. Field evaluation remains the most relevant approach, as comfort judgment is influenced by the environment (Negrini et al., 2025) and "*laboratory setting may be too sterile an environment for valid comfort studies*" (Casali et al., 1987). Furthermore, as mentioned by Casali et al. (Casali et al., 1987), comfort and preference perceptions of HPDs can evolve over extended wear periods and real-world conditions, which are often not reflected in controlled laboratory studies.

The second most influent characteristics related to experience with HPDs is the number of years participants have been using earplugs (variable $Expe_{Time}$) and which is shown to influence the following two functional comfort subdimensions "FC-Impact on work" and "FC-Insertion." However, the direction of this effect contradicts the expected long-term habituation: participants with less experience wearing earplugs at work (those who have used them for less than 26 years) tend to perceive them as having a positive impact on work and easier to insert. This effect is also observed through the participants' age variable, which influences the discomfort subdimension "AD-Internal noise", with younger participants (21–44 years old) reporting higher comfort levels compared to older participants (45–65 years old). As discussed in (Doutres et al., 2020), greater experience with earplugs tends to generate more extreme judgments (in this case, in a less favorable direction) and most likely associated to higher expectations or demands. It is also worth noting that the age variable shows a statistically significant correlation with the overall comfort latent variable in the study by (Negrini et al., 2025), which uses the same field data as presented here, with the effect direction remaining consistent.

One final person-related characteristic identified as having an important impact on functional comfort is the presence of hearing loss (in the left ear, right ear, or both). In Section 3.3, it was shown that individuals with hearing loss tend to perceive the earplug as having a rather positive impact on their work (e.g., concentration, quality of work, and productivity) and find earplugs easier to insert. The fact that individuals with hearing loss perceive a positive impact on their work could be explained by the idea that hearing loss may increase awareness of the benefits of using hearing protectors in noisy environments. In the case of insertion being perceived as easier, one hypothesis could be that people with hearing loss who frequently use hearing aids become accustomed to inserting a device in their ear. However, in the context of this study, we do not know whether participants with hearing loss typically wear hearing aids.

Regarding the characteristics of the "environment" component of the triad, only one is found to influence the (dis)comfort subdimensions of interest: participants whose work required them to hear useful sounds experienced less discomfort related to the intelligibility of external sounds. This is most likely due to the extensive experience of those participants with wearing hearing protectors (shared across the entire study population), combined with daily training in discerning useful sounds in a noisy environment while being protected.

Among the earplug-related characteristics, only two were found to influence functional or acoustical comfort. Most notably, the expansion time ($Expan_{Time75\%}$) emerged as the most influential characteristic associated with acoustical discomfort related to the perception of internal sounds when wearing protection. Specifically, discomfort induced by roll-down foam earplugs tends to decrease as their expansion time increases. As discussed in Section 3.4.2, this may be explained by the fact that earplugs with longer expansion times are easier to insert more deeply into the earcanal—an important consideration, as deep insertion is known to help mitigate the occlusion effect. Secondly, stemmed earplugs are associated with greater ease of insertion. This result is unsurprising and aligns with existing literature (see introduction section). Thus, no other physical properties of the earplugs appear to influence the (dis)comfort subdimensions of interest in this study. Regarding the level of protection and the perception of external sounds, this aligns with the findings of Terroir's comfort study (Terroir et al., 2022), which showed that acoustic comfort is weakly correlated with the theoretical attenuation of earplugs.

As mentioned previously, the functional and acoustical (dis)comfort subdimensions are primarily influenced by characteristics of the 'person' component of the triad. In contrast, the physical dimension of comfort has been found to be primarily influenced by the physical characteristics of the earplug (Poissenot-Arrigoni et al., 2023). This distinction in the influence of triad components on different dimensions of comfort is particularly noteworthy. It implies that addressing physical discomfort is largely the responsibility of earplug manufacturers, who must develop products designed to mitigate these physical challenges. Conversely, when it comes to enhancing functional and acoustical comfort, the focus seems to shift to employers, hygienists, and preventionists. Their role is to engage with earplug users, assess their individual characteristics and past experiences, and ensure the selection of commercial products that are best suited to their needs, thereby improving functional and acoustical comfort outcomes. This conclusion should, however, be nuanced by the fact that the earplugs studied here are commercially available 'disposable or reusable' types, without acoustic filters to adapt to external noise levels or features designed to reduce the occlusion effect (such as those proposed in (Carillo et al., 2022, 2023, 2025)). As a result, the tested earplugs do not stand out in terms of discomfort judgments related to the perception of external and internal sounds. Another nuance that could be added to this analysis is that its conclusions are based on a population with extensive experience wearing hearing protectors, and therefore not representative of the overall working population.

5. Limitations and perspectives

In general, the limitations of this study are the same as those described in the previous paper dedicated to the physical comfort of earplugs (see section 4 of (Poissenot-Arrigoni et al., 2023)). Overall, these limitations concern (i) the non-exhaustive nature of the triad characteristics, as not all could be measured or accurately obtained — which, for example, prevented the analysis of custom-molded earplugs, even though they were worn by participants during the study. The environment component of the triad is the one for which the fewest physical characteristics were measured. For example, extreme conditions like high temperature or humidity that could alter earplug properties and comfort judgments were not considered into our study. Furthermore, sound level exposure for participants was not directly measured during the study but instead estimated based on data from public health reports on occupational groups issued the year before the field study began. Another limitation relates to (ii) the robustness of linear mixed-effects models based on the ratio between the number of included variables and the number of participants. Due to the complexity of the seven-week research protocol implemented during the COVID-19 pandemic, some participants did not complete all questionnaires, either because of absences due to vacation or sick leave, or because they left the organization for a new job. In certain cases, the non-response rate exceeded 20 %. Despite this, the sample size for univariate statistical analyses remained sufficient, allowing for the selection of relevant triad characteristics to be included in subsequent linear mixed-effects models. However, in these models, the number of variables included was sometimes high relative to the number of participants. This ratio varied from one model to another depending on the targeted outcome variable. Thus, while the sample sizes were generally adequate to meet the study's objectives, some of the results obtained proved difficult to interpret, occasionally contradicting the initial hypotheses.

The comfort dimensions considered in this paper have helped identify additional limitations of the study, for example regarding the participant profile—particularly their experience with wearing hearing protectors—as well as limitations due to the lack of information on the properties resulting from the earcanal/earplug coupling, which for the acoustic dimension, are typically measured objectively to characterize the acoustic behavior of earplugs (i.e., insertion loss (IL), occlusion effect (OE)). These limits are detailed in the rest of this section.

Overall, the Canadian population studied here is highly experienced in using earplugs, with half of the respondents reporting wearing them for more than 16 years. This extensive experience implies a deeply ingrained long-term habituation, which may explain why, in general, the tested earplugs were perceived as relatively comfortable (see sec. 3.2) for these two comfort dimensions. According to the holistic model of earplug use (Doutres et al., 2022), most of this population would already be in a state of "action" and "maintenance," meaning that long-term habituation has already taken place. For future studies, it would be more appropriate to target worker populations with significantly less experience, where long-term habituation has not yet occurred (i.e., those in the "preparation phase" of the holistic model of HPD use (Doutres et al., 2022)). Another limitation arises from the often-contradictory analysis results regarding the effects of the morphological properties of the right and left earcanals. Although several hypotheses have been proposed to explain these contradictions, the shape differences between the right and left earcanals remain relatively small, and it might be more relevant in future studies to consider a binaural indicator. Furthermore, it would have been relevant to include additional morphological characteristics of the earcanal, such as the azimuth angle and elevation angle, to provide a more detailed description of its 3D shape, as done for example in Lee et al. (2018) and Liu et al. (2025). These geometric features of the earcanal are likely to provide valuable insights into specific comfort subdimensions, such as those related to earplug insertion and removal. Finally, although the mixed-effects models used standardized predictors (Z-transformation) that allow comparing the relative influence of each triad characteristics, the resulting coefficients (Beta) cannot be directly interpreted in physical units. Consequently, these values indicate how strongly and in which direction each variable affects comfort, but not by how much the (dis) comfort indices would change for a given physical variation (e.g., +1 mm in earcanal circumference). The aim was therefore to identify and rank the most influential triad characteristics, rather than to provide a precise predictive model. This approach highlights the complexity of earplug/earcanal interactions and the need for further experimental and modeling work to translate these statistical effects into quantifiable ergonomic guidelines.

Regarding the characteristics of the earplug component of the triad, this study showed that very few of the measured characteristics influenced functional and acoustical (dis)comfort subdimensions. This highlights a limitation of the study, namely the fact that properties typically used to characterize the acoustic behavior of the earplug when excited by external sources (i.e., insertion loss, IL) or internal sources (i.e., occlusion effect, OE) were not measured. These properties are not, strictly speaking, characteristics of the earplug component of the triad, as they describe the behavior of the coupled earcanal/earplug system, which depends on insertion quality as well as on the mechanical and geometrical properties of the person's earcanal, surrounding tissues, and the earplug itself. They should therefore be considered characteristics of the interaction phase in the comfort model (Doutres et al., 2022), and ideally should have been measured individually for each participant—preferably at several points during the test phase, including some close to the time of questionnaire completion. Unfortunately, the complexity and additional cost this would have added to an already demanding test protocol made such measurements unfeasible. This type of measurement is, of course, better suited to laboratory studies conducted on a smaller number of participants. For instance, a recent laboratory study on acoustical discomfort related to the occlusion effect showed that one's own voice is perceived as more natural when the objective occlusion effect (measured using microphones, one placed inside the occluded ear canal) is significantly reduced (Carillo et al., 2025). Another way to determine these acoustic properties could have been to use acoustic comfort testers, such as commercially available ATFs or custom test benches developed by the research team (Sgard et al., 2025). However, existing measurement devices do not currently allow for the estimation of properties at the individual level, or even across several representative populations, such as those identified in (Poissenot-Arrigoni et al., 2022).

As in the previous paper on physical comfort (Poissenot-Arrigoni et al., 2023), this study considered the tribological properties of the coupled 'rigid artificial earcanal/earplug' system (radial force, friction coefficient, extraction force) and used them as properties of the 'earplug' component of the triad. Ideally, these properties should belong to the coupled system during the interaction phase and therefore be measured for each participant (thus including inter-individual variability in earcanal geometry and tissue geometry and mechanical properties). However, no sensors or comfort testers are currently advanced enough to perform such measurements, not to mention the additional costs this would entail for a field study of the scale carried out in this research. Laboratory studies would be necessary to develop such sensors and perform comfort measurements in an effort to objectify them, similar to what was proposed by Baker et al. through numerical simulations (Baker et al., 2010).

6. Conclusion

Discomfort from earplugs can lead to improper use or frequent removal, reducing their effectiveness in preventing noise-induced hearing loss. Earplug comfort results from a complex interaction between the user, the environment, and the earplugs themselves—referred to as the triad concept. This study aimed to identify the physical and psychosocial characteristics of all three triad components that significantly impact earplug-induced functional and acoustical comfort. Specifically, four conceptual subdimensions associated to the functional comfort dimension were analysed ("protection against noise" and "impact on work", "removal" and "insertion") as well as two conceptual acoustical subdimensions associated with the perception of "External noises" (i.e., intelligibility of useful sounds) and "Internal noises" (i.e., occlusion effect). The comfort of seven 'disposable or reusable' earplug models was evaluated over seven weeks in a field study involving 173 workers from three Canadian companies. Objective measurements and questionnaires were employed to assess triad characteristics. Various physical properties of the earplugs were also evaluated using comfort testers designed for easy implementation by earplug manufacturers. From a methodological perspective, the strength of this study lies in its complementary approach analyzing both objective and self-reported data to study which (and how) physical and psychosocial characteristics of the triad significantly influence functional and acoustical comfort. Thus, the study provides a comprehensive and multifaceted view of the variables involved.

A rigorous series of statistical analyses was followed. First, descriptive analyses of independent and dependent variables revealed that participants have extensive experience with HPDs and generally perceive the tested earplugs as reasonably comfortable across all subdimensions of interest in this study. Then, linear mixed-effects models indicate that the 'person' component of the triad predominantly influences the functional and acoustical dimensions of earplug comfort. Most of these influencing characteristics are related to morphological properties of the earcanal or prior experience with HPDs. Regarding experience, individuals with greater use of earplugs tend to provide less favorable evaluations. Additionally, consistently using an earplug from the same family as the one tested during the study week has a positive impact on comfort perception for both dimensions of interest. Furthermore, morphological characteristics of the earcanal have been found to have a significant to moderate impact on both functional and acoustical comfort dimensions. Although these effects are complex to analyze, the fact that numerous morphological characteristics play a role suggests two important considerations: (1) the shape and size of the user's earcanal are crucial for achieving a more personalized and comfortable fit and thus an increased comfort, emphasizing the need for further research on shape compatibility between existing 'disposable or reusable' earplugs and representative earcanal geometries, and (2) artificial ears used to measure earplug acoustical properties such as sound attenuation and the occlusion effect should replicate the anatomical complexity and inter-individual variability of the human earcanal. This study also suggests that handedness, bilateral asymmetry in earcanal shape, and the presence of hearing loss have a significant impact on both acoustical and functional comfort dimensions. These factors should therefore not be overlooked during the design phase of earplugs and/or in training related to their fitting and use.

The findings presented in this research enhance the understanding of functional and acoustical comfort associated with earplug use in a realistic work environment. The significant influence of individual characteristics on comfort judgments suggests that ' disposable or reusable' earplugs should be tailored as closely as possible to the user's profile and experience. In the future, it would be relevant to conduct comfort studies targeting populations with limited experience in earplug use, in order to better understand the comfort perceived by individuals who have not yet regularly adopted HPD. Such studies would provide valuable insights into individuals who have not yet completed the acclimatization period, which is essential for full adherence to hearing protection use (Doutres et al., 2022). Furthermore, the results of this study pave the way for more in-depth laboratory investigations of earcanal morphology (and potential influencing factors such as age) and its effect on functional and acoustic comfort, with the aim of more precisely guiding the design and selection of 'disposable or reusable' earplugs for specific populations.

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.

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

During the preparation of this work the authors used GPT-5 (OpenAI, 2025), retrieved from https://chatgpt.com, in order to enhance the text's coherence, grammar, and syntax. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

CRediT authorship contribution statement

Bastien Poissenot-Arrigoni: Writing – review & editing, Validation, Methodology, Investigation, Formal analysis. **Olivier Doutres:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Alessia Negrini:** Writing – review & editing, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Djamal Berbiche:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Franck Sgard:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors acknowledge the support of the Institut de Recherche Robert-Sauvé en Santé et en Sécurité du Travail (IRSST) (Funding Reference No. 2015-0014) and the MITACS Accelerate program (Funding Reference No. IT10643). Authors would like to thank Laurence Martin, Marc-André Gaudreau, François-Xavier Coupal and the team of audiologists who conducted the field study. Authors also thank Luiz Melo for the management of the Blockwise measurements and Olivier Bouthot, for the support for the measurements on the earplug's extraction force test bench.

Data availability

Data will be made available on request.

References

Acton, W.I., 1967. Effects of ear protection on communication. Ann. Occup. Hyg. 10, 423–429. https://doi.org/10.1093/annhyg/10.4.423.

ANSI/ASA S12.42 (**2014**). "Methods for the Measurement of Insertion Loss of Hearing Protection Devices in Continuous or Impulsive Noise Using Microphone-in-Real-Ear or Acoustic Test Fixture Procedures.,".

Arezes, P. M., Abelenda, C., and Braga, A. C. (**2008**). "An evaluation of comfort afforded by hearing protection devices," Proc. AHFE 2008, AHFE International, Las Vegas, NV, USA, 1–8. Presented at the 2nd International Conference on Applied Human Factors and Ergonomics.

Baker, A.T., Lee, S., Mayfield, F., 2010. Evaluating hearing protection comfort through computer modeling. Proc, SIMULIA Cust. Conf., p. 15

Berger, E. H. (**2013**). "'Calibrating' the insertion depth of roll-down foam earplugs," Proc. ICA 2013, Acoustical Society of America, Montreal, QC, Canada, 3235. Presented at the ICA 2013.

Berger, E. H., and Voix, J. (**2022**). "Hearing protection devices (chapter 11)," In D. K. Meinke, E. H. Berger, R. L. Neitzel, D. P. Driscoll, and K. Bright (Eds.), Noise Man., 6th edition, AIHA Press, Falls Church (VA), 6th edition.

Bockstael, A., De Coensel, B., Botteldooren, D., D'Haenens, W., Keppler, H., Maes, L., Philips, B., et al., 2011. Speech recognition in noise with active and passive hearing protectors: a comparative study. J. Acoust. Soc. Am. 129, 3702–3715. https://doi.org/10.1121/1.3575599.

Canadian Standards Association (**2014**). "CSA Z94.2-14, Hearing protection devices: performance, selection, care and use.,".

Carillo, K., Sgard, F., Dazel, O., Doutres, O., 2022. Reduction of the occlusion effect induced by earplugs using quasi perfect broadband absorption. Sci. Rep. 12, 15336. https://doi.org/10.1038/s41598-022-19641-3.

Carillo, K., Sgard, F., Dazel, O., Doutres, O., 2023. Passive earplug including Helmholtz resonators arranged in series to achieve broadband near zero occlusion effect at low frequencies. J. Acoust. Soc. Am. 154, 2099–2111. https://doi.org/10.1121/10.0021185.

Carillo, K., Sgard, F., Dazel, O., Doutres, O., 2025. Enhancing acoustic comfort for earplug users: objective and subjective evaluation of bone-conducted sound with meta-earplugs incorporating Helmholtz resonators. Appl. Acoust. 240, 110929. https://doi.org/10.1016/j.apacoust.2025.110929.

Casali, J.G., Lam, S.T., Epps, B.W., 1987. Rating and Ranking Methods for Hearing Protector Wearability. Sound Vib. 21, 10–18.

Denk, F., Jürgensen, L., Husstedt, H., 2024. Evaluation of active Occlusion effect Cancellation in Earphones by Subjective, Real-Ear and Coupler Measurements. J. Audio Eng. Soc. 72, 145–160. https://doi.org/10.17743/jaes.2022.0124.

DeVellis, R.F., Thorpe, C.T., 2021. *Scale Development: Theory and Applications*.

Doutres, O., Luan, Y., Cyr-Desroches, M.-O., Carillo, K., Richert, R., Sgard, F., 2025. On the design of an acoustical test fixture for assessing the objective occlusion effect. Appl. Acoust. 228, 110295. https://doi.org/10.1016/j.apacoust.2024.110295.

Doutres, O., Sgard, F., Terroir, J., Perrin, N., Jolly, C., Gauvin, C., Negrini, A., 2019. A critical review of the literature on comfort of hearing protection devices: definition of comfort and identification of its main attributes for earplug types. Int. J. Audiol. 58, 824–833. https://doi.org/10.1080/14992027.2019.1646930.

Doutres, O., Sgard, F., Terroir, J., Perrin, N., Jolly, C., Gauvin, C., Negrini, A., 2020. A critical review of the literature on comfort of hearing protection devices: Analysis of the comfort measurement variability. Int. J. Occup. Saf. Ergon. https://doi.org/10.1080/10803548.2020.1772546.

Doutres, O., Terroir, J., Jolly, C., Gauvin, C., Martin, L., Negrini, A., 2022. Towards a Holistic Model explaining Hearing Protection Device use among Workers. Int. J. Environ. Res. Public Health 19, 5578. https://doi.org/10.3390/ijerph19095578.

Gardner, R. Jr. (**1992**). *Polymeric foam earplug*, WO92/06659, (00000).

Giguère, C., Berger, E.H., 2016. Speech recognition in noise under hearing protection: a computational study of the combined effects of hearing loss and hearing protector attenuation. Int. J. Audiol. 55, S30–S40. https://doi.org/10.3109/14992027.2015.1129460.

Gonçalves, C.G.O., Lüders, D., Guirado, D.S., Albizu, E.J., Marques, J.M., 2015. Perception of hearing protectors by workers that participate in hearing preservation programs: a preliminary study. CoDAS 27, 309–318. https://doi.org/10.1590/2317-1782/20152014139.

Grech, V., Eldawlatly, A.A., 2023. The P value - and its historical underpinnings – pro and con. Saudi J Anaesth 17, 391. https://doi.org/10.4103/sja.sja_223_23.

Hosmer, D. W., Lemeshow, S., and Sturdivant, R. X. (**2013**). *Applied Logistic Regression*, John Wiley & Sons, 528 pages.

Killion, M. C. (**1988**). "The hollow voice occlusion effect.," 13th Danavox Symp., Hearing aid fitting: Theoretical and practical views, J.H. Jensen, Copenhagen, Denmark, 231–241. Presented at the 13th Danavox Symposium.

Killion, M.C., 2012. Factors influencing use of hearing protection by trumpet players. Trends Amplif. 16, 173–178.

Kryter, K.D., 1946. Effects of Ear protective Devices on the Intelligibility of Speech in Noise. J. Acoust. Soc. Am. 18, 413–417. https://doi.org/10.1121/1.1916380.

Lee, W., Yang, X., Jung, H., Bok, I., Kim, C., Kwon, O., You, H., 2018. Anthropometric analysis of 3D ear scans of Koreans and Caucasians for ear product design. Ergonomics 61, 1480–1495. https://doi.org/10.1080/00140139.2018.1493150.

Liu, K., Yan, Y., Zeng, K., Wang, H., 2025. Statistical shape analysis of the chinese external ear for ergonomic design of in-ear products. Ergonomics 1–20. https://doi.org/10.1080/00140139.2025.2458631.

Mueller, H.G., 2003. There is less talking in barrels-but the OE is still with us. Hear. J. 56, 10–16.

Negrini, A., Gauvin, C., Berbiche, D., Terroir, J., Perrin, N., Jolly, C., Martin, L., et al., 2025. Development and validation of the north American COmfort of hearing PROtection Device questionnaire (COPROD-NAQ). Saf. Sci. 181, 106688. https://doi.org/10.1016/j.ssci.2024.106688.

Park, M.-Y., Casali, J.G., 1991. An empirical study of comfort afforded by various hearing protection devices: Laboratory versus field results. Appl. Acoust. 34, 151–179.

Poissenot-Arrigoni, B., Law, C.H., Berbiche, D., Sgard, F., Doutres, O., 2022. Morphologic clustering of earcanals using deep learning algorithm to design artificial ears dedicated to earplug attenuation measurement. J. Acoust. Soc. Am. 152, 3155–3169. https://doi.org/10.1121/10.0015237.

Poissenot-Arrigoni, B., Martin, L., Negrini, A., Berbiche, D., Doutres, O., Sgard, F., 2024. Reliability of an extended version of the 3m™ Eargage tool to assess earcanal size and assist earplug selection. Int. J. Audiol. 1–10. https://doi.org/10.1080/14992027.2024.2352045.

Poissenot-Arrigoni, B., Negrini, A., Berbiche, D., Sgard, F., Doutres, O., 2023. Analysis of the physical discomfort of earplugs experienced by a group of workers in Canadian companies and identification of the influencing variables. Int. J. Ind. Ergon. 98, 103508. https://doi.org/10.1016/j.ergon.2023.103508.

Saint-Gaudens, H., 2025. *Understanding the discomfort induced by earplug when hearing our own voice: an experimental investigation of the occlusion effect in laboratory conditions*. École de Technologie Supérieure, Montreal, QC, Canada. PhD thesis.

Sgard, F., Carillo, K., Kersten, S., Richert, R., Doutres, O., 2025. "Virtual and experimental acoustical comfort testers for earplugs," Malaga. Presented at the Forum Acusticum Euronoise, Spain, p. 2025.

Spomer, J., Estrich, C.G., Halpin, D., Lipman, R.D., Araujo, M.W.B., 2017. "Clinician Perceptions of 4 Hearing Protection Devices," JDR Clin. Transl. Res. 2, 363–369. https://doi.org/10.1177/2380084417715599.

Stinson, M.R., Lawton, B.W., 1989. Specification of the geometry of the human ear canal for the prediction of sound-pressure level distribution. J. Acoust. Soc. Am. 85, 2492–2503. https://doi.org/10.1121/1.397744.

Suter, A.H., 1992. Communication and Job Performance in Noise : A Review, Vol. 28. American Speech-Language-Hearing Association, Rockville (MD).

Sweetland, K. F. (**1983**). *Physical predictors for earmuff comfort.* (Master's thesis), Loughborough University of Technology, England. Retrieved from https://dspace.lboro.ac.uk/dspace-jspui/handle/2134/12214.

Terroir, J., Perrin, N., Wild, P., 2022. Comfort of earplugs: results of a field survey based on the COPROD questionnaire. Ergonomics 65, 1173–1193. https://doi.org/10.1080/00140139.2021.1990415.

Terroir, J., Perrin, N., Wild, P., Doutres, O., Sgard, F., Gauvin, C., Negrini, A., 2021. Assessing the comfort of earplugs: development and validation of the French version of the COPROD questionnaire. Ergonomics 1–14. https://doi.org/10.1080/00140139.2021.1880027.

Valentin, O., Ezzaf, S., Gauthier, P.-A., Berbiche, D., Negrini, A., Doutres, O., Sgard, F., et al., 2024. Assessing the multidimensional comfort of earplugs in virtual industrial noise environments. Appl. Ergon. 121, 104343. https://doi.org/10.1016/j.apergo.2024.104343.