# Understanding the Discomfort Induced by Earplugs when Hearing our Own Voice: an Experimental Investigation of the Occlusion Effect in Laboratory Conditions

by

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**Compréhension de l’inconfort induit par les bouchons d’oreille lors de l’écoute de sa propre voix : une étude expérimentale de l’effet d’occlusion en laboratoire**

Hugo SAINT-GAUDENS

## RESUMÉ

L’effet d’occlusion est généralement décrit comme une perception amplifiée et déformée des bruits physiologiques du corps, tels que la parole, la mastication et les battements cardiaques. Dans de nombreux cas, l’effet d’occlusion induit par les protecteurs auditifs entraîne un inconfort acoustique qui peut mener à une exposition accrue au bruit en raison d’une utilisation inadéquate ou du retrait du protecteur par l’utilisateur pour soulager son inconfort. Malgré de nombreuses études menées au cours des dernières décennies, plusieurs aspects liés à la mesure de l’effet d’occlusion et à l’évaluation de l’inconfort qu’il génère restent encore à investiguer.

Dans cette thèse, l’effet d’occlusion causé par les protecteurs auditifs de type bouchons d’oreille est étudié afin de mieux comprendre l’inconfort qu’il engendre, au moyen d’une étude expérimentale réalisée en laboratoire avec des participants humains. À cette fin, la thèse s’articule autour de trois objectifs : (i) proposer une méthodologie pour mesurer l’effet d’occlusion objectif induit par la parole, (ii) identifier et hiérarchiser les caractéristiques physiques et psychosociales de la triade environnement–personne–protecteur qui influencent l’inconfort ressenti par l’utilisateur, et (iii) objectiver l’effet d’occlusion ressenti à l’aide d’indicateurs objectifs basés sur des mesures microphoniques. De plus, la formulation des questions utilisées pour évaluer l’inconfort lié à l’effet d’occlusion, ainsi que la méthodologie relative à son évaluation, sont également investiguées.

Les données nécessaires à l’atteinte de ces objectifs ont été recueillies à travers deux campagnes de mesures en laboratoire menées auprès de 63 participants humains, ainsi qu’un sondage réalisé auprès de 21 répondants.

Dans une première partie, divers aspects liés à la mesure objective de l’effet d’occlusion sont examinés, notamment l’indicateur, la source de stimulation et la méthode de mesure. La quantification de l’effet d’occlusion objectif à partir d’indicateurs dépendant de la fréquence demeure l’approche la plus adaptée pour analyser le phénomène sur l’ensemble du spectre fréquentiel. Toutefois, les indicateurs de valeur unique basés sur la bande moyenne 160–500 Hz permettent d’observer des tendances, sont simples à calculer et présentent une variabilité moindre. Par ailleurs, l’induction de l’effet d’occlusion par la parole continue permet une mesure simple et reproductible de l’effet d’occlusion objectif, tout en demeurant représentative de la situation dans laquelle cet inconfort est généralement rapporté par les utilisateurs. Enfin, une méthode fondée sur des mesures simultanées à l’intérieur et à l’extérieur du conduit auditif occlus, analogue à la méthode de réduction du bruit pour l’évaluation de l’atténuation sonore, permet, à partir d’une seule mesure, d’obtenir un indicateur objectif de l’effet d’occlusion dans chaque oreille indépendamment, sans nécessiter de mesure oreille ouverte.

Dans une deuxième partie, des éléments clés relatifs à l'évaluation de l'inconfort à l'aide d'un questionnaire sont mis en évidence. Bien que plusieurs termes puissent être utilisés pour évaluer l'inconfort en français, le mot « gêne » apparaît adéquat et bien compris, à condition que sa définition soit donnée aux participants avant les tests. La comparaison entre l'« effet d'occlusion ressenti » et l'« effet d'occlusion perçu » a révélé des différences significatives sur l'échelle de cotation, soulignant l'importance de questions claires, précises et facilement compréhensibles lors de l'évaluation de l'inconfort.

Dans une troisième partie, les caractéristiques les plus influentes de la triade environnement–personne–protecteur auditif sont identifiées à l'aide d'une approche statistique basée sur des modèles linéaires mixtes. Parmi les facteurs liés à l'utilisateur, la familiarité avec l'expérimentateur (associée à un inconfort plus élevé), la morphologie non circulaire du conduit auditif au niveau du second coude (associée à un inconfort accru), et les pertes auditives à 250, 500 et 1000 Hz (influant à un degré moindre sur l'inconfort) ont été identifiés. Le modèle de bouchon d'oreille n'a pas montré d'influence significative, alors que le niveau de bruit ambiant augmentait significativement l'inconfort. Concernant l'interaction entre l'utilisateur et le protecteur, la profondeur d'insertion a eu un effet notable, les insertions profondes réduisant l'inconfort en comparaison aux insertions superficielles.

Dans une quatrième partie, l'inconfort associé à l'effet d'occlusion est objectivé à l'aide d'une approche statistique basée sur des modèles linéaires mixtes. Lorsqu'on se base uniquement sur des indicateurs microphoniques, l'inconfort est lié à l'augmentation du niveau sonore dans l'oreille occluse dans la bande d'octave centrée à 125 Hz, ainsi qu'au niveau global de bruit ambiant dans l'environnement de test. Toutefois, ce premier modèle présentait une faible puissance statistique et une précision prédictive limitée. Lorsque les caractéristiques influentes de la triade environnement–personne–protecteur auditif sont combinées à ces indicateurs objectifs, la puissance statistique et la précision prédictive du modèle s'améliorent. Ce second modèle a également mis en évidence l'influence plus marquée des caractéristiques physiques et psychosociales des utilisateurs par rapport aux indicateurs objectifs.

Le travail réalisé dans le cadre de cette thèse contribue à une meilleure compréhension de l'inconfort associé à l'effet d'occlusion induit par les bouchons d'oreille et propose des méthodes pour améliorer sa mesure à l'aide de microphones et son évaluation à l'aide de questionnaires. Les résultats de ce travail contribueront également au développement de bouchons d'oreille générant un effet d'occlusion réduit, et donc plus confortables, ainsi qu'à une meilleure sélection des bouchons sur le terrain, en tenant compte de cet aspect du confort.

**Mots Clefs** : Effet d'occlusion, Bouchons de protection, Confort acoustique, Sa propre voix

**Understanding the Discomfort Induced by Earplugs when Hearing our Own Voice: an Experimental Investigation of the Occlusion Effect in Laboratory Conditions**

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## ABSTRACT

The occlusion effect is typically described as an amplified and distorted perception of physiological sounds of one's own body, such as speech, chewing, and heartbeat. In many cases, the occlusion effect induced by hearing protection devices leads to acoustical discomfort that can result in increased noise exposure due to improper use or removal of the protector by the wearer as a way to alleviate discomfort. Despite numerous studies over the past decades, several aspects relating to the measurement of the occlusion effect and the assessment of the discomfort it causes remain to be investigated.

In this thesis, the occlusion effect caused by earplug-type hearing protection devices is investigated to achieve a better understanding of the discomfort it produces through an experimental study with human participants in laboratory conditions. For this purpose, this thesis focuses on (i) proposing a methodology for measuring the objective occlusion effect induced by speech, (ii) identifying and prioritizing the physical and psychosocial characteristics of the environment–person–protector triad that influence the discomfort experienced by a user, and (iii) objectivizing the occlusion effect experienced by a user using indicators derived from microphonic measurements. In addition, the formulation of questions used to evaluate occlusion effect-related discomfort, as well as the methodology for its assessment, are also investigated.

The data necessary to achieve these objectives were collected through two measurement campaigns conducted in laboratory conditions with 63 human participants, along with a survey of 21 respondents.

In the first part, various aspects related to the objective measurement of the occlusion effect are examined, namely the indicator, the stimulation source, and the measurement method. The quantification of the objective occlusion effect based on frequency-dependent indicators remains the most suitable approach to analyze the phenomenon across the frequency range. However, single-value indicators based on the averaged 160–500 Hz band allow trends to be observed, are simple to compute, and show lower variability than others. Moreover, inducing the occlusion effect through continuous speech enables easy and reproducible measurement of the objective occlusion effect, while remaining representative of the situation for which this discomfort is generally reported by users. Finally, a method based on simultaneous measurements inside and outside the occluded earcanal, analogous to the noise reduction method for sound attenuation assessment, allows from a single measurement the derivation of an objective occlusion effect indicator in each ear independently, without the need for an open-ear measurement.

In the second part, key aspects related to assessing discomfort through a questionnaire are highlighted. Although various terms can be used to assess discomfort in French, the word "gêne" appears suitable and well understood, provided that its definition is given to participants before testing. The comparison between the "experienced occlusion effect" and the "perceived occlusion effect" revealed significant differences on the rating scale, highlighting the importance of clear, precise, and easily understandable questions when evaluating discomfort.

In the third part, the most influential characteristics of the environment–person–hearing protection device triad are identified using a statistical approach based on mixed linear models. User-related factors included acquaintance with the experimenter (associated with higher discomfort), non-circular earcanal morphology at the second bend (associated with greater discomfort), and hearing loss at 250, 500, and 1000 Hz (which influenced discomfort to a lesser degree). The earplug model did not significantly affect discomfort, whereas environmental background noise level significantly increased discomfort. Regarding the interaction between the user and the protector, insertion depth had a significant effect, with deeper insertions leading to less discomfort than shallow ones.

In the fourth part, discomfort associated with the occlusion effect is objectivized using a statistical approach based on mixed linear models. When relying solely on microphonic-based indicators, discomfort was linked to increasing noise level in the occluded ear within the 125 Hz octave band and to the overall background noise level of the test environment. However, this first model presented low statistical power and limited predictive accuracy. When the influential characteristics of the environment–person–hearing protection device triad were combined with these objective indicators, the model's statistical power and predictive accuracy improved. This second model also highlighted the stronger influence of users' physical and psychosocial characteristics compared to objective indicators.

The work conducted in this thesis contributes to a deeper understanding of the discomfort associated with the occlusion effect induced by earplug-type hearing protection devices and proposes methods to improve its measurement using microphones and its assessment using questionnaires. The results of this work will also contribute to the development of earplugs that generate less occlusion effect and are therefore more comfortable, as well as to improved earplug selection in the field by taking this aspect of comfort into account.

**Keywords** : Occlusion Effect, Earplugs, Acoustical Comfort, Own voice

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| | |
|---|---|
| AC | Air Conduction |
| AIC | Akaike Information Criterion |
| ANOVA | Analysis of Variance |
| AVG | average |
| BC | Bone Conduction |
| B-L | bandwidth-limited |
| BNL | background noise level |
| BT | Bone Transducer |
| C1 | Measurement Campaign 1 |
| C2 | Measurement campaign 2 |
| CUS | Custom earplug |
| ERM | Earmuff |
| ERP | Earplug |
| ÉTS | École de technologie supérieure |
| HF | High Frequency |
| HL | Hearing Loss |
| HPD | Hearing Protection Device |
| HTL | Hearing Threshold Level |
| IEM | Inner Ear Microphone |
| IL | Insertion Loss |
| LF | Low Frequency |
| Ln | Percentile Level |

| | |
|---|---|
| MF | Mid Frequency |
| MLM | Mixed Linear Model |
| NIHL | Noise Induced Hearing Loss |
| NR | Noise Reduction |
| OE | Occlusion Effect |
| $OE_{exp}$ | Experienced Occlusion Effect |
| OEI | Occlusion Effect Index |
| OEM | Outer Ear Microphone |
| $OE_{obj}$ | Objective Occlusion Effect |
| $OE_{perc}$ | Perceived Occlusion Effect |
| $OE_{subj}$ | Subjective Occlusion Effect |
| P2F | Push-to-fit earplug |
| PM | Premolded earplug |
| PTA | Pure Tone Average |
| RDF | Roll-down foam earplug |
| REAT | Real Ear Attenuation at Threshold |
| ref | Reference |
| RMS | Root Mean Square |
| RT | Real Time |
| SD | Standard Deviation |
| SNR | Signal-to-noise ratio |
| SPL | Sound Pressure Level |

| | |
|---|---|
| SRT | Speech reception Thresholds |
| STD | Standard |
| SVI | Single Value Indicator |
| VLF | Very Low Frequency |

## LIST OF SYMBOLS

| | |
|---|---|
| dB | decibel |
| dB(A) | A-weighted decibel |
| g | grams |
| h | hour |
| Hz | Hertz (with prefix k for kilo-) |
| in | inch |
| $L_{eq}$ | equivalent continuous sound pressure level |
| $L_{eq(A)}$ | A-weighted equivalent continuous sound pressure level |
| m | meter (with prefix m for milli-) |
| p | acoustic pressure [Pa] |
| s | seconds (with prefix m for milli-) |

# INTRODUCTION

## 0.1 Context

Occupational noise-induced hearing loss (NIHL) resulting from industrial noise exposure is one of the most common occupational diseases in Quebec, Canada, and worldwide. According to data compiled by the Canadian Health Measures Survey for the period from 2012 to 2015, 11 million Canadian workers worked in a noisy environment, of which 6 million (56%) were considered vulnerable to noise (Ramage-Morin & Gosselin, 2018). Despite legislation governing regulations on occupational health and safety (Article S-2.1, (RLRQ, 2023)), which obliges the employer to implement measures to protect workers from noise exposure, NIHL remains the most reported occupational injury in Quebec and the most costly to the Quebec state and these numbers continue to rise year after year (Busque, Lebeau, Tremblay, Boucher, & Dugauy, 2022; CNESST, 2023; Lamarche & Aubin, 2019). On a global scale, occupational hearing loss is the second most significant occupational disease, accounting for approximately 22% of total cases (World Health Organization, 2018). However, the effects of noise on health are 100% preventable. The three general solutions to address the issue of workers' exposure to noise (Berger & Voix, 2022; Driscoll & Royster, 2003) are :

- Elimination at the source, which involves purchasing quieter machinery;
- Engineering methods, which involve reducing noise at the source or constraining sound transmission pathways using noise enclosures and acoustic materials;
- Administrative methods, which involve using employee management strategies to minimize their exposure time;
- The use of hearing protection devices (HPD), which are provided to each employee.

Although the first two approaches are preferable, their implementation can be challenging due to budgetary or technical constraints (e.g., the inability to enclose certain types of machines, such as conveyors). Therefore, the use of HPDs is widespread, even though they represent the last line of defense for workers against the noise (Berger & Voix, 2022). HPDs are available in two types, either earplugs (ERP) and earmuffs (ERM), and operate based on two principles: (i) passive sound reduction, which relies on the mechanical properties of materials and (ii) active sound reduction, which uses electronic systems embedded in the HPD. In the particular case where a user combines the simultaneous use of ERP and ERM, this is referred to as double protection (Berger & Voix, 2022). Several examples of HPDs are presented in Figure 0.1. Although their purpose is the same, they differ in terms of geometry, constituent materials, and positioning technique (Berger & Voix, 2022). In this doctoral thesis, emphasis is placed on passive ERP-type HPDs, as they accounted for over 85% of all HPD units used in 2023 (BCC Publishing, 2021).

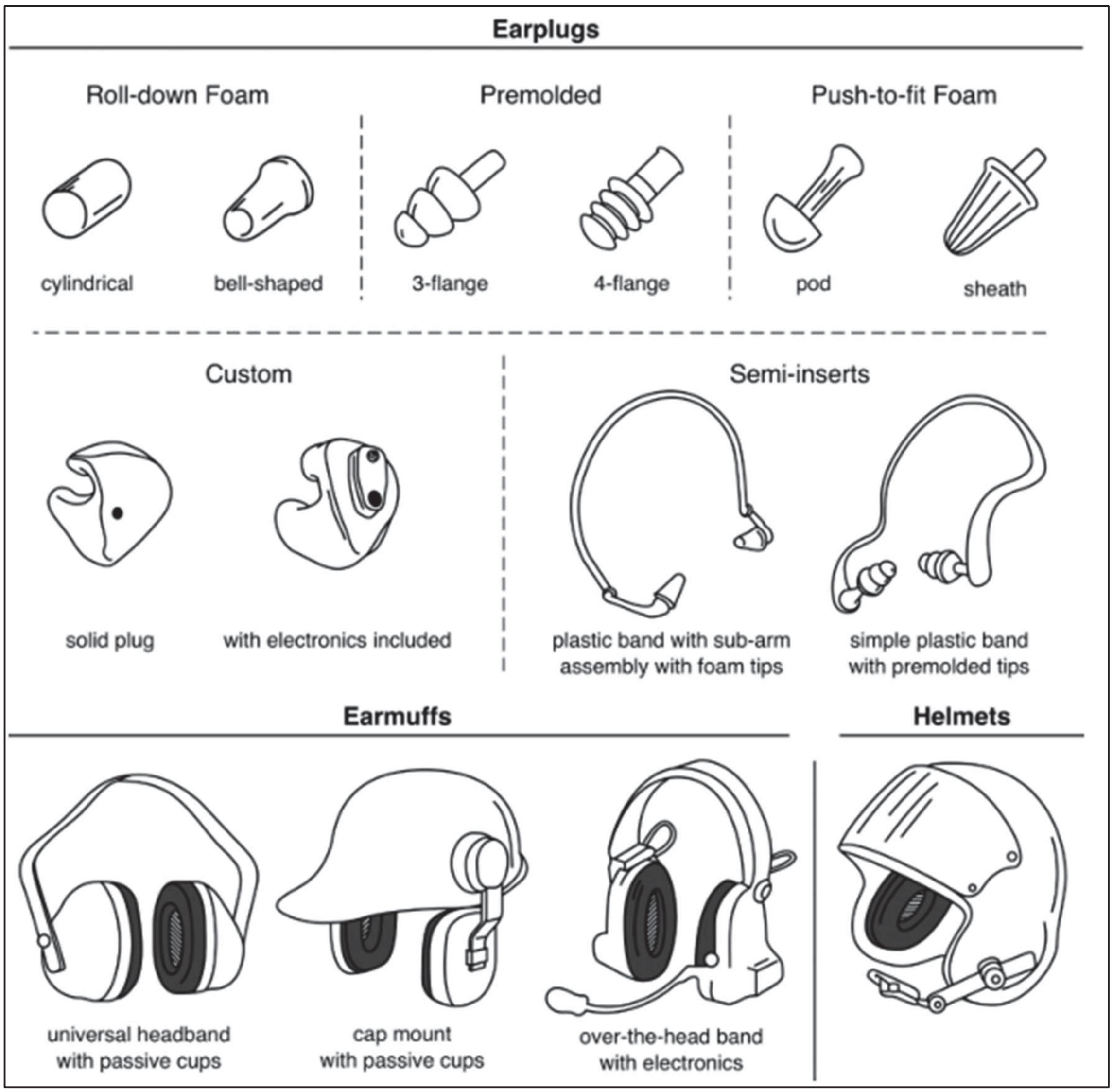



Figure 0.1 Example of various types of earplugs (ERPs) and earmuffs (ERMs) hearing protection devices (HPDs)
Taken from Berger, E. H., & Voix, J. (2022)

## 0.2 Earplug (dis)comfort and its model

Reducing noise entering the ear with HPDs is often ineffective due, in particular, to improper use by the wearer. This includes wearing them incorrectly, inconsistently, or not at all, leading to reduced, partial, or no effectiveness (Berger, 1980; Doutres et al., 2019; Morata et al., 2001). The inadequate use of HPDs is partly attributed to the discomfort associated with their use. As proposed by Doutres et al. (Doutres et al., 2019), the discomfort generated by HPDs can be analyzed through the four dimensions of comfort, defined as:

- The functional dimension, concerning the user's perception of usability, efficiency, and utility;
- The physical dimension, concerning the user's perception of biomechanical and thermal interactions of the earcanal with the HPD;
- The psychological dimension, concerning the user's well-being (e.g., confidence, habituation, and satisfaction with the HPD);
- The acoustic dimension, concerning the modification of the user's perception of internal (e.g., body's physiological noises) and external (e.g., machine) noises.

According to the comfort model proposed by Doutres et al. (Doutres et al., 2022) and schematized in Figure 0.2, discomforts arise from the complex interactions among three components, which are the person, the HPD (specifically the earplug in this PhD work), and the environment in which it is used. Together, these components form what is referred to here as the person-environment-HPD triad. The three components of the triad are defined by a multitude of physical and psychosocial characteristics, as shown on the left-hand side of the comfort model in Figure 0.2, specifically in the orange boxes within the columns representing the triad's components. Understanding how physical and psychosocial characteristics affect the comfort of wearing earplugs is crucial for improving their effectiveness and preventing the risk of NIHL. A better understanding of the impact of these characteristics would enable the design of more comfortable earplugs and the recommendation of those suited to a worker's specific needs and work environment.

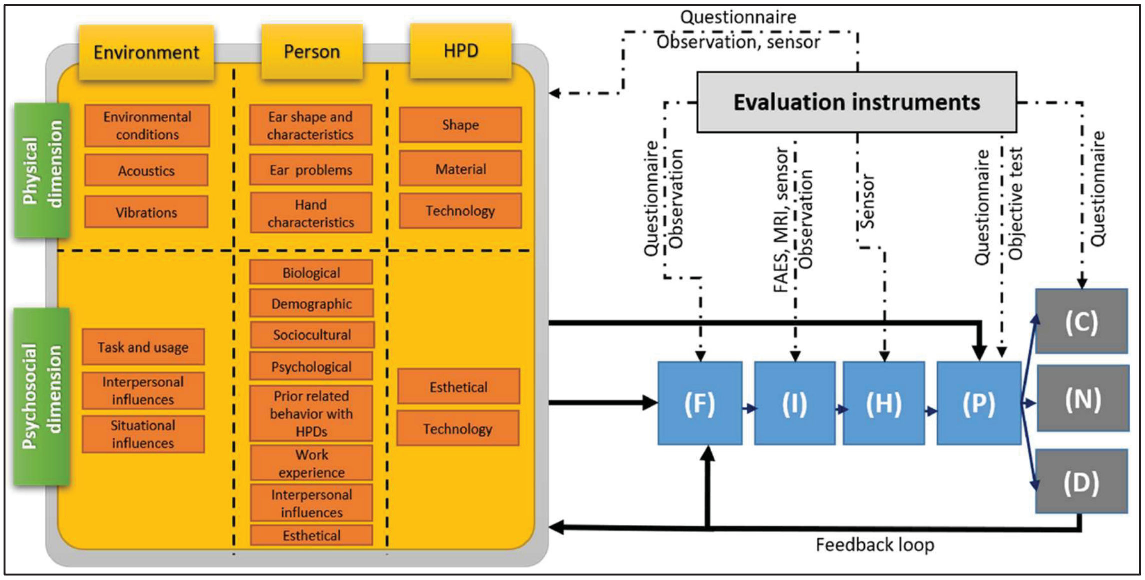



Figure 0.2 Holistic model of HPD comfort. On the left-hand side, the environment-person-HPD triad, consisting of multiple physical and psychosocial characteristics that are inputs to the model. In the center, the four phases where these characteristics interact, leading to, on the right-hand side, the (dis)comfort experienced by the user, the model's output
Taken from Doutres et al. (2022)

## 0.3 The discomfort related to the occlusion effect (OE)

This thesis will investigate a specific aspect of acoustic (dis)comfort: the occlusion effect (OE). The occlusion effect occurs when an earplug (or any other occlusion device, such as earmuffs, hearing aids, or earbuds) blocks the earcanal entrance, typically changing the auditory self-perception of one's body physiological sounds. Example of such changes include an enhanced perception of bodily sounds, such as mastication, heartbeats, and footsteps (Courtois, Johansen, Larsen, Christensen, & Beilin, 1988; M.O. Hansen, 1997; Mead C Killion, Wilber, & Gudmundsen, 1988), as well as a distorted perception of one's own voice, making it sound "hollow", "boomy" or as if "talking like in a barrel" (Berger & Voix, 2022; Courtois et al., 1988; Dillon, 2012). This can lead to a person disliking the sound of their own voice (Berger, 1986; Kiessling, Brenner, Thunberg Jespersen, Groth, & Jensen, 2005; F. Kuk, Keenan, & Lau, 2005; Suter, 2002), and may even result in speech inhibition (Eriksson-Mangold & Erlandsson, 1984). For musicians using HPDs, the OE can alter how they perceive their own instrument while playing (Chesky, Pair, Yoshimura, & Landford, 2009; Mead C. Killion, 2012; Laitinen & Poulsen, 2008). Additionally, the OE might alter how one speaks due to the distortion of self-perception, notably by decreasing vocal effort (Howell & Martin, 1975). For example, the experienced acoustical discomfort related to the OE strongly participates to the feeling of overall (dis)comfort induced by earplugs (Terroir et al., 2021) and thus should be reduced to prevent in-ear device non-use or misuse, which can be critical for the wearer (Doutres et al., 2019, 2020). Although the OE is a well-documented phenomenon, the discomfort it causes when wearing an HPD (or any other type of occlusion device) remains a problem on a daily basis with severe consequences in many cases (e.g., NIHL for workers, environmental- and social isolation for hearing aid users). Moreover, while standardized procedures, metrics, and field-adapted tools exist to assess and compare the sound attenuation provided by various HPDs, such resources are currently unavailable for the OE, limiting the ability to select the most suitable HPD for specific needs. Thus, this PhD work aims to investigate the OE specifically induced by earplug-type HPDs, notably by trying to better understand the discomfort related to the phenomenon and thus the influencing triad characteristics, while also providing both subjective and objective tools to measure and assess it.

## 0.4 Structure of the thesis

The remainder of this thesis is organized as follows. CHAPTER 1 presents a literature review on the three main challenges highlighted: (i) the measurement of the objective occlusion effect ($OE_{obj}$), (ii) the analysis of the triad characteristics influencing the OE, and (iii) the relationship between the experienced occlusion effect ($OE_{exp}$) and the $OE_{obj}$. CHAPTER 2 outlines the main objective and specific objectives that the thesis will address. CHAPTER 3 details the methodology used to collect and analyze the data collected from two measurement campaigns involving human participants in laboratory conditions. CHAPTER 4 presents the analyses and results addressing the research objectives and discusses the limitations of the study. Finally, this doctoral thesis ends with the conclusion that summarizes the main findings and presents the scientific contributions, limitations and perspective of this work.

# CHAPTER 1

# LITERATURE REVIEW

This chapter presents a literature review on the measurement of the OE and the documented influence of the characteristics of the environment-person-HPD triad. First, Section 1.1 provides a more precise definition of the OE by distinguishing it into three distinct types. Next, Section 1.2 outlines the various approaches used in prior studies to measure these three types of OE. Then, Section 1.3 discusses the correlations identified so far between the different types of OE. Subsequently, Section 1.4 examines the characteristics of the triad whose influence has been investigated and documented. Finally, the literature review is summarized in Section 1.5.

## 1.1 The three forms of the occlusion effect

Although the “occlusion effect” refers to the phenomenon that occurs when the ears are occluded by a device (or other means), the term OE is used interchangeably to describe three methods the OE is actually measured or assessed. To prevent ambiguities throughout this document, the definitions proposed by Hansen (1997, 1998) have been adopted and adapted for this work, namely: (i) the objective occlusion effect (denoted $OE_{obj}$), (ii) the subjective occlusion effect (denoted $OE_{subj}$), and (iii) the experienced occlusion effect ($OE_{exp}$), as summarized in Table 1.1. The $OE_{obj}$ refers to the changes in sound pressure level (SPL) that occur when the ear is occluded by a device and is typically characterized as the low-frequency SPL within the occluded earcanal below 2 kHz, in comparison to the unoccluded SPL (Berger & Kerivan, 1983; M.O. Hansen, 1998). The measurement of the $OE_{obj}$ is discussed in greater detail in Section 1.2.1. The $OE_{subj}$ refers to the shift in hearing thresholds that occur when the earcanal is occluded, characterized by improved low-frequency hearing thresholds below 2 kHz (Berger & Kerivan, 1983; Reinfeldt, Stenfelt, & Håkansson, 2013). It is often regarded as the baseline (or “gold standard”) method for assessing the OE through bone conduction (BC) audiometry, by measuring hearing thresholds with- and without an occlusion device (Berger & Kerivan, 1983; Goldstein & Hayes, 1965; Huizing, 1960; Reinfeldt et al., 2013; Stenfelt & Reinfeldt, 2007). The measurement of the $OE_{subj}$ is discussed in greater detail in Section 1.2.2.

Finally, the $OE_{exp}$ refers to the discomfort associated with the OE, as described in Section 0.3, namely an amplification and/or distortion of physiological noises when the ears are occluded. It is primarily assessed through questionnaires or interviews answered by the user (M.O. Hansen, 1997; Kiessling, Brenner, Thunberg Jespersen, et al., 2005; F. Kuk et al., 2005; H. G. Mueller, 2003; Terroir et al., 2021; Vasil-Dilaj & Cienkowski, 2011). The measurement of the $OE_{exp}$ is discussed in greater detail in Section 1.2.3. Although the three types of OE occur simultaneously, their interrelationship remains unclear and is discussed in greater detail in Section 1.3. With the goal of making HPDs more comfortable and thus reduce the risk of NIHL, focusing on the $OE_{exp}$ is crucial. However, no tools are currently available to manufacturers to assess the $OE_{exp}$ as the process is complex, difficult and time consuming due to the subjective nature of interviews and questionnaires. To alleviate this problem, the $OE_{exp}$ should be objectivized[1] as to allow manufacturers to predict the discomfort's severity caused by an HPD used in specific conditions. To do so, measuring the earcanal SPL is, a priori, the best approach as it is simple, reliable and easy to implement in various conditions (e.g., laboratory, field), and is easily accessible to manufacturers. However, the current lack of understanding of the interrelationship between the OEs prevents the objectivization of the $OE_{exp}$, and therefore the design of more comfortable HPDs.

[1] According to the Merriam-Webster dictionary, objectivization is the act of making something objective. In this project, the objectivization of the OE seeks to characterize the discomfort experienced by a user solely through objective indicators derived from sensor-based measurement instrument .

Table 1.1 Definitions of the three occlusion effects

| Term | Abbreviation | Definition |
|---|---|---|
| Occlusion Effect | OE | Physical and psychoacoustical changes occuring when the earcanal entrance is blocked. |
| Objective occlusion effect | $OE_{obj}$ | Objectively measurable changes occurring in the occluded earcanal relative to the open one, typically measured using miniature microphone. |
| Subjective occlusion effect | $OE_{subj}$ | Hearing threshold shifts measured using bone conduction audiometry with the blocked earcanal entrance relative to the open one, considering all BC pathways to the inner ear. |
| Experienced occlusion effect | $OE_{exp}$ | Discomfort related to the physiological noises occurring when the earcanal is blocked, and usually assessed using questionnaires. |

## 1.2 Measurement and assessment of the OEs

As the three types of OE are distinct, the approaches used for their measurement differ. The approaches related to the measurement of the $OE_{obj}$, $OE_{subj}$, and $OE_{exp}$ are presented and discussed in Sections 1.2.1, 1.2.2, and 1.2.3, respectively.

### 1.2.1 Measurement of the $OE_{obj}$

Three experimental aspects of the methodology for measuring the $OE_{obj}$ are defined when attempting to measure it: (i) the stimulation source used to generate the OE (see Section 1.2.1.1), (ii) the method for measuring SPLs using microphones (see Section 1.2.1.2), and (iii) the indicator used to quantify the $OE_{obj}$ (see Section 1.2.1.3). This section provides an overview of these three experimental aspects as discussed in the literature.

#### 1.2.1.1 Stimulation source

The first experimental aspect focuses on the stimulation source used to induce the OE. Under laboratory conditions, bone transducers are commonly used to generate BC stimulation (Geal-Dor, Adelman, Chordekar, & Sohmer, 2020; Reinfeldt et al., 2013; Stenfelt & Reinfeldt, 2007). Typically, a bone transducer is placed on the mastoid process or the forehead, secured with a headband. Other sites, such as the neck or chin, have also been used to elicit soft tissue conduction (Geal-Dor et al., 2020). To measure the $OE_{obj}$ with a bone transducer, SPLs in the earcanal are assessed both with and without the occlusion device. This method is similar to evaluating the sound attenuation of HPDs through measurements of objective insertion loss (IL) (Berger & Voix, 2022), but it uses supraliminal BC stimulation instead of a noise field.

While bone transducers provide precise and repeatable stimulation, certain limitations arise during measurements. The transducer's position on the skull affects both the magnitude and repeatability of the OE, as transcranial attenuation and soft tissue excitation near the ear vary depending on whether the transducer is placed on the mastoid process or the forehead (Klodd & Edgerton, 1977; Reinfeldt et al., 2013). Additionally, the transducer's operation limit at low and high frequencies may lead to measurement artifacts caused by acoustic radiation from its outer casing which could influence the unoccluded ear SPL (Reinfeldt et al., 2013; Shipton, 1980). Furthermore, using a bone transducer requires cumbersome equipment, such as an audiometer, and is thus impractical for field measurements, making it more suited for laboratory settings.

A simpler method to induce the OE involves using the subject's own physiological noises. As with a bone transducer, the $OE_{obj}$ is measured by measuring the SPL in the earcanal with and without the occlusion device. A commonly used physiological noise is the subject's own voice. Since speech is user-controlled, BC stimulation can be induced through two types of speech content: continuous speech (e.g., reading aloud or enumerating numbers) (M.O. Hansen, 1998; Sgard, Nélisse, & Laville, 2016) or vocalizing specific phonemes, often one of the cardinal vowels (/i/, /æ/, or /u/) (Mead C Killion et al., 1988; Stender & Appleby, 2009; Vasil-Dilaj & Cienkowski, 2011). Speech is sometimes monitored with a feedback system (e.g., a sound level meter) to ensure consistent intensity during open and occluded ear measurements (M.O. Hansen, 1998; Schlieper, Li, Preihs, & Peissig, 2019; Sgard et al., 2016; Stender & Appleby, 2009; Vasil-Dilaj & Cienkowski, 2011). However, monitoring vocal effort using a feedback system as such adds unnecessary complexity to the procedure since it does not seem to influence the $OE_{obj}$ (Nélisse, Le Cocq, Boutin, Voix, & Laville, 2013).

Compared to bone transducers, speech is more accessible, as it requires no specialized equipment beyond a basic feedback system if vocal effort needs monitoring. Speech is also relevant as a stimulation source because it is frequently linked to discomfort in real-world scenarios (Dillon, 2012; Doutres et al., 2019; Kochkin, 2010; Terroir et al., 2021). Despite these advantages, using one's voice as a stimulation source has limitations. Vocalizing vowels introduces greater variability compared to continuous speech because the OE affects self-perception, making it difficult to reproduce a vowel with identical spectral content and intensity (M.O. Hansen, 1998). Additionally, the chosen phoneme impacts the measured OE magnitude, as the AC and BC components produced in the vocal organs vary with phoneme type (M.O. Hansen, 1998; Reinfeldt, Östli, Håkansson, & Stenfelt, 2010). Continuous speech offers a more repeatable stimulus due to the consistency of its long-term average spectra, but it requires more time for measurements (D. Byrne et al., 1994).

Other physiological noises, such as mastication, heartbeats, blood flow, swallowing, and footsteps, have also been used to measure the $OE_{obj}$ (Courtois et al., 1988; M.O. Hansen, 1997, 1998; Stone, Paul, Axon, & Moore, 2014). These noises are inherently difficult to reproduce consistently. For instance, the magnitude and variability of $OE_{obj}$ during mastication depend heavily on the type of food (e.g., crispy vs. soft) (Courtois et al., 1988; M.O. Hansen, 1997, 1998; M.C. Killion, 1988; Mead C Killion et al., 1988). Heartbeats produce significant $OE_{obj}$ values below 125 Hz but are challenging to measure due to their low SPL in the unoccluded ear (Stone et al., 2014).

#### 1.2.1.2 Measurement methods

The second experimental aspect concerns what is hereby referred to as the measurement method used to obtain the $OE_{obj}$. This aspect encompasses the selection of ears for measurement, whether one or two separate stimuli are required to excite the ear(s) via BC, and the location of the microphones for SPL measurement. Three primary measurement methods are discussed in the literature. The first method, here referred to as the "standard method" ($OE_{obj}^{STD}$), involves performing successive SPL measurements within the earcanal of a single ear, first in the occluded condition and then in the unoccluded condition. This approach is widely used due to its straightforward implementation but requires the stimulation to be produced twice, making it sensitive to sources with low repeatability (M.O. Hansen, 1998).

The second method, referred to here as the "real-time method" ($OE_{obj}^{RT}$), involves simultaneous SPL measurements in both ears using a single stimulation. In this method, one ear is occluded while the other remains unoccluded, allowing for real-time comparison of the SPLs (M.O. Hansen, 1998; Mead C Killion et al., 1988). This approach provides more reliable results when using short and variable stimulations, such as phoneme vocalizations, since the stimulus needs to be produced only once. However, it relies on symmetrical ear anatomy and requires the stimulation source to be centered on the sagittal plane to ensure equal stimulation of both ears (M.O. Hansen, 1998). Although promising, the real-time method is rarely employed and requires further validation to assess its reliability.

A third method, referred to here as the "NR-based method" ($OE_{obj}^{NR}$), also utilizes simultaneous measurements of the occluded and unoccluded SPLs but focuses on a single ear. In this approach, the unoccluded SPL is approximated by measuring just outside the occlusion device in the occluded condition. This method has been integrated into commercially available devices such as the Audioscan Verifit 2 and the Etymotic Research ER-33 Occlusion Meter (Audioscan, 2021; United States Patent Patent No. 5,577,511, 1996). Moreover, it is analogous to the evaluation of the sound attenuation provided by an HPD using the noise reduction (NR) (Berger & Voix, 2022). While it offers the advantage of requiring only a single stimulation to achieve simultaneous measurements, it does not fully align with the $OE_{obj}$ definition used in most studies. Furthermore, discussions on the limitations and performance of this method in comparison to the other two remain sparse in the literature.

Still regarding the measurement method, the placement of the microphone for measuring SPLs in the occluded earcanal is another important consideration. One approach involves using a probe tube microphone positioned near the tympanic membrane. This placement provides precise SPL measurements but requires careful handling to avoid discomfort or harm to the test subject. In general, the placement of the probe tube into the earcanal must be performed by an audiologist or by a person trained by an audiologist. Additionally, the probe tube must be positioned correctly to prevent acoustic leaks, especially when testing earplug-type HPDs, where maintaining a proper seal is critical for accurate results. A second approach involves measuring SPL at the medial face of the in-ear device, which keeps the microphone at a safer distance from the tympanic membrane. This approach is facilitated by using in-ear devices with built-in probe tubes, such as 3M E-A-RLink earplugs (3M, St. Paul, MN). Despite differences in placement, both approaches produce comparable results when measuring the $OE_{obj}$, particularly at frequencies below 2000 Hz where the occlusion effect is most significant, and microphone location has minimal influence on the measured SPL (Berger & Kerivan, 1983; Bonnet, Nélisse, & Voix, 2018; MacKenzie, Mueller, Ricketts, & Konkle, 2004; Xu, 2019).

#### 1.2.1.3 Indicators

The third experimental aspect deals with the indicator used to quantify the OE. $OE_{obj}$ values are typically presented as a spectrum at various frequencies in octave, third octave or twelfth octave bands (Lundh, 1986; Reinfeldt et al., 2013; Sgard et al., 2016; Stenfelt & Reinfeldt, 2007). An indicator that is a function of frequency provides the most information about the phenomenon, but at the cost of making the analyses frequency-dependent, hence more complex and more time consuming. Some authors have instead quantified the $OE_{obj}$ using different single value indicators (SVI), as they offer the simplicity of having only a single number to characterize the phenomenon, making comparisons and analyses simpler. However, as these indicators are not standardized, the choice of the indicator varies from one study to another. These indicators are either based on the magnitude of $OE_{obj}$ at a specific frequency, e.g., at 250 Hz (Mead C Killion et al., 1988; F. Kuk et al., 2005; K. Lee & Casali, 2011; Olivier Valentin & Laville, 2017); on the magnitude averaged over a specific frequency range, e.g., between 125 and 500 Hz (Biering-Sørensen, Pedersen, & Parving, 1993; M.O. Hansen, 1997; Kiessling, Brenner, Thunberg Jespersen, et al., 2005); or based on the maximum value of the OE in the measured frequency range (May & Dillon, 1992) cited in (M.O. Hansen, 1997). Some authors have also quantified the magnitude using occluded/unoccluded squared root mean square (rms) sound pressure integrated over a specific frequency range (Audioscan, 2021; M.O. Hansen, 1997; H. G. Mueller, 2003; Stender & Appleby, 2009). In most cases, the selection of a SVI over another is not much discussed, which contributes to the lack of consensus in the literature on how to represent $OE_{obj}$.

### 1.2.2 Measurement of the $OE_{subj}$

The $OE_{subj}$ is obtained through psychometric tests during which the participant's perception of the OE is quantified. Unlike the $OE_{obj}$, which involves only sound transmission paths up to the external earcanal where acoustic pressure is measured, the measurement of $OE_{subj}$ accounts for all sound transmission paths up to the inner ear. Typically, the $OE_{subj}$ is derived from BC audiometry using a bone transducer, which allows for determining auditory thresholds in both open and occluded ear conditions. This approach is analogous to the real-ear attenuation at threshold (REAT) method used to assess the sound attenuation provided by HPDs as presented in the ANSI/ASA S12.6 standard (ANSI/ASA, 2016). In this approach, a tonal signal is generated with a clinical audiometer and transmitted to a bone transducer to determine the hearing thresholds for each tested audiometric frequency, typically ranging between 125 Hz and 8000 Hz. (Berger & Kerivan, 1983; Biering-Sørensen et al., 1993; Dean & Martin, 2000; Elpern & Naunton, 1963; Fagelson & Martin, 1998; Goldstein & Hayes, 1965; Huizing, 1960; Reinfeldt et al., 2013; Stenfelt & Reinfeldt, 2007; Studebaker, 1962; Olivier Valentin & Laville, 2017). Alternatively, variations of this approach are also found in the literature, such as the use of speech reception thresholds (SRT) rather than BC hearing thresholds (Dempsey, 1990; Klodd & Edgerton, 1977), the use of a soft tissue transducer instead of a bone transducer (Nishimura, 2014), or generating a BC stimulus via the oral cavity using a loud speaker (Le Cocq, Laville, & Gargour, 2010), albeit the use of these approaches is rare.

Similar to the $OE_{obj}$, as discussed in Section 1.2.1.3, several indicators are used to quantify the $OE_{subj}$. However, quantifying the $OE_{subj}$ faces the same challenges as there is no consensus on which indicator to employ; it may be presented as a function of frequency or as an average value of multiple frequency bands.

In contrast to the $OE_{obj}$, the $OE_{subj}$ is measured using the standard approach, which involves producing a signal twice to assess the hearing threshold with and without an HPD. Furthermore, when the bone transducer generates stimulation, vibrations propagate through the skull, stimulating both ears simultaneously. Consequently, the $OE_{subj}$ must be assessed one ear at a time: the designated tested ear is used to determine hearing thresholds, while a masking noise is applied to the non-tested ear to ensure that the signal is not detected by it. Therefore, assessing the $OE_{subj}$ under a specific set of conditions (e.g., HPD type and model, insertion depth, etc.) is cumbersome and lengthy as four individual measures are necessary to test both ears.

Additionally, assessing the $OE_{subj}$ suffers from several artefacts and challenges. First, obtaining accurate low-frequency hearing thresholds when the ear is occluded can be particularly challenging due to the physiological noises masking effect in this condition (Berger & Kerivan, 1983). Then, challenges arise from the use of a bone transducer, as described in Section 1.2.1.1, which also impact $OE_{subj}$. These include variability related to the site of excitation and acoustic radiation from the bone transducer, especially during threshold assessments with the ear open, and the transducer's acoustic radiation from its outer casing that could influence unoccluded BC hearing threshold (Berger & Kerivan, 1983). Finally, although other subjective methods could theoretically be employed to assess the $OE_{subj}$, such as the loudness balance test (Keidser, Katsch, Dillon, & Grant, 2000), no study has been found that have done so. Consequently, they are neither discussed nor considered within this doctoral thesis, which rather focuses on the $OE_{obj}$ and the $OE_{exp}$.

### 1.2.3 Assessment of the $OE_{exp}$

The $OE_{exp}$ is obtained through questionnaires and interviews during the discomfort experienced by the participants. In many cases, the $OE_{exp}$ is assessed using a rating scale to convert the severity of the discomfort into a numerical value (Cubick et al., 2022; M.O. Hansen, 1997; Kiessling, Brenner, Jespersen, Groth, & Jensen, 2005; F. Kuk et al., 2005; Alessandra G. Samelli et al., 2018; Sunohara, Osawa, Hashiura, & Tateno, 2015; Vasil-Dilaj & Cienkowski, 2011), but open-ended questions are sometimes used as to obtain descriptors of the $OE_{exp}$ (Laitinen & Poulsen, 2008). In contrast with the $OE_{obj}$ and $OE_{subj}$ that are assessed using various stimulation sources, the $OE_{exp}$ is solely obtained using the participant's physiological noises. As one's own voice is often associated with the OE (see Section 0.3), speech is mostly used when assessing the $OE_{exp}$. However, multiple discrepancies are found in the literature, which highlights the difficulty of assessing the $OE_{exp}$ using rating scales, and therefore the challenge in understanding it and comparing the results originating from the various studies. This lack of consensus is observed through three specific methodological elements, namely (i) the wording of the questions about the $OE_{exp}$, (ii) the rating scales used to quantify the $OE_{exp}$, and (iii) using a participant calibration phase. Moreover, additional aspects related to the assessment of discomfort also complexify data collection. These three elements are discussed below. Although the literature on comfort assessment related to the OE is limited, research on other types of comfort, such as automotive comfort, has been explored to provide information relevant to this doctoral thesis on the $OE_{exp}$.

#### 1.2.3.1 Question wording about the $OE_{exp}$

The challenge of formulating clear, precise, and easy-to-understand questions about the $OE_{exp}$ lies in the fact that there is a multitude of descriptors for the discomforts (as described in Section 0.3) and that the phenomenon of OE can be difficult for individuals with little- or no exposure to it to understand. Although several studies have investigated the $OE_{exp}$, discrepancies in question formulation are found across the studies. In some cases, participants are asked to rate the naturalness of their own voice (Kiessling, Brenner, Thunberg Jespersen, et al., 2005), how boomy and hollow their own voice sounds (F. Kuk et al., 2005), or how annoying it is to hear their own voice (M.O. Hansen, 1997). In other cases, they must rate how occluded they feel (Cubick et al., 2022; Sunohara et al., 2015) or simply rate the OE itself (Alessandra G. Samelli et al., 2018; Vasil-Dilaj & Cienkowski, 2011). The lack of consensus makes it difficult to determine which phrasing should be used and also introduces several challenges when collating information from the literature.

The first issue stems from the fact that, even though all the studies listed above investigated the $OE_{exp}$ according to their respective authors, the different question formulations make it difficult—if not impossible—to compare results. Specifically, the formulation of a question dictates the type of information collected from participants. As such, it is challenging to interpret whether discomfort is comparable when comparing a maximum score for "unnatural voice" to a maximum score for "feeling occluded."

The second issue arises from the ambiguity of certain formulations, casting doubt on whether the $OE_{exp}$ was actually measured. For instance, a maximum score for "unnatural voice" indicates that the participant perceived a change in their own voice, but it does not specify whether the participant experienced a discomfort. Hiramatsu et al. observed that participants evaluated the loudness, noisiness, and annoyance of various sounds differently, despite a certain degree of correlation among these attributes (Hiramatsu, Takagi, & Yamamoto, 1988). Similarly, it is plausible that this distinction applies in the context of the OE. Specifically, participants may provide different judgments when asked whether they perceive the changes caused by OE compared to whether they are disturbed by these changes. In other words, there may be a difference between the perception of OE (i.e., referred to as the $OE_{perc}$) and the discomfort caused by OE (i.e., $OE_{exp}$, as previously discussed). This distinction between the perception of comfort, as defined per ergonomists, and its evaluation is already an integral part of the holistic comfort model proposed by Doutres et al. (2022). Indeed, the comfort perception phase (P) precedes the judgment phase—comfort (C), discomfort (D), or neutral (N)—as schematized in Figure 0.1. However, this distinction between the $OE_{perc}$ and the $OE_{exp}$ has not been previously addressed outside the research team's theoretical HPD comfort model and therefore warrants investigation. Consequently, the phrasing of questions must avoid any form of ambiguity.

Finally, the third issue concerns the complexity of question formulations, which may be misinterpreted or misunderstood by participants. Since the phenomenon is not widely known, participants with little or no knowledge of the OE may provide responses that do not accurately reflect what they experience. This issue is likely to occur as the phenomenon can easily be confused with other acoustical effects resulting from ear occlusion, such as the attenuation of high frequencies caused by the sound attenuation of an HPD placed over the ears (Terroir, Doutres, & Sgard, 2017). It is thus imperative that questions be formulated with a level of complexity appropriate to the participants' knowledge of the OE recruited for the study.

However, it is possible to address these issues during the development of an experimental protocol. First, participants can be provided with the necessary information to fully understand the $OE_{exp}$ resulting from the use of in-ear devices. This information can be delivered orally or in writing, such as through the study's information and/or consent form.

Second, an iterative questionnaire design process can be conducted, aimed at designing, testing, and refining a questionnaire through a series of pretests with research team members or participants who will not take part in the study. This process not only improves question phrasing but also enhances the process of administering questions to participants to ensure accurate responses (M.O. Hansen, 1997).

Finally, a calibration phase can be included in the experimental protocol to help participants become familiar with the sensations they will experience and practice responding to the questions. The calibration phase is detailed further in Section 1.2.3.3.

#### 1.2.3.2 $OE_{exp}$ rating scales

Response scales are measurement tools originating from the psychophysics field, enabling the association of a physical stimulus to the sensation experienced by participants through a numerical value (Gescheider, 1985). They are typically used in comfort studies, including those on acoustic comfort, such as those on the $OE_{exp}$. Although numerous scales exist, this review focuses on those used in $OE_{exp}$ or acoustic comfort research, making it non-exhaustive. Beyond the method of administration, response scales are characterized by two parameters: (i) the type of scale and (ii) the number of points they include. These characteristics are discussed below.

The first characteristic is the type of scale, which can be either (i) monopolar or (ii) bipolar (Han, Song, & Kwahk, 1999). Monopolar scales are unidirectional, allowing participants to evaluate a stimulus using a strictly positive scale. They measure stimulus magnitude, ranging from a lower bound (e.g., typically 0) indicating its absence, to an upper bound representing its maximum intensity. Intermediate points indicate proportional magnitude relative to the maximum (e.g., a score of 5 on a scale from 0 to 10 suggests moderate magnitude). In OE studies, unipolar scales help participants evaluate how much $OE_{exp}$ they experienced, such as perceiving changes in their own voice (Kiessling, Brenner, Jespersen, et al., 2005; F. Kuk et al., 2005) or the discomfort of hearing their own voice (M.O. Hansen, 1997).

Conversely, bipolar scales are bidirectional, enabling participants to evaluate stimuli positively or negatively. They typically assess agreement or disagreement with a statement. The lower and upper bounds indicate strong agreement or disagreement, while intermediate points allow nuanced responses (e.g., slight agreement). A key feature of bipolar scales is the central point, which enables neutral responses (i.e., neither agreement nor disagreement). Bipolar scales may use symmetrical values (e.g., -3 to +3, with 0 as neutral) or strictly positive values (e.g., 1 to 7, with 4 as neutral). In OE studies, bipolar scales allow participants to express agreement or disagreement with statements about the $OE_{exp}$ (Alessandra Giannella Samelli, Rocha, Theodósio, Moreira, & Neves-Lobo, 2015; Sunohara et al., 2015).

Although both scale types have been used in studies on the $OE_{exp}$, results interpretation is more complex with bipolar scales due to the central point. Since the $OE_{exp}$ is defined as a discomfort, interpreting favorable or neutral scores is challenging. For instance, in Samelli et al.'s (2018) study, participants evaluated the $OE_{exp}$ on a 7-point scale from "best" to "neutral" to "worst." How should the neutral point be interpreted? If a participant selects neutral, does "best" imply OE has a beneficial effect (i.e., the opposite of discomfort), or does neutral indicate an average $OE_{exp}$ while "best" signifies minimal $OE_{exp}$? Despite these uncertainties, only two studies have used bipolar scales, while unipolar scales appear to provide unambiguous data, even though problems were discussed in Section 1.2.3.1.

The second characteristic of response scales is the number of points they include. Some studies use as few as four points (e.g., $OE_{exp}$ as a magnitude of annoyance, from "not annoying" to "very annoying" (M.O. Hansen, 1997)), while others use up to 11 points (e.g., $OE_{exp}$ evaluated as one's own voice quality, from "extremely hollow voice quality" to "very natural voice quality without any hollowness" (F. Kuk et al., 2005)). Moreover, although not problematic, the direction of the scale can vary, as opposite ends may represent different meanings, as seen in the studies above.

The lack of consensus on the number of scale points raises an issue: previous studies on the $OE_{exp}$ studies provide no clear guidelines for future research. While recommendations exist regarding the number of points to use, factors influencing the choice include individual versus sample-level observations, desired response precision and variability, the nature of the observed stimulus, and its discretization into a scale (Friedman & Amoo, 1999). Ultimately, experimenters must decide the appropriate number of points for their scale by considering these factors and validate their choice through pretests.

#### 1.2.3.3 Participant calibration

The calibration phase of the participant, sometimes referred to as the preliminary phase, anchoring phase, familiarization phase, training phase, or jury testing, is a step in an experimental protocol aimed at "calibrating" a participant regarding the stimuli used in the study. It is often considered an essential step in experimental protocols for studies on comfort, such as automotive comfort (seats, pedals, acoustics) (Otto, Amman, Eaton, & Lake, 1999; Palomares et al., 2011; Shen & Parsons, 1997; Wang, Le Breton-Gadegbeku, & Bouzon, 2004), sound environments & speech (Kerrick, Nagel, & Bennett, 1969; Kuwano, Namba, & Nakajima, 1980; Loizou, 2011), ergonomics (Chung, Lee, & Kee, 2005; Dickerson, Martin, & Chaffin, 2006), or pain thresholds (Gustafson & Källmén, 1988).

More specifically, this phase serves to expose the participant to the different stimuli tested in a study to improve the quality of the data. While there are distinctions between the approaches listed above, it involves exposing the participant to various stimuli so that they can become accustomed before data collection. The approaches differ in how the stimuli are presented to the participant. In some cases both extremes (i.e., low and high) plus a middle point between the two are shown as to illustrate the possible range (Otto et al., 1999). This allows to equalize the perception of the participants so they a have a common understanding of the stimulus' range (Loizou, 2011). In other cases, the stimuli are presented in a random order and do not necessarily correspond to the extremes (Kerrick et al., 1969). Simultaneously, the rating scale used to measure the stimuli is presented to the participant so they can practice linking a stimulus to a point on the rating scale. Generally, the approach used for the calibration depends on the familiarity of the participant relative to the stimuli; common and simple stimuli might only require a simple calibration phase, whereas uncommon and complex stimuli might require a more complex and extensive calibration phase (Otto et al., 1999). Therefore, the calibration phase's parameter, namely the stimuli, the time allocated to the participant, and the number of exposure to the stimuli are chosen based on the study's constraints, though sometimes these parameters are merely listed. In any case, measurements taken during the calibration phase are excluded from the analyses.

Despite the positive aspects of including a calibration phase in a study, it is rarely included in studies on $OE_{exp}$; only few studies mention it (Cubick et al., 2022; Vasil-Dilaj & Cienkowski, 2011). However, given the complexity of the discomfort associated with OE, due to the lack of consensus on vocabulary (see Section 1.2.3.1) and the different forms this discomfort can take (see Section 0.3), including a calibration phase in the study of $OE_{exp}$ is, a priori, a necessity and is thus included in the research work of this doctoral thesis.

## 1.3 Relationship between $OE_{obj}$, $OE_{subj}$ and $OE_{exp}$

Although the three types of OEs manifest simultaneously (i.e., $OE_{obj}$, $OE_{subj}$, and $OE_{exp}$), their interrelationship remains poorly understood. Specifically, it is still not possible to predict the degree of discomfort (i.e., $OE_{exp}$) solely based on $OE_{obj}$ or $OE_{subj}$ measurements. Several studies have attempted to establish a relationship between the $OE_{obj}$/$OE_{subj}$ and the $OE_{exp}$, but with limited success. Research focusing on the correlation between the $OE_{exp}$ and the $OE_{obj}$ has primarily involved hearing aids, investigating factors like the influence of vent size on the OE (Kiessling, Brenner, Jespersen, et al., 2005; F. Kuk et al., 2005; Vasil & Cienkowski, 2006; Vasil-Dilaj & Cienkowski, 2011).

While the objective indicator for the $OE_{obj}$ and the evaluation method for the $OE_{exp}$ vary across studies, a positive correlation is generally observed, suggesting that discomfort increases with higher $OE_{obj}$. For instance, a correlation of $r^2 = 0.46$ was reported between voice naturalness and the average $OE_{obj}$ at 250 Hz, 500 Hz, and 750 Hz narrow bands (Kiessling, Brenner, Jespersen, et al., 2005). In studies by Vasil-Dilaj and Cienkowski, correlations ranged from $r = 0$ to $r = 0.57$ across different hearing aids between narrow frequency bands (200 Hz to 1500 Hz in 100 Hz steps) and the $OE_{exp}$, defined as the degree of occlusion (Vasil & Cienkowski, 2006; Vasil-Dilaj & Cienkowski, 2011). Similarly, Kuk et al. reported a correlation of $r = 0.33$ between the $OE_{obj}$ at 258 Hz and the $OE_{exp}$, defined as "hollowness of own voice", using a single prosthesis model with varying vent diameters (F. Kuk et al., 2005).

Other studies have explored the correlation between the $OE_{obj}$ and the $OE_{subj}$ in bone conduction audiometry. For example, a correlation as high as $r = 0.82$ between the $OE_{obj}$ and $OE_{subj}$ was reported by Fagelson and Martin when pooling measurements from the 250 Hz, 500 Hz and 1000 Hz frequency bands, and using stimuli applied to both the forehead and the mastoid (Fagelson & Martin, 1998). Although no specific correlation coefficient was provided, similar observations were made by Goldstein & Hayes and by Huizing, who noted that increased hearing thresholds were proportionate to the rise in acoustic pressure in the earcanal when the ear was occluded by an earplug (Goldstein & Hayes, 1965; Huizing, 1960). However, while measuring the $OE_{subj}$ is often considered the "gold standard," these studies primarily contribute to understanding sound propagation through the hearing mechanisms, but they have limited relevance to the $OE_{exp}$. This limitation arises because the excitation used to measure the $OE_{subj}$ is generated by a bone transducer, rather than by physiological noises associated with the $OE_{exp}$. As a result, these correlations offer little utility in improving the understanding or objectivization of the $OE_{exp}$.

## 1.4 Influential characteristics on the $OE_{exp}$

As presented in Section 0.2, the discomfort associated with OE can be modeled through the components of the environment-person-HPD triad, the physical and psychosocial characteristics that comprise it, and the complex interactions that occur between them. However, it remains unclear which characteristics are influential on the $OE_{exp}$.

The following sections compile the influence of these characteristics on the $OE_{exp}$ found in the literature. Moreover, the influence of these characteristics on the $OE_{obj}$ is also discussed. The influence of the physical characteristics of the person, the HPD, and the environment are discussed in Sections 1.4.1, 1.4.2, and 1.4.3, respectively. Subsequently, the influence of psychosocial characteristics of the person, the HPD, and the environment are covered in Sections 1.4.4, 1.4.5, and 1.4.6. Finally, the influence of characteristics related to the interactions between the components of the triad are presented in Section 1.4.7.

### 1.4.1 Physical characteristics of the person

The influence of three physical characteristics related to the user has been investigated in past studies: biological sex, earcanal morphology, and hearing loss. Their influence on the $OE_{exp}$ is presented in Sections 1.4.1.1, 1.4.1.2, and 1.4.1.3, respectively.

#### 1.4.1.1 Biological sex

Despite physiological differences between men and women, the user's biological sex does not appear to influence the $OE_{exp}$ (H. G. Mueller, 2003). Although differences in $OE_{obj}$ can be observed between the sexes, these inter-individual variations are more likely attributed to other user-related characteristics, such as voice spectrum, earcanal morphology (see Section 1.4.1.2), and hearing loss (see Section 1.4.1.3). Moreover, general tolerance and capacity to adapt to unwanted noise could also contribute to the sensitivity to the $OE_{exp}$ for each individual person (H. Mueller, Bright, & Northern, 1996; H. G. Mueller, 2003).

#### 1.4.1.2 Earcanal morphology

The influence of earcanal morphology on the OE remains poorly documented. The few studies conducted thus far have utilized either lumped-element or numerical models. This limitation is primarily due to the complexity and risks associated with performing measurements in the human ear to determine the various morphological indicators (i.e., diameter, length, section’s aspect ratio) and the mechanical properties of its constituent tissues (i.e., soft, bony, cartilages). Consequently, the limited results from these studies pertain exclusively to $OE_{obj}$, as the $OE_{exp}$ cannot be evaluated using these measurement methods. These findings, though sparse, are summarized below.

While minor variations have been observed, the length of the earcanal does not significantly influence the $OE_{obj}$ (Zurbrügg, Stirnemannn, Kuster, & Lissek, 2014). The size of the earcanal has a limited effect on the $OE_{obj}$, with larger canals leading to slightly higher $OE_{obj}$ values compared to smaller canals. However, this influence is marginal, amounting to approximately

3 dB at 600 Hz when comparing canals of extreme sizes (e.g., small vs. large) (Stenfelt & Reinfeldt, 2007), or substantial 20 dB at 1000 Hz when comparing canals with diameters of 4 mm and 10 mm (Zurbrügg et al., 2014).

Furthermore, the geometry of the junction between the cartilaginous and bony regions of the earcanal affects the vibratory field within it and, consequently, the acoustic radiation contributing to the $OE_{obj}$ (Kévin Carillo, Doutres, & Sgard, 2021). The mechanical properties of the tissues that make up the ear are also factors influencing the $OE_{obj}$. Using a 3D model of a human head, Xu observed variations in the $OE_{obj}$ of up to 7 dB at low frequencies by altering values assigned to the Poisson's ratio, Young's modulus, and the density of soft tissues, bone, and cartilage constituting the ear (Xu, 2019).

Unfortunately, these findings provide no insight into the contribution of earcanal morphology to the severity of the $OE_{exp}$, as the correlation between the $OE_{obj}$ and $OE_{exp}$ remains poorly understood (see Section 1.3).

Nevertheless, a recent study explored the influence of earcanal morphology on the physical comfort of HPDs using a safe and non-invasive approach. Poissenot-Arrigoni et al. developed a method to extract morphological indicators from 3D scans of earcanal impressions used in the fabrication of custom earplugs (Bastien Poissenot-Arrigoni, 2023). Although their study did not yield any information directly related to OE, the method for recovering morphological indicators could be applied in research focused on the $OE_{exp}$.

#### 1.4.1.3 Hearing loss

There is a notable lack of data on the influence of hearing loss on the OE generated by HPDs. This is primarily because participants recruited in studies on the OE generated by HPDs typically have normal hearing (Berger & Kerivan, 1983; Reinfeldt et al., 2013; Olivier Valentin & Laville, 2017). In contrast, studies on hearing aids have recruited participants with diverse auditory profiles, including those with hearing loss (M.O. Hansen, 1997; Lundh, 1986, 1986;

Mackenzie, Browning, & McClymont, 1989; Wimmer, 1986), those without hearing loss (Dempsey, 1990; Fagelson & Martin, 1998; Goldstein & Hayes, 1965; Stone et al., 2014; Vasil-Dilaj & Cienkowski, 2011), and a mix of both (Kiessling, Brenner, Thunberg Jespersen, et al., 2005).

Despite these studies, the influence of hearing loss on the OE remains poorly understood, with conflicting results reported in the literature. For instance, hearing aid users with hearing loss may experience an OE to a similar degree as those with normal hearing (M.O. Hansen, 1997; Kiessling, Brenner, Thunberg Jespersen, et al., 2005). Conversely, individuals with significant sensorineural or conductive hearing loss may perceive the OE differently compared to those with normal hearing (Carle, Laugesen, & Nielsen, 2002; H. G. Mueller, 2003). Furthermore, tinnitus may also influence the perception and annoyance associated with OE although it is independent of hearing loss (M.O. Hansen, 1997).

Thus, the impact of hearing impairment on the OE requires further investigation, particularly in the context of HPDs, where no data currently exists. Understanding this potential influence is critical to explain why some workers are more bothered by OE than others.

### 1.4.2 Physical characteristics of the occlusion device

The influence of two physical characteristics related to the occlusion device have been investigated in past studies: acoustic vents and the occlusion device's shape and material. Their influence on the OE is presented in Sections 1.4.2.1 and 1.4.2.2, respectively.

#### 1.4.2.1 Acoustic vents

The influence of controlled acoustic leaks (i.e., acoustic vents) on the OE is well-known and documented and is typically used as a solution to mitigate discomfort associated with OE in hearing aids. The reduction of both the $OE_{obj}$ and $OE_{exp}$ depends on several characteristics of the vent, including its length, diameter, and acoustic mass (Courtois et al., 1988; Kiessling, Brenner, Jespersen, et al., 2005; M.C. Killion, 1988; F. K. Kuk, 1991; F. Kuk et al., 2005; F. Kuk, Keenan, & Lau, 2009; Lundh, 1986; H. G. Mueller, 2003; Revit, 1992; Vasil-Dilaj &

Cienkowski, 2011; Wimmer, 1986; Winkler, Latzel, & Holube, 2016). However, although this solution appears simple and effective, it is not applicable to HPDs for the simple reason that adding an acoustic leak (even a controlled one, as with a vent) eliminates acoustic sealing and, consequently, dramatically reduces sound attenuation (Martin Brummund, 2014; Sgard, Carillo, & Doutres, 2019). Thus, the results from these studies are of limited use in the context of the doctoral thesis.

#### 1.4.2.2 Shape and material

The HPDs provided by manufacturers are available in a wide variety of shapes and materials, which can be described by multiple characteristics, such as the device length and diameter, or the material's density and Young's modulus. While their influence on physical comfort has been studied, research on their impact in the context of OE offers limited insight into their effects on $OE_{exp}$. Key findings from the literature are summarized below.

In hearing aids, studies have shown that earmold volume and mass directly affect the $OE_{exp}$ (Conrad & Rout, 2013; Dempsey, 1990; Kiessling, Brenner, Jespersen, et al., 2005; Vasil-Dilaj & Cienkowski, 2011). However, these findings are difficult to transpose to HPDs, as most studies focused on earmolds with acoustic vents—a feature that significantly reduces OE (see Section 1.4.2.1). This makes it particularly difficult, if not impossible, to isolate the effects of shape and material characteristics from those of the acoustic vent. Thus, findings originating from the aforementioned studies are of little use in the context of HPDs.

In several studies on HPDs, the influence of the device's shape has been investigated by comparing the OE induced by both types, namely earplugs and earmuffs. Typically, both $OE_{obj}$ and $OE_{subj}$ are lower with earmuffs than with earplugs (Berger & Kerivan, 1983; Nélisse et al., 2013), although these outcomes depend on variables like earplug insertion depth (see Section 1.4.7.1). For earmuffs, OE is inversely proportional to the occluded volume beneath the cup (Berger & Kerivan, 1983; Berger & Voix, 2022). However, no research has investigated how earplug shape (e.g., cylindrical foam vs. bullet-shaped) affects the OE while maintaining the other characteristics constant, such as the insertion depth and material composition. Additionally, no studies on either type of HPDs have investigated the impact of the shape specifically on the $OE_{exp}$.

Regarding the effects of material properties on the OE, existing studies focus exclusively on earplugs, with no comparable research on earmuffs. Moreover, most studies measure the $OE_{obj}$ or $OE_{subj}$, leaving the impact of material characteristics on the $OE_{exp}$ largely unexplored. These findings are discussed below.

Multiple studies have observed that material affects the $OE_{obj}$ and $OE_{subj}$. Foam earplugs typically generate lower $OE_{obj}$ levels than other materials, with differences of more than 10 dB compared to silicone (M. K. Brummund, Sgard, Petit, & Laville, 2014; Kévin Carillo et al., 2021; Stone et al., 2014), acrylic (M.O. Hansen, 1998), or medical balloon earplugs (K. Lee & Casali, 2011). Similarly, the same can be noted with the $OE_{subj}$, with differences reaching up to 10 dB between foam and vinyl earplugs (Berger & Kerivan, 1983). These variations are attributed to properties such as density and Poisson's ratio. For instance, Hansen observed a higher $OE_{obj}$ with a 5 g acrylic earplug than with a 1 g version, attributing the difference to modified vibratory responses by the additional mass in the earplug-ear system under a BC excitation (M.O. Hansen, 1998). More recently, Carillo et al., using numerical models, attributed the higher $OE_{obj}$ of silicone earplugs to their greater Poisson's ratio relative to foam, which increases the acoustic pressure generated by volume velocity within the occluded cavity (Kévin Carillo et al., 2021). Notably, the influence of the Poisson's ratio is significant with deep insertion, yet negligible or minimal at shallow or standard insertion depths.

To the author's knowledge, only few studies have assessed the $OE_{exp}$ induced by earplugs of varying shapes and materials. A study by Samelli et al. explored the role of comfort attributes in HPD selection (Alessandra G. Samelli et al., 2018). Their findings revealed that the OE significantly influences a participant's choice of an earplug, yet the material and shape of the tested earplugs (two foam and two silicone models were tested) did not affect their perception of the $OE_{exp}$.

Despite the previous studies, collected $OE_{obj}$ and $OE_{subj}$ data remain inadequate for understanding the impact of the HPD's shape and material on the $OE_{exp}$, since their correlation with the latter remains to be understood. Further studies are essential to clarify how earplug shape and material properties influence user discomfort relative to the OE.

### 1.4.3 Physical characteristics of the environment

The influence of a single physical characteristic related to the environment has been investigated in past studies, namely the background noise level and its effect on speech production. Its influence on the OE is presented in Section 1.4.3.1.

#### 1.4.3.1 Background noise level

The influence of background noise level (BNL) on the OE is scarcely documented, yet this characteristic of the environment significantly impacts speech production. Several studies have shown changes in vocal effort and speech characteristics (e.g., formant frequencies, pitch) attributed to the Lombard effect, which affects an individual's speech production as a function of BNL (EPA, 1977). However, the effect of BNL becomes even more complex when HPDs are worn by the talker and/or the listener, notably due to the interaction between the Lombard effect (i.e., causing an increase in vocal effort) and OE (i.e., causing a decrease in vocal effort) (Berger, 1986; Bouserhal, Macdonald, Falk, & Voix, 2016; Brungart, Cord, Solomon, Burns, & Block, 2012; D. C. Byrne, 2013; Hormann, Lazarus-Mainka, Schubeius, & Lazarus, 1984; Suter, 1992; Tufts & Frank, 2003; Vaziri, Giguère, & Dajani, 2022). Hence, it can be hypothesized that BNL indirectly influences the OE via changes in vocal effort. However, the data needed to support this hypothesis are lacking in the literature, and many questions remain unanswered.

For instance, it would be pertinent to investigate whether the degree of $OE_{exp}$ is the same when an earplug is tested in silence, in moderate-, or in high-level noise. This question is all the more relevant because most studies on the $OE_{exp}$ are typically conducted in a silent environment, even though workers usually wear HPDs in moderate to highly noisy environments. Similarly, it would be worthwhile to determine the impact of BNL on the $OE_{obj}$ indicators, which partly depend on an open-ear measurement (or a measurement outside the ear in the case of the $OE_{obj}^{NR}$) and are thus influenced by the acoustic environment. For these reasons, further research is needed to establish the extent to which BNL directly or indirectly influences both the $OE_{obj}$ and the $OE_{exp}$.

### 1.4.4 Psychosocial characteristics of the person

The influence of a single psychosocial characteristic related to the environment has been investigated in past studies, namely the habituation to HPD use. Its influence on the OE is presented in Section 1.4.4.1.

#### 1.4.4.1 Experience of HPD use

The influence of HPD use experience on the $OE_{exp}$ is examined in two parts: (i) the influence of the type of participants recruited, and (ii) the influence of habituation to HPD use. Regarding participant type, two groups can be distinguished: naïve and non-naïve. The difference between the two lies in the fact that non-naïve participants have prior HPD use experience in their jobs and/or personal activities and work in a noisy environment, whereas naïve participants do not have these experiences. According to studies compiled by Doutres et al. in their review on HPD comfort, the type of participants recruited has a non-negligible impact on the resulting data (Doutres et al., 2020). Typically, non-naïve participants tend to provide comfort evaluations at the extremes (both positive and negative) and can offer more detailed observations and critiques regarding the performance or characteristics of an HPD due to their familiarity and knowledge about them. Conversely, a few studies have found no difference in $OE_{exp}$ responses between naïve and non-naïve participants in the context of hearing aids (M.O. Hansen, 1997; Kiessling, Brenner, Jespersen, et al., 2005). However, it should be noted that in these studies, participants differed not only in their hearing aid use experience but also in their degree of hearing loss (i.e., non-naïve participants typically had sufficiently significant hearing loss to justify the use of hearing aids), thus limiting the applicability of these findings to HPDs. Therefore, further research is needed to determine the extent to which naivety regarding HPD use influences the $OE_{exp}$ they induce.

Next, habituation to HPD use refers to the change in perceived comfort that occurs after the HPD is placed in the ears. Typically, two periods are defined: (i) the short-term period, lasting from 1 h to 2 h, and (ii) the mid-term period, lasting from a few days to a few weeks. In the context of this doctoral thesis, the short-term period is the more critical of the two for laboratory measurements, as they fall within the typical short-term period duration. However, in the studies compiled by Doutres et al. in their review on HPD comfort, the observed influence of the short-term period is not always the same: in some cases, discomfort remains constant throughout the short-term period, whereas in others, it may increase before stabilizing (Doutres et al., 2020). To mitigate the influence of habituation, the authors therefore recommend that the duration of tests conducted with HPDs exceed the short-term period. They note, however, that determining this duration can be challenging, as it may depend not only on the type of participants recruited (i.e., naïve vs. non-naïve) but also on the specific comfort dimension and attribute under study. Moreover, establishing the necessary duration of tests aimed at evaluating the $OE_{exp}$ induced by HPDs is difficult due to the lack of data on this topic in the literature. Looking at studies in the context of hearing aids, some have shown that the $OE_{exp}$ may decrease after a few weeks of use (i.e., mid-term habituation), but no data have been gathered for the short-term period (Mackenzie et al., 1989; Navarro, 1996). Consequently, additional studies are needed to determine whether habituation influences $OE_{exp}$ induced by HPDs.

### 1.4.5 Psychosocial characteristics of the occlusion device

Psychosocial characteristics of the HPD have been reported to influence certain dimensions of HPD comfort, notable psychological and functional comfort, due to their discreetness, color, aesthetics, and attractiveness (Doutres et al., 2020, 2022). However, no data have been identified in the literature regarding the potential influence of these characteristics in the context of the OE, which can be attributed, at least in part, to the lack of studies investigating HPDs with respect to the $OE_{exp}$. Therefore, additional research is needed to determine whether users may have predispositions that could explain the degree of $OE_{exp}$ induced by one device rather than another.

### 1.4.6 Psychosocial characteristics of the environment

In the context of OE, the only documented psychosocial characteristic known to have an influence is the excitation source. More specifically, for a worker using HPDs, the most likely source of excitation that could generate OE is their own voice during verbal communication with a colleague. Nevertheless, the influence of the excitation source was previously discussed in Sections 1.2.1.1 and 1.2.3.

### 1.4.7 Characteristics of the interaction between the person and the HPD

Unlike the characteristics presented thus far, interaction characteristics do not belong to one of the three components of the triad; rather, they characterize the interaction that arises between them. In the context of this research project, two characteristics of the person-occlusion device are discussed, namely the insertion depth of an earplug into the earcanal and the sound attenuation provided by the HPD when it is in place in the earcanal. Their influence on OE is discussed in Sections 1.4.7.1 and 1.4.7.2, respectively.

#### 1.4.7.1 Insertion depth

The influence of insertion depth on the OE has been documented and studied in the context of both HPDs and hearing aids. Despite available $OE_{obj}$ and $OE_{subj}$ data, few studies have measured the $OE_{exp}$ using rating scales, although a decrease in OE-related discomfort is consistently reported with deeply inserted devices. The main findings from the literature are discussed below, beginning with the definition of the insertion depth.

The insertion depth is defined as the occlusion device's length inserted into the earcanal, measured from the device's medial face to an anatomical landmark, typically the entrance of the earcanal, defined as the base of the concha (Berger, 2013; Bastien Poissenot-Arrigoni, Law, Berbiche, Sgard, & Doutres, 2022). Studies commonly refer to three distinct insertion depths: (i) shallow, (ii) medium, and (iii) deep. However, there are discrepancies in the definitions of these three insertion depths, which can range from about 4–7 mm, 10–12 mm, and 15–22 mm for shallow, medium, and deep, respectively (Berger, 2013; Berger & Kerivan, 1983; M. K. Brummund et al., 2014; Kévin Carillo et al., 2021; Stenfelt & Reinfeldt, 2007).

Overall, the OE is observed to be inversely proportional to insertion depth, and this relationship holds for all three types of OE. Multiple studies show that the $OE_{obj}$ is significantly lower with a deep insertion than with a shallow insertion, with differences reported to be reaching up to 20 dB, depending on the earplug and the excitation source tested, in measurements on human subjects, artificial ears, or numerical models (Berger & Kerivan, 1983; M. K. Brummund et al., 2014; Kévin Carillo et al., 2021; M.C. Killion, 1988; Mead C Killion et al., 1988; K. Lee & Casali, 2011; Revit, 1992; Sgard et al., 2019; Stenfelt & Reinfeldt, 2007; Xu, 2019). Similarly, reductions of up to 10 dB have been observed in $OE_{subj}$ when measured with a deep insertion compared to shallow insertion (Dean & Martin, 2000; Stenfelt & Reinfeldt, 2007). This reduction in $OE_{obj}$ (and indirectly $OE_{subj}$) is explained by the lower acoustic pressure generated in the occluded earcanal, stemming from a decrease in free earcanal wall normal velocity due to increased insertion depth (Kévin Carillo et al., 2021)

With respect to the $OE_{exp}$, few studies have examined the influence of insertion depth using rating scales. However, it is widely accepted that deeply inserting an earplug or hearing aid significantly reduces the discomfort associated with the OE (e.g., one's own voice sounding "boomy," "hollow," or "distorted," as well as amplified chewing noises) (M.C. Killion, 1988; Mead C. Killion, 2012; H. G. Mueller, 2003). Reference manuals for both types of devices explicitly recommend deep insertion to mitigate OE-related discomfort (Berger & Voix, 2022; Dillon, 2012). Nevertheless, while the influence of insertion depth has been quantified for the $OE_{obj}$ and $OE_{subj}$, no data using rating scales are available in the literature for the $OE_{exp}$. Further research is therefore needed to quantify the effects of insertion depth on the $OE_{exp}$.

#### 1.4.7.2 Sound attenuation

The influence of sound attenuation on the OE has not been documented, although it is plausible that it plays a significant role. Both phenomena stem from the insertion of an HPD into the ears; however, sound attenuation is typically relevant when exposed to an external excitation source (e.g., industrial noise), whereas the OE is of interest during exposure to a source with an internal BC component (e.g., one's own voice). However, the significance of attenuation with respect to the OE might depend on the excitation source that induces it.

In the case of excitation sources primarily composed of a BC component, such as chewing or a bone transducer, sound attenuation likely does not influence the OE due to the absence of an AC contribution, which cannot be modified by the HPD. However, since the voice comprises both AC and BC components, sound attenuation could have an impact on both the $OE_{obj}$ and $OE_{exp}$. Studies have demonstrated that the ratio between AC and BC components depends on speech content (Mie Ostergaard Hansen & Stinson, 1998; Reinfeldt et al., 2010) and that this ratio influences the OE (as discussed in Section 1.2.1.1). Therefore, it is plausible that the OE could be further affected by sound attenuation if the AC-to-BC ratio is also altered by the HPD.

Nevertheless, this hypothesis has not been tested, and further studies are required to investigate it.

## 1.5 Summary

The literature review presented in this chapter has highlighted many unanswered questions and knowledge gaps regarding the measurement of the three forms of OE (i.e., $OE_{obj}$, $OE_{subj}$, $OE_{exp}$), their interrelationship, and the influence of various characteristics of the environment-person-HPD triad on the phenomenon. The key findings are listed below.

The absence of a standard governing the $OE_{obj}$ measurement creates a lack of consensus regarding methodology and restricts the use of findings from prior studies, notably due to variability caused by differing approaches. Some approaches are more complex than others, difficult to reproduce, or do not induce an OE representative of discomfort. However, those based on voice appear most pertinent because they induce an OE representative of discomfort. Nonetheless, aspects such as the measurement method, voice production and speech content, and the objective indicator for quantifying the $OE_{obj}$ amplitude still need to be established.

Concerning the evaluation of discomfort induced by the OE, few studies have provided quantitative data suitable for objectivization (i.e., rating scales data). Consequently, along with the scarcity of $OE_{exp}$ data induced by HPDs, methodological considerations such as question formulation, questionnaire administration, and rating scale design also remain undefined.

Moreover, the objectivization of the OE induced by HPD remains unanswered, as no strong correlation has yet been identified to link an objective indicator to the discomfort experienced by a user. The few originating from studies on hearing aids are typically weak, their distinctive differences with HPDs limit how these correlations provide useful information in the context of hearing protection.

Furthermore, the influence of numerous physical and psychosocial characteristics of the user-HPD-environment triad on the OE is either unknown or poorly documented, with far fewer studies focusing on psychosocial factors than on physical ones. It is likely that several of these characteristics exert a significant impact on the OE; a deeper understanding of their influence would enhance both the explanation of this phenomenon, and the discomfort associated with it.

It is therefore necessary to undertake further studies on the OE induced by HPDs.

# CHAPTER 2

# RESEARCH OBJECTIVES

This research project aims to have a better understanding of the occlusion effect discomfort induced by earplug when talking, through an experimental study with French-speaking participants in laboratory conditions. To achieve this goal, three specific objectives are pursued:

Specific objective 1 : Propose a methodology for measuring the objective occlusion effect induced by speech in the laboratory, based on microphone measurements. This method must be simple and robust to be adapted for field use.

Specific objective 2 : Identify and prioritize the physical and psychosocial characteristics of the environment-person-HPD triad that influence the experienced occlusion effect by a user of earplugs in a laboratory context.

Specific objective 3 : Objectivize the occlusion effect  experienced in a laboratory context.

The outcomes of this doctoral thesis will enhance our understanding of the OE phenomenon and thus provide better insight into the discomfort induced by earplugs when a user speaks while wearing them. Additionally, the proposed objective measurement method and the objectivization of OE will serve as useful tools for experts. Occupational hygienists will be able to apply the proposed methodology in the field to measure the OE easily, helping workers choose and fit their earplugs optimally. In the near short term, manufacturers, in turn, will be able to use these tools to more readily test earplugs during the design phase, ultimately creating earplugs with reduced OE. In the long term, the earplug design phase could be done without the need for measurements involving human participants.

# CHAPTER 3

# METHOD AND MATERIAL

This chapter outlines the methodology used to address the specific objectives presented in Chapter 2 throughout two measurement campaigns conducted under laboratory conditions with human participants. The first campaign (referred to as C1), conducted from November 2018 to August 2019, is presented in Section 3.1. Prior to the second measurement campaign, a series of pretest was conducted to improve the questionnaire that would be used; the methodology related to those is presented in Section 3.2. The second campaign (referred to as C2), conducted from December 2022 to May 2023, is presented in Section 3.3. Although C1 and C2 target different objectives (i.e., propose a methodology to measure the $OE_{obj}$ vs. understand which characteristics of the triad influence the $OE_{exp}$ and objectivize it), they share several methodological elements; as a result, references to relevant sections of C1's methodology are provided when discussing C2's methodology.

## 3.1 Measurement Campaign C1

This section outlines the methodology for the C1 measurement campaign, as approved by the École de technologie supérieure (ÉTS) Research Ethics Committee (Certificate #H20180402). The primary objective of this campaign was to address the first specific objective: propose a simple and robust methodology to measure the $OE_{obj}$.

The methodology is organized as follows: the selection of participants is outlined in Section 3.1.1, the experimental setup for the various measurements is described in Section 3.1.2, and the microphonic earpieces used for measuring acoustic pressure in the earcanal are presented in Section 3.1.3. The experimental protocol and the stimulation sources used to generate and measure the OE are detailed in Section 3.1.4, while the objective indicators used to quantify $OE_{obj}$ are described in Section 3.1.5. Finally, the statistical tools applied for analyzing the collected data are discussed in Section 3.1.6.

### 3.1.1 Participant Selection

Thirty participants (26 males, 4 females, age: 25.1 ± 4.4 years) volunteered to participate in the study. Most participants were university students, had no prior experience with OE measurements, and were not accustomed to daily earplug use. Each participant attended two separate sessions: the first to assess their eligibility for the study and the second to conduct the experiments. To be eligible, participants had to meet the following criteria: (i) AC and BC hearing thresholds equal to, or better, than 20 dB HL within the frequency range of 125 Hz–8000 Hz, and (ii) both ears free of anomalies upon otoscopic inspection and no history of ear surgeries. Hearing thresholds were evaluated using a Shoebox Pro Audiometer (Shoebox Ltd., Canada), paired with a RadioEar B-81 bone transducer (RadioEar Corporation, USA) for BC hearing thresholds, and 3M™ E-A-RTone insert earphones (3M, USA) for AC hearing thresholds. A RadioEar P-3333 headband was employed to secure the bone transducer on the participant's skull. All assessments were conducted by the experimenter, trained by a Quebec-registered audiologist.

Before participating, all participants read the project's general information and signed a consent form. Although participants were free to withdraw from the trial at any time for any reason, all sessions were completed. Each participant received a $30 compensation for their participation.

During the eligibility session, the better ear (defined as the ear with the lowest AC hearing threshold) of each participant was identified. Given that some stimulation sources used in the study were off-centered relative to the body's sagittal plane, one ear was closer to the stimulation than the other. This ear is referred to as the ipsilateral ear, while the other ear is designated as the contralateral ear throughout the document.

### 3.1.2 Experimental Setup

During the second session, two types of measurements were conducted: (i) microphonic measurements to assess the $OE_{obj}$ using multiple stimulation sources, and (ii) hearing threshold measurements to assess the $OE_{subj}$ with a bone transducer. Although C1 primarily focuses on the $OE_{obj}$, $OE_{subj}$ was also measured for comparison, as the subjective approach is typically regarded as the "gold standard" for assessing the OE.

All measurements were performed in a 20 m³ audiometric booth (Industrial Acoustics Company Inc., USA) located in the ICAR laboratory at the ÉTS in Montreal, Canada, as shown in Figure 3.1. The room was equipped with four uncorrelated Klipsch™ speakers (Klipsch LLC., USA), positioned in each corner. Participants were seated comfortably in a chair, facing a ceiling-mounted computer screen used for communication and feedback.

Two microphones were positioned 1.2 m above the floor and approximately 0.6 m in front of the participants' mouths. A 1 in G.R.A.S. type 26 HF microphone with a type 12HF amplifier (G.R.A.S., Denmark) and a 0.5 in B&K type 2669 microphone with a type 2829 amplifier (Brüel & Kjaer, Denmark) served as reference microphones. The 1 in microphone was connected to a real-time sound level meter developed in LabVIEW (National Instruments, USA), which displayed the A-weighted equivalent continuous sound pressure level with a 500-millisecond integration time ($L_{eq(A),500ms}$) on the screens of both the experimenter and the participant. The 0.5 in microphone signal was processed using an in-house Matlab script (MathWorks, USA) and was employed for calibrating the earpieces' probe tubes (see Section 3.1.3) and measuring the room's noise levels during various measurements.

Both microphones and the four speakers were connected to two NI PXI 4461 and two PXI 4462 cards mounted on a NI PXI 1033 chassis, located outside the booth and connected to the experimenter's computer. Measurements with the bone transducer involved the RadioEar B-81 bone transducer, the RadioEar P-3333 headband, and the 3M E-A-RTone insert earphones. The bone transducer and insert earphones were connected to the Shoebox Audiometer situated outside the booth and operated by the experimenter.

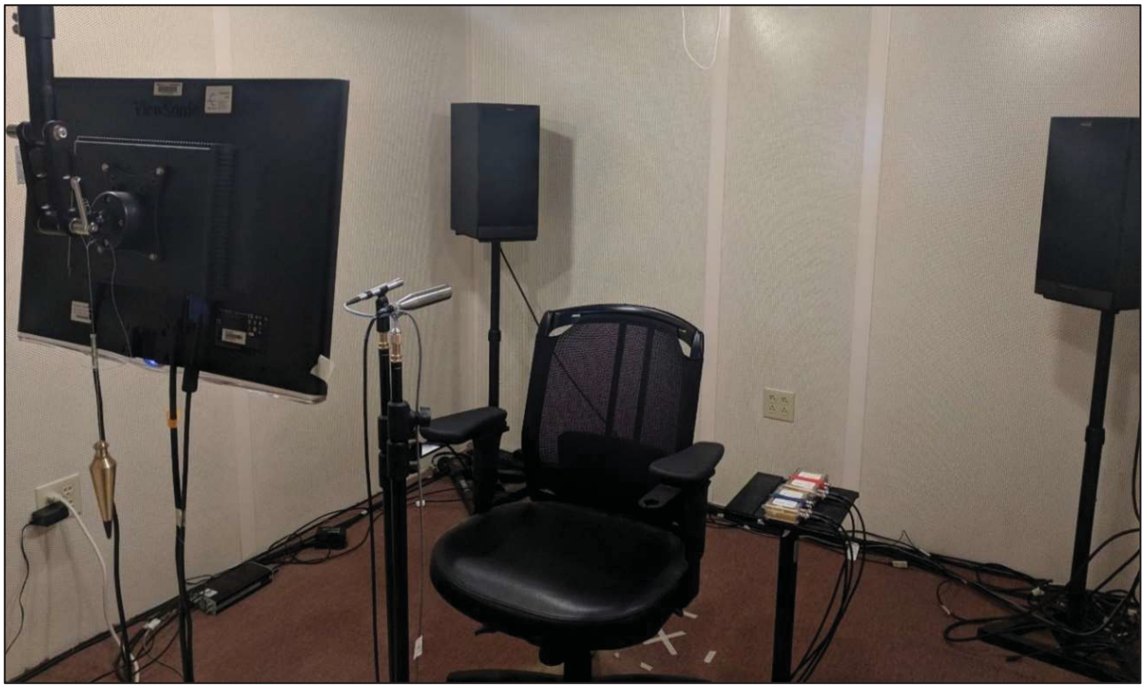


Figure 3.1 Experimental setup for C1, consisting of the participant's chair, four uncorrelated speakers (only two shown here), two reference microphones and a screen displaying the real time feedback system

### 3.1.3 Microphonic Earpieces

SPLs in earcanals were measured using two pairs of custom-made microphonic earpieces (Bonnet, Nélisse, Nogarolli, & Voix, 2019; Coser Nogarolli, 2019) as shown in Figure 3.2. The first pair consisted of protecting earpieces (Figure 3.2a and Figure 3.2b), used for the occluded ear condition. It was designed to fit three sizes of Comply T-400 Isolation ear tips (Comply, USA): small, medium, and large. The size of the ear tips was chosen according to the participant's earcanal size and the ability to obtain an adequate acoustic seal, verified with a sound attenuation measurement. The second pair consisted of open earpieces (Figure 3.2c and Figure 3.2d), used for unoccluded ear measurements.

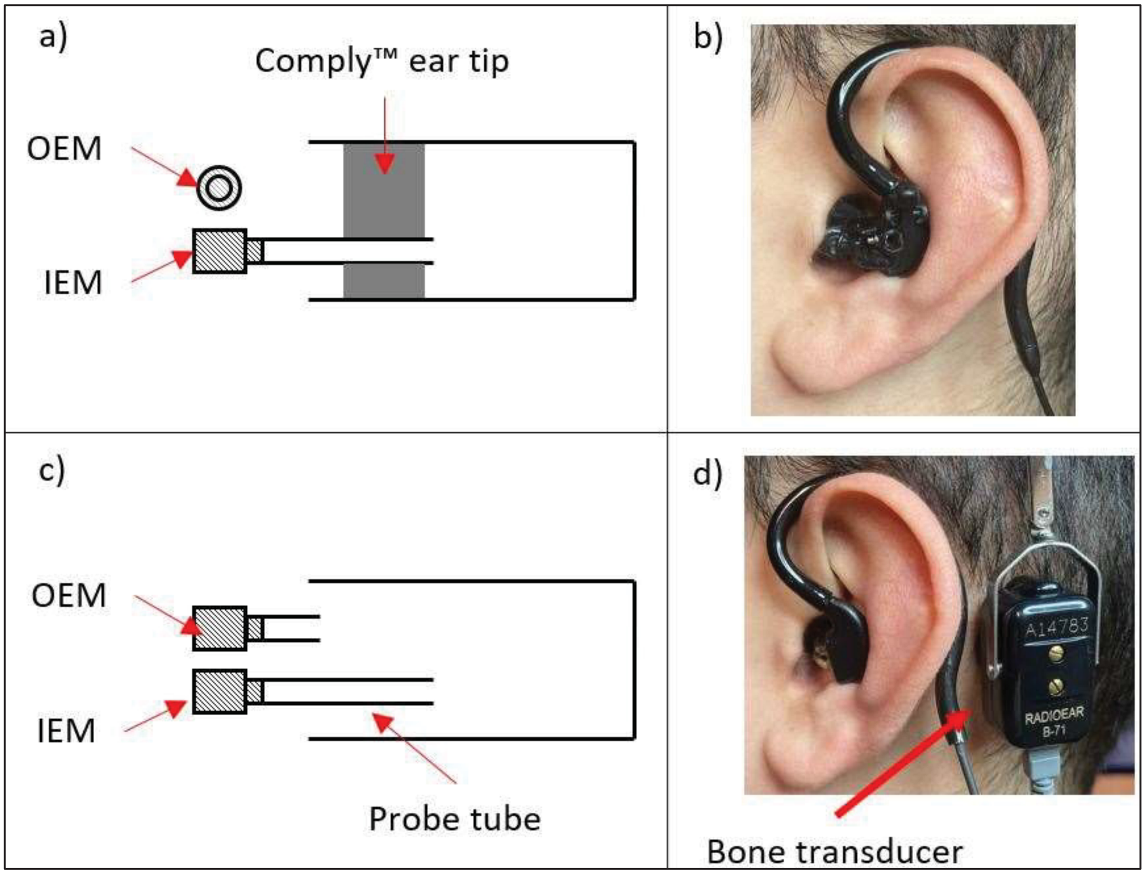



Figure 3.2 Schematics and pictures of the custom-made earpieces (Bonnet et al., 2019; Coser Nogarolli, 2019) used for C1. (a) Schematic of the protecting earpiece. The OEM measures the SPL at the earcanal's entrance, and the IEM measures the SPL inside the earcanal with a probe tube passing through the Comply T-400 ear tip. (b) Protecting earpiece installed in the ear. (c) Schematic of the open earpiece. The OEM measures the SPL at the earcanal's entrance with a probe tube and the IEM measures the SPL inside the earcanal with a probe tube. (d) Open earpiece installed in the ear with the bone transducer placed on the temporal bone

Each earpiece was equipped with two miniature microphones: an inner ear microphone (IEM) connected to a probe tube to measure the SPL approximately 15 mm into the earcanal relative to the tragus and an outer ear microphone (OEM) to measure the SPL at the earcanal's entrance. Each probe tube microphone was calibrated by placing its opening next to the calibrated 0.5 in reference microphone inside the audiometric booth and by generating a 90 dB(A) uncorrelated Gaussian white noise with the four speakers. This process allowed the calculation of a frequency-dependent calibration factor. A stopper integrated into the earpieces ensured an identical positioning of the inner probe tube microphone opening in the earcanal for the occluded and unoccluded conditions.

### 3.1.4 Experimental Protocol & Stimulation Sources

The second session with each participant was divided into seven parts during which the $OE_{obj}$ and $OE_{subj}$ were measured with various stimulation sources, namely a bone transducer, speech, and mastication. Before proceeding to the measurements, participants were given time to understand and practice the different tasks. The tasks, described below, were conducted with the protecting earpiece (occluded ear) and the open earpiece (unoccluded ear).

To measure the $OE_{obj}$ with the bone transducer, a 25 dB HL pure-tone signal centered at the 250, 500, 750, 1000, 1500, and 2000 Hz audiometric frequencies for a 20-sec duration was used. The signal intensity was chosen to ensure that the noise generated in the earcanal was supraliminal and above the noise floor levels, but low enough to avoid measurement artifacts due to the bone transducer's operational limits and acoustic radiation (e.g., distortion or radiating noise from the transducer casing).

To measure the $OE_{subj}$ with the bone transducer, BC hearing thresholds were assessed using the modified Hughson-Westlake procedure at the 250, 500, 750, 1500, and 2000 Hz audiometric frequencies (Carhart Raymond & Jerger James F., 1959). To ensure the measured hearing thresholds were from the chosen ear, the opposite ear was masked with a broadband white noise controlled and generated by the audiometer at 60 dB HL, delivered through a 3M E-A-RTone earphone. The 60 dB HL level was chosen to provide adequate masking without leaking to the other ear through transcranial transmission. As the BC audiometry required significant concentration from the participants, hearing thresholds were obtained only for the ipsilateral ear for all participants.

To reduce variability due to earplug fitting, all measurements were conducted for a single fit of the earpiece. Measurements followed a specific sequence to avoid reinstalling the bone transducer and refitting the protecting earpieces multiple times. Before proceeding, the earplug's positioning and fit were verified in the participant's earcanals. This verification involved generating a broadband AC noise field using four uncorrelated speakers and measuring the sound attenuation provided by the earplug. A NR of at least 10 dB at 160 Hz was considered a sufficient fit for the study. If inadequate attenuation was measured, the earplug was removed, refitted, and the verification process repeated until adequate attenuation was achieved. Once the earplug was properly fitted, measurements were conducted according to the sequence shown in Table 3.1.

Table 3.1 Sequence divided into seven different parts

| **Part** | **Ipsi. ear config.** | **Contra. ear config.** | **Stimulation source** | **Stimulation level** |
|---|---|---|---|---|
| 1 | Open | Open | Bone transducer | Supraliminal |
| 2 | Open | Masked | Bone transducer | Threshold |
| 3 | Protected | Masked | Bone transducer | Threshold |
| 4 | Protected | Protected | Bone transducer | Supraliminal |
| 5 | Protected | Protected | Speech, mastication | Supraliminal (user generated) |
| 6 | Protected | Open | Speech, mastication | Supraliminal (user generated) |
| 7 | Open | Open | Speech, mastication | Supraliminal (user generated) |

The sequence varied by ear configuration (open or closed), stimulation type, and stimulus level. In parts 1, 2, 3, and 4, the bone transducer was used to induce the OE. When the experimenter installed the bone transducer on the participant's temporal bone, as shown in Figure 3.2d, they verified that it did not contact the pinna or the pinna hook of the earpieces and that its positioning was stable. If slippage occurred during measurement, the bone transducer was removed, replaced, and preceding measurements were discarded. In parts 5, 6, and 7, the OE was induced by participant-generated stimulations, such as speech and mastication. Speech-based stimulations involved enumerating numbers and vocalizing the vowels /i/ and /ə/ at three distinct vocal efforts, namely normal, loud and shouting voices, corresponding to 60, 70, and 80 dB(A), respectively, as measured by the reference microphone. A list of randomly generated numbers and a sound level meter displayed on the screen helped participants maintain a continuous flow at the designated noise level. For mastication, participants were instructed to masticate chewing gum according to four specific guidelines: (1) masticate on the side of the ipsilateral ear only, (2) keep the lips shut, (3) maintain a normal rate, and (4) avoid exaggerated movements. These instructions ensured consistency across participants. Table 3.2 summarizes the stimulations in parts 5, 6, and 7, randomized for each configuration and participant to reduce order effects.

Table 3.2 Stimuli produced by the participants in part 5, 6 and 7, in a randomized order

| **Stimulation** | **Effort** | **Duration** |
|---|---|---|
| Enumeration of random numbers | 60, 70, 80 dB(A) | 20 seconds |
| Vocalization of the vowel /i/ | | 5 seconds |
| Vocalization of the vowel /ə/ | | 5 seconds |
| Mastication of a chewing gum | - | 20 seconds |

The test sequence enabled objective measurement of the occlusion effect using three methods from the literature: (1) the standard method, (2) the real-time method, and (3) the NR-based method. As described in Section 1.2.1.2, these methods differ in when and where the occluded and unoccluded sound pressures are measured. Figure 3.3 illustrates the SPL measurement positions for each method. Measurements in parts 1 and 4 were used to compute the $OE_{obj}$ via the standard method for bone transducer stimulation, while parts 5 and 7 were used for speech and mastication stimulation. Measurements in part 6 were used to compute the $OE_{obj}$ via the real-time method for speech and mastication stimulation. For this, the ipsilateral ear was fitted with the protecting earpiece (occluded SPL), and the contralateral ear with the open earpiece (unoccluded SPL). SPLs were measured simultaneously in the earcanals using the IEMs of both earpieces. Part 6 measurements were also used to compute the $OE_{obj}$ using the NR-based method. Here, only the protecting earpiece was used; the occluded SPL was measured with the earpiece's IEM, while the unoccluded SPL was estimated using the earpiece's OEM. As to conduct a direct comparison with the standard and real-time methods, only part 6 measurements were used for the NR-based method. For the $OE_{subj}$, only the standard method was employed, as it is based on hearing threshold measurements. The $OE_{subj}$ was computed using measurements from parts 2 and 3 for the ipsilateral ear only.

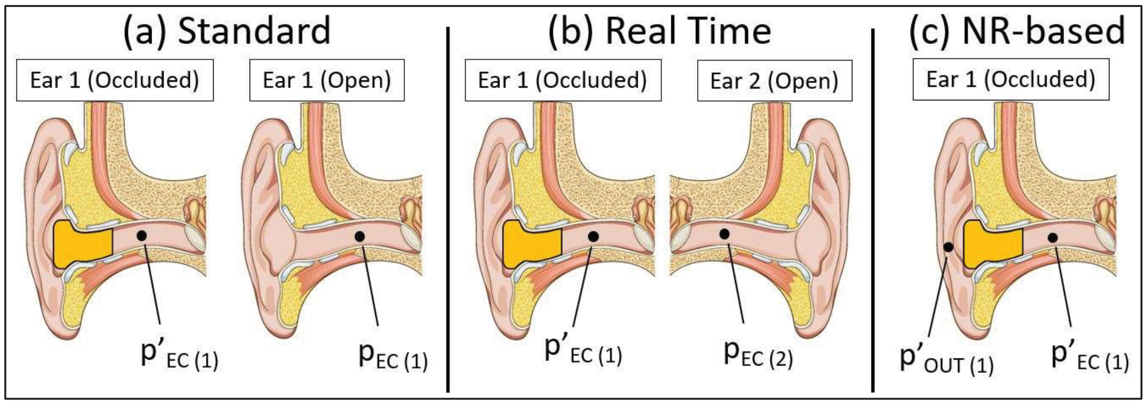



Figure 3.3 Positions of the sound pressure measurements used to compute the $OE_{obj}$ with the three measurement methods: (a) the standard method, (b) the real-time method, (c) the NR-based method. $p'_{EC}$ and $p'_{EC}$ are respectively measured with the IEM of the open and protected earpieces. $p'_{OUT}$ is measured respectively with the OEM of the protected earpiece

### 3.1.5 Definition of indicators

Two types of sound attenuation and OE indicator are used in the study: spectral (frequency-dependent) and single value. Indicators based on the $OE_{obj}$ are considered objective indicators whereas those based on the $OE_{subj}$ are considered subjective indicators.

Hearing threshold levels (HTL) measured at the different audiometric frequencies are used to compute the $OE_{subj}$, defined in Eq (3.1) as :

$$OE_{subj} = HTL_{unoccluded} - HTL_{occluded} \quad (3.1)$$

For the NR and the $OE_{obj}$, the RMS sound pressure ($p_{rms}$) is measured with the microphonic earpieces to compute equivalent continuous sound pressure level ($L_{p,eq,t}$) measured with the different microphones with a 20 seconds integration time, defined in Eq. (3.2) as :

$$L_{p,eqT} = 10\ log_{10}\left(\frac{1}{T}\int\left(\frac{p(t)}{p_0}\right)^2 dt\right), \quad (3.2)$$

with $p_0 = 20\mu Pa.$

The sound attenuation provided by the protecting earpieces was verified by measuring the NR, using a white noise generated by the room's speakers, defined in Eq. (3.3) as :

$$\mathrm{NR} = L_{p'_{OUT(1)}} - L_{p'_{EC(1)}} \quad (3.3)$$

The $OE_{obj}$ can be obtained using the three distinct measurement methods. $OE_{obj}$ measured with the standard, the real-time, and the NR-based methods, are respectively defined in Eq. (3.4), (3.5), and (3.6) as :

$$OE_{obj}{}^{STD} = L_{p'_{EC(1)}} - L_{p\ EC(1)} \quad (3.4)$$

$$OE_{obj}{}^{RT} = L_{p'_{EC(1)}} - L_{p\ EC(2)} \quad (3.5)$$

$$OE_{obj}{}^{NR} = L_{p'_{EC(1)}} - L_{p'_{OUT(1)}} \quad (3.6)$$

Based on these frequency-dependent $OE_{obj}$ (and $OE_{subj}$) values, SVIs are computed to quantify the OE with a single number, thereby simplifying comparisons and analyses as previously discussed (see Section 1.2.1.3). Multiple SVIs were computed, as outlined in Table 3.3. The SVIs are based on those found in the literature to enable comparisons between them. As both $OE_{obj}$ and $OE_{subj}$ typically exhibit a maximum at low frequencies, the 160–500 Hz range was chosen for the computation of the SVIs. Following the comparison of the different SVIs, the most robust—defined as the one with the smallest variability and the fewest outliers—will be identified as the occlusion effect index (OEI).

Table 3.3 List and description of the different SVIs computed for the analysis of the data collected in C1

| Single value indicators (SVI) | Description |
|---|---|
| $OE_{160\ Hz}$ | OE magnitude at 160 Hz. |
| $OE_{250\ Hz}$ | OE magnitude at 250 Hz. |
| $OE_{500\ Hz}$ | OE magnitude at 500 Hz. |
| $OE_{max}$ | Maximum OE in the 160-500 Hz range. |
| $OE_{AVG}$ | Arithmetic mean of the OE in the 160-500 Hz range. |
| $OE_{B\text{-}L}$ | Occluded/unoccluded level difference of the band-integrated square rms sound pressure in the 160-500 Hz bandwidth-limited (B-L) range. |

### 3.1.6 Statistical Tools

Matlab routines developed in-house were used to perform all statistical analyses of the data collected in C1 using the Statistics and Machine Learning Toolbox add-on. The analyses included: (i) calculating descriptive statistics for the various measured indicators and (ii) comparing different sources of excitation, measurement methods, and objective indicators. The comparisons were conducted using analysis of variance (ANOVA) for repeated measures and a multiple comparison test. Additionally, the Pearson correlation coefficient (r) was calculated to assess the correlation between certain variables. The interpretation of all results was performed with a significance threshold set at 5% ($p \leq 0.05$).

## 3.2 Pre-tests for the design of the C2 measurement campaign questionnaire

The questionnaire used for the C2 campaign (see Section 3.3) was developed following a series of pretests, approved by the ÉTS Ethical Committee. (Certificate #H20220409), that improved the phrasing of questions related to the OE. More specifically, a brief survey was conducted with respondents to gather their feedback and identify the optimal formulation of questions addressing the $OE_{exp}$. This survey was deemed necessary, as no French-language questionnaire addressing discomfort associated with the OE currently exists. As explained in Section 1.2.3.1, ambiguities in question formulation can introduce challenges in data interpretation. Within the context of this study, these ambiguities were hypothesized to stem from linguistic regional differences (e.g., Quebec French versus France French) and participant characteristics (e.g., naive versus non-naive individuals). These difficulties were clearly observed during the initial rounds of pretesting, which emphasized the need to refine the questionnaire through additional pretest. The respondent sample is described in Section 3.2.1, while the survey procedure is detailed in Section 3.2.2.

### 3.2.1 Survey respondents

The survey was conducted among individuals who were colleagues, friends, or family members of the experimenter, as well as among workers and students present on the university campus, with whom there was no prior acquaintance. In total, 21 individuals were interviewed to identify the most suitable formulation for assessing the discomfort associated with the OE. Table 3.4 summarizes the characteristics of the surveyed sample. Naive individuals were those unfamiliar with the experimenter's research project and thus may not have been aware of the OE induced by HPDs. Additionally, due to linguistic differences between Quebec French and French spoken in France, special attention was given to the linguistic region of the individuals (Quebec or France) to better understand the connotations of certain words specific to each linguistic region.

Table 3.4 Characteristics of the sample of individuals who participated in the survey on discomfort assessment

| | | | |
|---|---|---|---|
| Total respondents | | 21 | |
| | | | |
| Workers | 10 | Non-workers | 11 |
| Naive regarding the research project | 12 | Non-naive regarding the research project | 9 |
| Male | 17 | Female | 4 |
| French-speakers from Québec | 18 | French-speakers from France | 3 |

### 3.2.2 Survey conduct

The survey was conducted in the form of an interview with the respondents, lasting from 3 to 15 minutes. The context given to the participant was that the purpose of the survey was not to evaluate their perception of the OE, but rather to assess their understanding of a question that would be asked to them in different ways. Respondents were asked to identify the formulation that seemed most precise to them, as well as to provide all comments and explanations to justify their preference; these elements of response were also noted by the experimenter. Interviews were conducted individually or in groups depending on the individuals involved. The interview protocol was as follows:

1. **Presentation of the survey**: Explanation to the respondent that the survey aims to obtain their opinion regarding the wording of a question about the perception of OE generated by their own voice.

2. **Brief introduction to OE**: Oral presentation in two sentences of the phenomenon induced by HPDs, earbuds, or even one's own fingers by blocking the entrance of the earcanal.

3. **Experiencing and perceiving OE while speaking**: Invitation for the respondent to pay particular attention to the changes they perceive and experience when counting

from 1 to 5 when their ears are blocked by their fingertips. Words used by the respondents to describe the sensations caused by the OE were noted.

4. **Presentation of the questions to assess the discomfort**: Invitation for the respondent to imagine a situation during which these sensations are perceived for a longer period. Considering this hypothetical situation, the question was asked in three ways in *French*:

   - « Lorsque vous parlez, la *gêne* causée par votre propre voix est : »
   - « Lorsque vous parlez, *l'inconfort* causé par votre propre voix : »
   - « Lorsque vous parlez, le *désagrément* causé par votre propre voix est : »

   Which, when translated to English, corresponds to :

   i. "When you speak, the *annoyance* caused by your own voice is:"
   ii. "When you speak, the *discomfort* caused by your own voice is:"
   iii. "When you speak, the *inconvenience* caused by your own voice is:"

It was explained to the respondents that the answer to this question was a rating scale from "Very weak" to "Very strong", but that they did not need to provide an answer besides their preferred formulation.

## 3.3 Measurement Campaign C2

This section outlines the methodology for the C2 measurement campaign, as approved by the ÉTS Research Ethics Committee (Certificate #H20220409). The primary objectives of this campaign were to address the second and third specific objectives: objectivizing the OE and identifying the characteristics of the triad that significantly influence the OE. The methodology is structured as follows: first, the study procedure is presented in Section 3.3.1. Next, the participant details are provided in Section 3.3.2, followed by a description of the experimental setup used for the various measurements in Section 3.3.3. Subsequently, the characteristics of the vocal effort employed to induce the OE are specified in Section 3.3.4. This is followed by a description of the earplugs and microphone doublets used for objective measurements in Section 3.3.5. The questionnaire and its administration to participants is detailed in Section 3.3.6, and the procedures for measurement sessions are outlined in Section 3.3.7. The assessment of the triad's characteristics is presented in Section 3.3.8, followed by an explanation of the various objective indicators measured during the tests in Section 3.3.9. Finally, the data analysis process and the statistical tools used for post-processing are described in Section 3.3.10.

### 3.3.1 Study Conduct

Each participant was met individually during three separate sessions, as depicted in Figure 3.4. The first session aimed to verify their eligibility to participate in the study, based on the criteria described in Section 3.3.2. The second session aimed to conduct an impression of their earcanal by an audiologist for the fabrication of their custom earplugs, as described in Section 3.3.5. The third session aimed to conduct the $OE_{obj}$ and $OE_{exp}$ measurements. For a given participant, the measurement session always began with a training phase during which the participant was briefly explained the phenomenon of OE and where they could familiarize themselves with the OE by testing different devices generating various occlusion effect. After the training phase, participants then tested 11 configurations divided into three phases, namely (i) testing four earplug models, (ii) testing three insertion depths of a specific earplug, and (iii) testing a specific earplug in four levels of background noise. The order of the three phases was randomized for each participant. More details on the training and the three phases are provided in Sections 3.3.7.1 to 3.3.7.5.

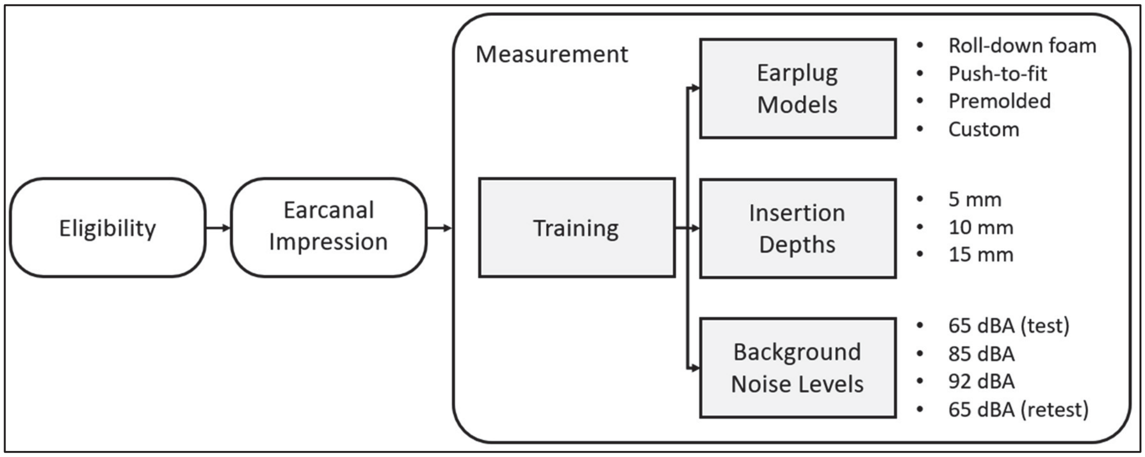



Figure 3.4 Conduct of the study. The three white boxes represent the three sessions to which participants took part during the study. The grey boxes within the measurement session represent the four phases, namely the training followed by the testing of different earplugs, different insertion depths and different background noise levels. The bullet points next to the grey boxes represent the configurations tested within each phase, respectively

### 3.3.2 Participant Selection

Thirty-three French-speaking participants (24 M, 9 F) took part in this research project. The data from one single participant (1 M) was excluded during post-processing because their responses during the training phase (see Section 3.3.7.2) were not deemed reliable. Participants recruited for the study came from different backgrounds, allowing for a sample of non-naïve and naïve participants, i.e., with and without experience using HPDs, respectively. To be eligible to participate in the study, the criteria were verified by the experimenter, who received a training from a certified Quebec audiologist, according to the methodology presented in Section 3.1.1. Three criteria were verified: (i) an otoscopic inspection of the earcanals to verify the absence of lesions or abnormalities, (ii) no hypersensitivity of the earcanal during the insertion of an earplug, (iii) hearing loss equal to or less than 20 dB HL in AC and BC. At the end of their participation in the study, participants were given their custom-made earplugs as a material compensation.

### 3.3.3 Experimental Setup

The first and third sessions with the participants (i.e., eligibility- and measurement sessions) took place in the audiometric booth of the ICAR laboratory. The four uncorrelated speakers of the room were positioned in the four corners of the audiometric booth to generate different acoustic fields at different sound levels, as to perform attenuation measurements and simulate an industrial sound environment; further details regarding the acoustic fields are provided in Section 3.3.7.1 and 3.3.7.5. A chair was placed in the center of the room to comfortably seat the participant facing an adjustable-height table, on which a laptop was placed so they could answer the questionnaire throughout the measurement session. A B&K type 4961 reference microphone (Brüel & Kjaer, Denmark) was used to monitor the noise level in the booth during various tests. The reference microphone was placed at 1.2 m from the floor in two distinct position using a rotating support : (i) in the middle of the room when calibrating microphones and probe tube microphones, (ii) 0.6 m 45-degrees Azimuth at the (seated) participant's eye level, was used to monitor the noise level in the booth during various tests. The 45-degrees Azimuth position of the microphone was selected to prevent the participant interfering with the microphone when answering the questionnaire on the laptop. The two positions are schematized in Figure 3.5. The NI (National Instruments, USA) chassis and cards presented in Section 3.1.2 were used for signal acquisition and generation using a Matlab (MathWorks, USA) routine developed in-house. The experimental setup is shown in Figure 3.6, with the reference microphone placed in the second position.

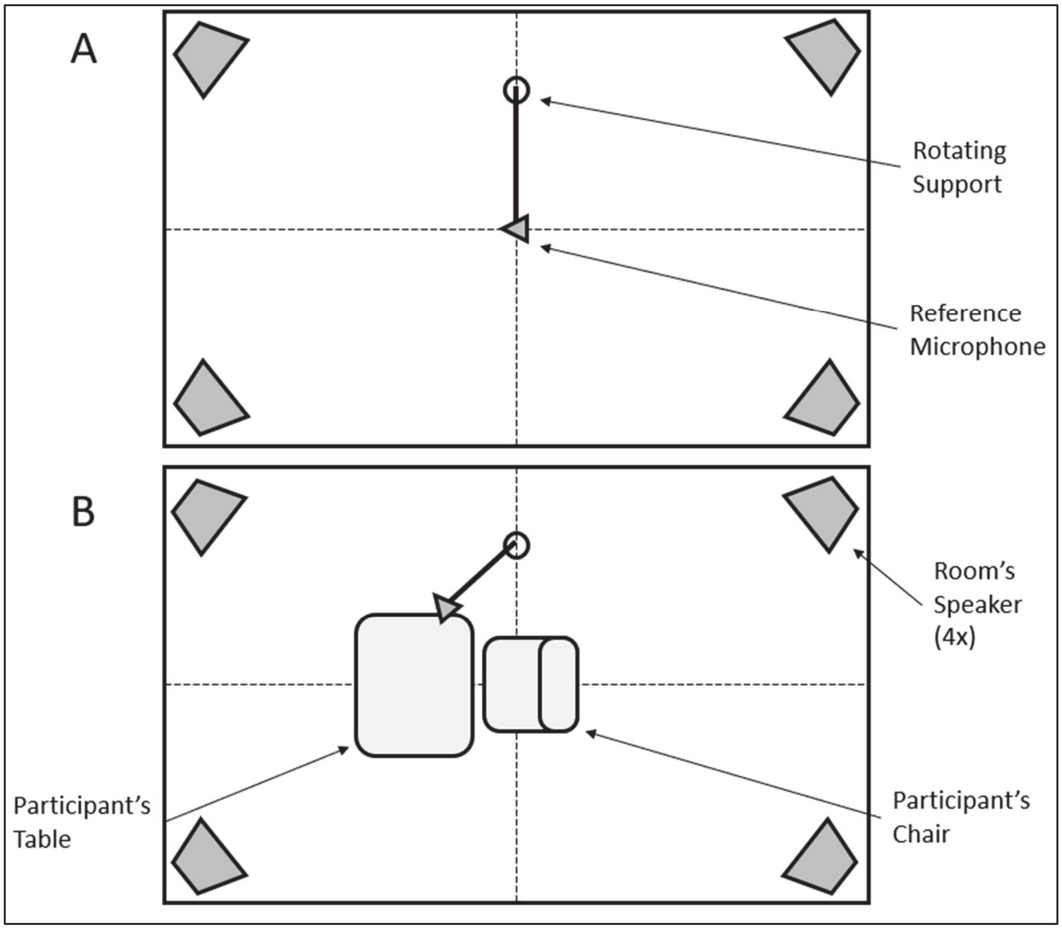



Figure 3.5 Schematic of the experimental setup and the two positions of the reference microphone: (A) calibration position at the center of the room, (B) measurement position during the tests at a 45-degree azimuth relative to the participant.

Figure 3.6 Experimental setup for C2, consisting of the participant's chair, four uncorrelated speakers (only two shown here), a reference microphone and a laptop placed on an adjustable height table for the participant to answer the questionnaire. A computer monitor, a keyboard and a mouse allowed for the experimenter to remain in the room with the participant throughout the measurement session while controlling (remotely) the room's computer for data acquisition and generation

### 3.3.4 Speech-Induced Occlusion Effect

Speech was the sole source of stimulation used during the study since it is typically associated with the $OE_{exp}$ induced by HPDs (Berger & Voix, 2022; Courtois et al., 1988; Dillon, 2012), and was found to be the most simple and robust stimulation source following C1 data analysis (see Section 4.1.3.1). During the measurement session, participants were tasked with speaking aloud while focusing on how they experienced hearing their own voice. Participants were free to say whatever they wanted, but to help them overcome a potential shyness about speaking in front of a stranger (i.e., the experimenter) or not knowing what to say during the tests, suggestions were made to the participants: (i) to count from 1 to 25 or enumerate random numbers, (ii) to vocalize vowels (e.g., /a/, /ə/, /i/) or sounds (e.g., "boom-beat," (Berger & Voix, 2022)), (iii) to describe the sensations they perceived regarding their voice (e.g., "I perceive my voice as [...] when I speak") to themselves or the experimenter, (iv) to read aloud sentences from a fictitious conversation between two employees in an industrial workshop, printed on a sheet of paper available to the participant throughout the measurement session, (v) talk with the experimenter about a subject of their choice. During the tests, participants were instructed to speak at an effort they deemed adequate for the background noise they were exposed to, and so that the experimenter, also wearing HPDs, could understand them from a distance of 1.5 m. Since the levels of background noise varied from quiet to loud, as explained in Section 3.3.7.5, the vocal effort the participant had to produce ranged from speaking normally to needing to shout. If the participant spoke too softly or too loudly, the experimenter made a hand gesture to indicate to adjust their vocal effort accordingly; however, in practice, except for a few isolated occurrences, the experimenter did not need to intervene as the participants naturally adjusted their vocal effort appropriately throughout the tests.

### 3.3.5 Earplug & Microphonic Doublets

In the context of this study, only the $OE_{obj}$ and $OE_{exp}$ induced by earplugs were assessed during the measurement session. However, earmuff-type HPDs were also used during a training at the beginning of the measurement session to train and familiarize the participants to the concept of $OE_{exp}$ (see Section 3.3.7.2). Besides the training phase, four models of probed earplugs were used during the study to assess the $OE_{obj}$ under different conditions. The probed earplugs allowed for the measurement of the SPLs inside and outside the earcanals using a microphonic doublet, consisting of two Knowles FG-23329-D65 microphones (Knowles Corporation, USA) encased into a metallic casing. The inner ear microphone is connected to the probed earplug, the probe's opening being located at the center of the medial face of the earplug inside the earcanal, while the outer ear microphone is facing outward the casing. The microphonic doublet was connected to NI cards through a connection box developed in-house at the ÉTS. When connected to a probe earplug and installed into the participant's ear, the OEM is typically facing downward at the jaw level, as shown in Figure 3.7. Prior tests showed no significant difference in SPL measured at this location vs. near the earplug's lateral face. The instrumented earplugs were used in the present study to first verify, in real time, the fit of the earplug through a measurement of attenuation (i.e., Noise Reduction (NR)), and secondly to perform measurements of $OE_{obj}$ (using the $OE^{NR}$ method as described in the methodology of C1 in Section 3.1.4). These $OE_{obj}$ measurements were done with the aim of achieving the third specific objective of the research project, that is to objectivize the $OE_{exp}$. Four earplugs were used as pictured in Figure 3.8. Three commercially available 3M (3M, USA) probed earplugs (also known as surrogate earplugs (ANSI/ASA, 2018)) were used: the 3M Classic, 3M the Push-In and the 3M Ultrafit, representing the Roll-down foam (denoted RDF), the push-to-fit (denoted P2F) and premolded (denoted PM) earplug families, respectively. The fourth earplug was a custom earplug (denoted CUS) made by Embouts Québec (Embouts Québec, Canada) from earcanal impressions made by a certified Québec audioprosthetist (Paulette Girard Audioprothésiste(s), Canada) during the earcanal impression session. Although an acoustic filter is normally installed within a duct of this model of custom earplug, it was removed for the duration of the study and replaced by a probe tube extracted from a 3M surrogate earplug as to allow for objective in-ear SPL measurements. Before being handed over to the participants at the end of the study, the probe tubes were removed, and the acoustic filters were reinstalled within the custom earplugs. The probed earplugs were chosen for this study for their compatibility with the microphonic doublet and for their practicality, as they allowed for quick and reliable swapping throughout the measurement session. The transfer function between the IEM and the probe tube opening was measured for each individual earplug tested to verify there were no manufacturing defects or blockage within the tube. Each signal measured throughout the trial was then corrected with the corresponding transfer function to obtain the corrected inner- and outer SPL measurements. The procedure consisted of placing the probe opening face-to-face to a reference microphone in the center of the audiometric booth and generating a Gaussian White Noise at 95 dB to measure the broadband transfer function. Throughout the measurement session, the probed earplugs were inserted and fitted by the experimenter. The insertion depth of the earplugs was a controlled variable during the study, and it was defined as the distance between the earplug's medial face and the earcanal's entrance, as defined by Lee et al. (W. Lee et al., 2018). To obtain reliable and consistent insertion depths, lines were drawn on the RDF and P2F earplugs for the 5mm, 10mm and 15 mm insertion depths, approximately corresponding to the "Shallow", "Medium" and "Deep" insertion, respectively, as defined by Berger (Berger, 2013).

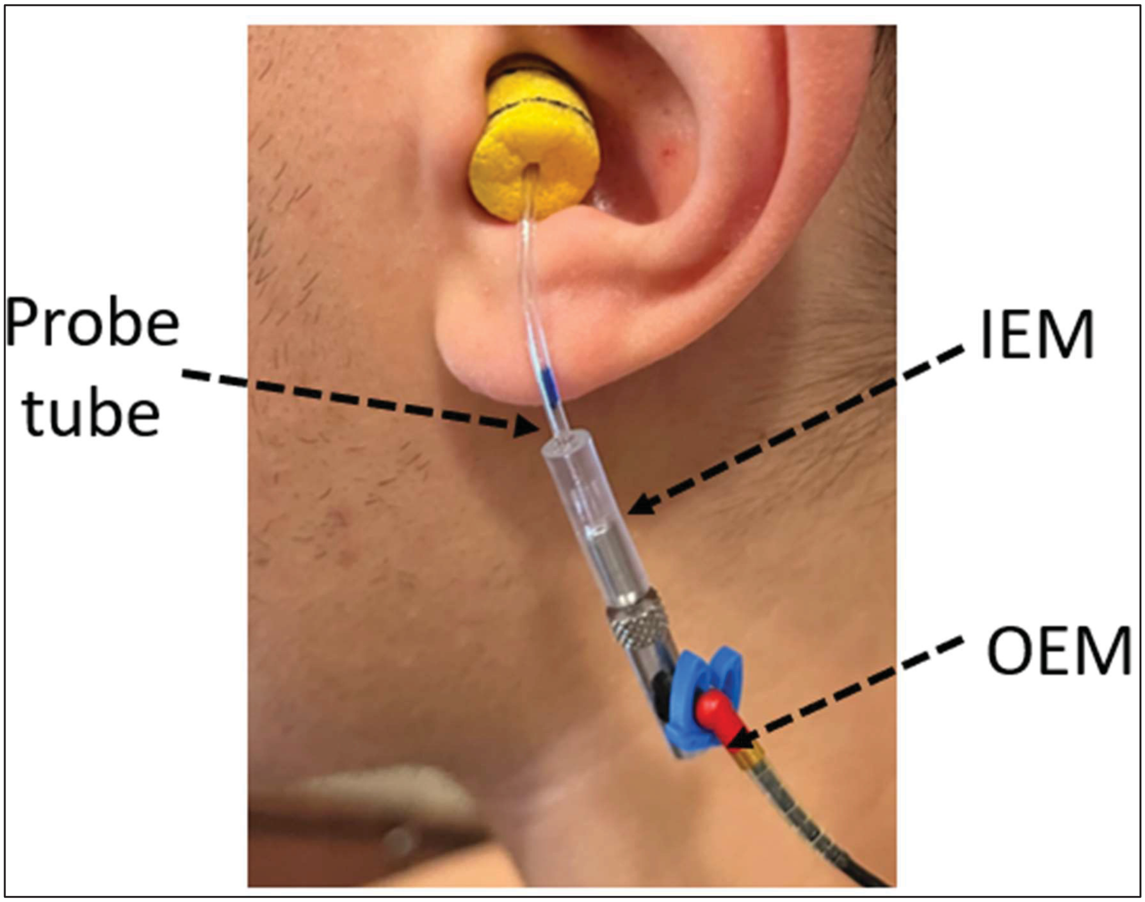



Figure 3.7 Picture of the microphonic earpiece connected to the probe tube of an earplug. The inner ear microphone (IEM) and outer ear microphone (OEM) openings are indicated by the arrows (although hardly visible)

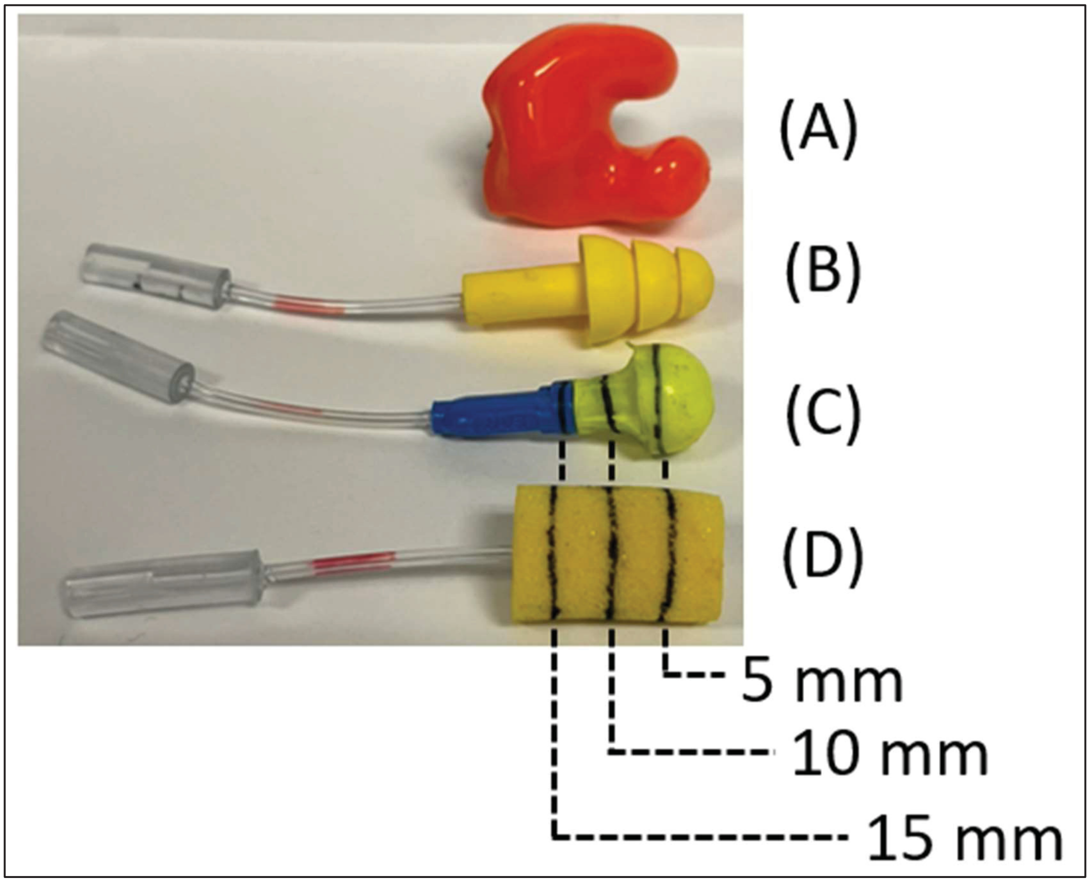



Figure 3.8 Photo of the four earplugs tested during the study. (A) Custom earplug (pictured without the probe installed). (B) Premolded earplug. (C) Push-to-fit earplug. (D) Roll-down foam. The Roll-down foam and Push-to-fit earplugs are marked with three reference lines indicating 5 mm, 10 mm, and 15 mm distance from the medial face as to control the insertion depth

### 3.3.6 Questionnaire

The questionnaire, formulated exclusively in French and designed using the SnapSurvey 11 software (SnapSurvey, England), was divided into two parts. The first part aimed to assess the participants' socio-demographic profile, while the second part focused on the evaluation of the $OE_{perc}$ and $OE_{exp}$ generated during the various configurations tested. Although the study primarily focuses on $OE_{exp}$, the assessment of $OE_{perc}$ was incorporated into the questionnaire to examine the impact of question phrasing, as discussed in Section 1.2.3.1—specifically, to determine whether participants differentiate between the two concepts (i.e., perceiving a change caused by the OE vs. experiencing discomfort related to that change). The complete questionnaire is provided in ANNEX I.

The first part of the questionnaire was completed at the beginning of the measurement session. Questions covered the participant's identity (e.g., age, biological sex) as well as their habits regarding the use of HPDs in both work and personal contexts. The psychosocial characteristics assessed are detailed in Section 3.3.8.1.

The second part of the questionnaire was completed progressively throughout the session. As participants tested the configuration one after another, the $OE_{perc}$ and $OE_{exp}$ were evaluated through two questions (in French) :

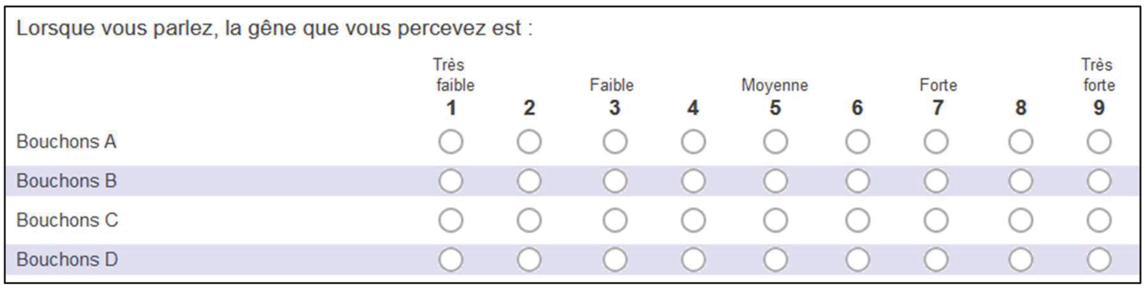
"*Lorsque vous parlez, l'effet d'occlusion que vous percevez est:*"
"*Lorsque vous parlez, la gêne que vous ressentez est:*"

Translated into English, the questions were phrased as follows:

"*When you speak, the occlusion effect you are perceiving is:*"
"*When you speak, the discomfort you are experiencing is:*"

Participants evaluated both $OE_{perc}$ and $OE_{exp}$ for each configuration using a 9-point monopolar rating scale, ranging from "*Very Low (1)*" to "*Very High (9)*." Monopolar rating scales were chosen because they yielded more exploitable data for correlating with the $OE_{obj}$ indicator, contributing to the achievement of the third specific objective. Furthermore, the choice of a 9-point scale was supported by pretests, which revealed that participants found it challenging to assess the $OE_{perc}$ and $OE_{exp}$ using fewer points. Specifically, participants reported that a 9-point scale allowed for finer discrimination of small variations in $OE_{perc}$ and $OE_{exp}$ compared to 5- or 7-point scales.

Regarding the instructions for completing the questionnaire, participants were permitted to revise scores assigned to previously tested configurations to better reflect their experience. They were encouraged to proceed at their own pace and to wear the earplugs for as long as they deemed necessary during testing to familiarize themselves thoroughly with the sensations. Once ready, participants were prompted to complete the questionnaire through a web platform displayed on a laptop, as illustrated in Figure 3.9.


Lorsque vous parlez, la gêne que vous percevez est :

| | Très faible 1 | 2 | Faible 3 | 4 | Moyenne 5 | 6 | Forte 7 | 8 | Très forte 9 |
|---|---|---|---|---|---|---|---|---|---|
| Bouchons A | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Bouchons B | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Bouchons C | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Bouchons D | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |

Figure 3.9 Example of a question block (in French) and the 9-points monopolar rating scale, ranging from “Very low (1)” to “Very high (9)”, used by the participant to rate the $OE_{exp}$ (and $OE_{perc}$, albeit not shown here) during the earplug model phase

### 3.3.7 Conduct of the Measurement Session

The measurement session consisted of four successive phases during which the participant rated the $OE_{exp}$ induced during different test configurations. The measurement session always began with the training and familiarization phase, followed by the others three phases (i.e., testing of earplugs models, insertion depths and background noise levels), tested in a randomized order. The test protocol is described in Section 3.3.7.1 and the specificities of each phase are described in sections 3.3.7.2 to 3.3.7.5.

#### 3.3.7.1 Test Protocol

All configurations tested within the four measurement phases were done according to the test protocol described below. First, following the insertion of an earplug into the ear, the fit was verified by a real-time measurement of the noise attenuation using the NR (see Eq. (3.3)). If a low attenuation was obtained (i.e., zero or less than 5 dB between 100 Hz and 500 Hz), the earplugs were refitted, and the attenuation was rechecked until deemed adequate as per the aforementioned criteria. Second, participants were asked to speak and thus to generate an OE (e.g., by counting, talking to themselves and/or talking to the experimenter, as described in Section 3.3.4), for as long as the participant deemed necessary. Third, when participants were ready, they evaluated the $OE_{exp}$ and $OE_{perc}$ generated during the tested configuration by answering the questionnaire. When these three steps were completed, the next configuration was tested. In general, approximately 5 minutes were required to complete the three steps; however, there were large variations between participants as some required more time to answer the questionnaire.

#### 3.3.7.2 Training and Familiarization Phase

The training and familiarization phase consisted of explaining the concept of the OE to the participant and to expose them to various degrees of OE so they could familiarize themselves to the psychoacoustical sensations associated with it. Moreover, participants were trained with the various tasks and ratings they would have to complete during the measurement session. To do so, they were asked to experience successively six occlusion situations that induced various degrees of OE, namely three pairs of earmuffs (described below), a pair of premolded earplugs (a non-probed model not tested during the other phases), and the participant's fingertips, tested in a randomized order. These occlusion situations were introduced for training purposes only; although participants rated the $OE_{exp}$ using the same rating scale presented in Section 3.3.6, the data from this phase were excluded from the analyses. While the study focuses on OE induced by earplugs, earmuffs were used during the training and familiarization phase for their practicality and ease of use, but also because they allowed to induce different degrees of $OE_{exp}$ while generating physical sensations (i.e., pressure exerted on the skull, around the ears). The earmuffs used in the study were the 3M Optime 105; one pair was unmodified while the other two were modified to generate less- and more OE, by varying the occluded volume under the earcup (Berger & Voix, 2022). Large holes were drilled into the earcups of one pair to obtain an infinite occluded volume (i.e., minimizing the OE), whereas closed-cell foam filling was added in the other one as to obtain a minimal occluded volume (i.e., maximizing the OE). The unmodified earmuffs, by contrast, generated an OE ranging between the other two. The three pairs of earmuffs are shown in Figure 3.10. All six situations were tested in a quiet environment (i.e., 20 dBA background noise) with the exception of the unmodified earmuffs, which were also tested in a noisy environment (i.e., 65 dBA white Gaussian noise) so they could familiarize themselves with the OE with- and without background noise, as the influence of this background noise levels is also assessed in the study. The six situations were tested according to test protocol presented in Section 3.3.7.1, but excluding the sound attenuation measurements as the fit was not controlled during this training and familiarization phase. Finally, the situations were first tested in a random order so that participants could make an initial rating of the $OE_{exp}$ induced by each situation. Then, if the participant desired, they could test one or more situations again and readjust the $OE_{exp}$ score, as explained in Section 3.3.6. Contrary to the rest of the measurement session where the experimenter was responsible for installing blindly for the participant, the earplugs in the participant's ears, the participants had to install the devices on their head during the training and familiarization session. Thus, they could experience different fits of the earplugs or with fingertip pressure to generate different degrees of OE with these two devices.

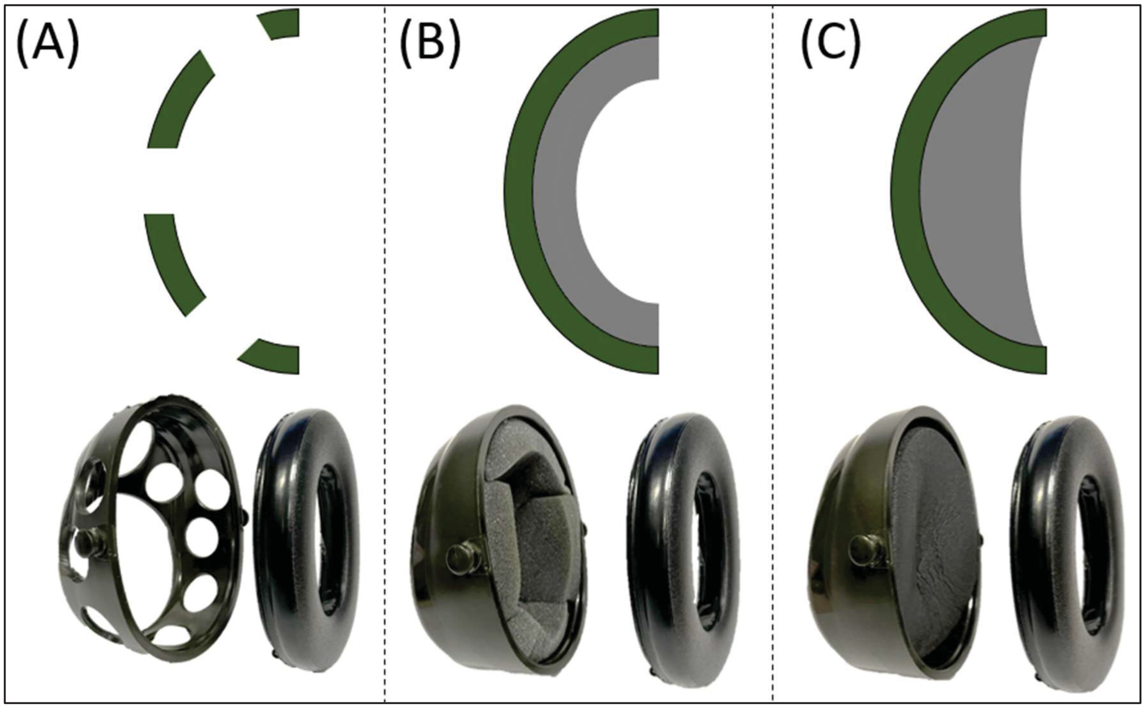



Figure 3.10 The three pairs of earmuffs used during the training and familiarization phase. Diagrams of the cross-section of each earcup is shown in the upper row while the disassembled earcups are pictured in the lower rower. (A) Modified earmuffs with holes drilled into the earcup to induce a minimal OE. (B) Unmodified earmuffs, inducing an OE ranging between the other two. (C) Modified earmuffs with foam filling added inside the earcups to induce a maximal OE

#### 3.3.7.3 Earplug Model Phase

This phase consisted of testing successively the four models of earplug presented in Section 3.3.5 in a randomized order, following the test protocol described in Section 3.3.7.1. The RDF, P2F and PM earplugs were inserted at the "medium" insertion depth (i.e., approximately 10 mm, as defined in Section 3.3.5). While the insertion depth of the CUS earplug could not be precisely controlled, it is designed to perfectly fit to the shape of the participant's earcanal so the portion of the earplug inserted into the earcanal typically corresponded to a distance of approximately 10 mm; thus, its insertion is comparable to that of the three other earplugs tested. The four earplugs were tested by all participants, with the exceptions of one participant who could not test the P2F earplug as its earcanals were too small and another participant who did not test the CUS earplugs (the participant declined the earcanal impression, but still wanted to participate in the study). An example of the insertion of the four plugs into a participant's earcanal is presented in Figure 3.11.

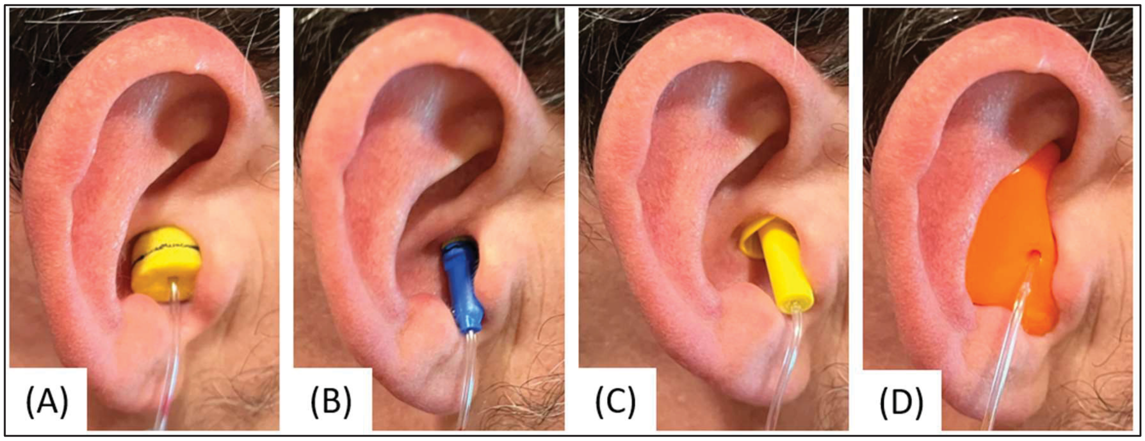



Figure 3.11 The four earplug models inserted at an insertion depth of 10 mm in one participant’s ear. (A) Roll-down foam earplug (RDF). (B) Push-to-fit earplug (P2F). (C) Premolded earplug (PM). (D) Custom earplug (CUS)

#### 3.3.7.4 Insertion Depth Phase

This phase consisted of testing successively three insertion depths, namely 5 mm, 10 mm, and 15 mm (as defined in Section 3.3.5), for a single earplug in a randomized order, following the protocol described in Section 3.3.7.1. In order to achieve the three insertion depths without causing physical discomfort to the participant, the experimenter used his judgement to select the earplug most compatible with the earcanal’s morphology. Based on this criterion, 26 participants tested the RDF earplug during this phase while 6 tested the P2F earplug. The PM earplug was never used during this phase because its conical shape would not allow the 5 mm insertion (i.e., the earplug would fall out of the earcanal). Despite choosing the “a priori” most compatible earplug, the 15 mm insertion could not be achieved for 6 out of the 32 participants. The inability to obtain a 15 mm insertion in some participants is due to the fact that some earcanals were too small or too tortuous for the models of earplug used in the study, or the participants experienced intolerable physical discomfort at this insertion depth although they did not exhibit prior hypersensitivity of the earcanal. An example of the three insertion depths into a participant’s earcanal is shown in Figure 3.12.

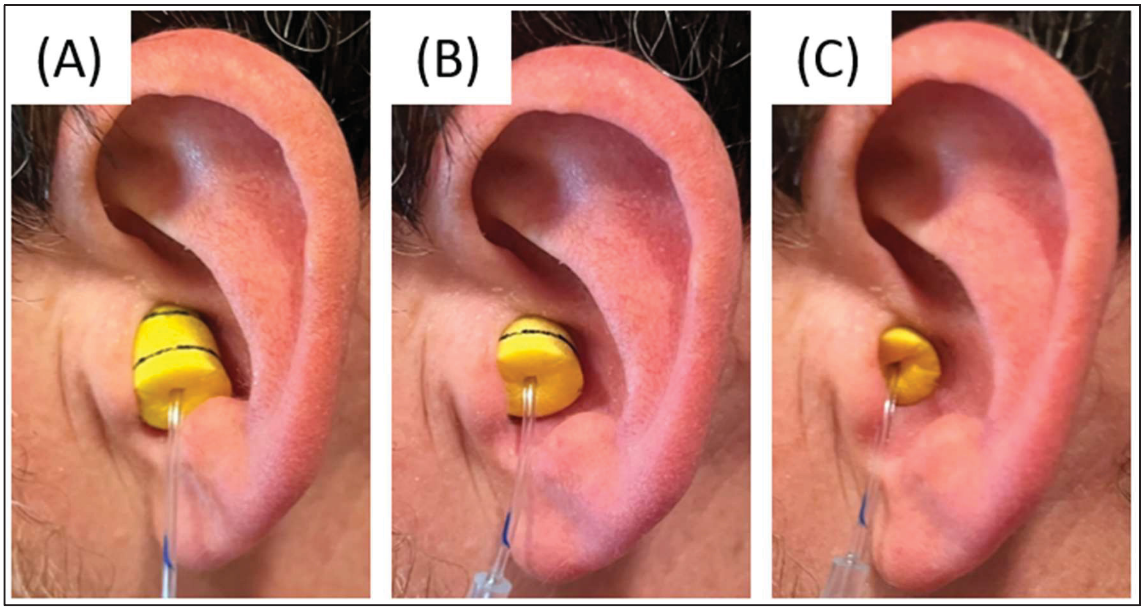



Figure 3.12 A Roll-down foam (RDF) earplug inserted at the three insertion depths, measured as the distance between the earcanal's entrance and the earplug's medial face. (A) 5 mm. (B) 10 mm. (C) 15 mm

#### 3.3.7.5 Background Noise Levels Phase

Since the influence of background noise level on the $OE_{exp}$ has not, to the author's knowledge, been previously investigated (as outlined in Section 1.4.3.1), this phase aimed to test two hypotheses proposed by the research group regarding how background noise might affect the OE. The first hypothesis posits that an increase in background noise level may reduce the $OE_{exp}$ due to a masking effect, whereby background noise diminishes the perception of one's own voice. Consequently, a person speaking with occluded ears in a quiet environment would perceive their voice—distorted by the OE—more prominently than in a noisy setting. In contrast, the second hypothesis suggests that the $OE_{exp}$ increases with higher background noise levels due to the greater vocal effort required for intelligibility. As vocal effort rises, the BC component of the voice necessarily increases as well, resulting in elevated acoustic pressure within the occluded earcanal. To evaluate these hypotheses, this phase involved testing a single earplug model while participants were exposed to a typical industrial noise reproduced at three different levels using the room's speakers to investigate the influence of background noise on the OE. The noise used was from a sound recording made in an industrial environment as part of a previous research project (O. Valentin et al., 2022; Olivier Valentin et al., 2024), consisting of broadband spectrum noise in which presses, rollers, and pneumatic tools could be heard. To prevent correlated noise in the audiometric booth, four non-overlapping 30-second segments were extracted and looped into four independent 8-minutes tracks, each played through its respective speaker. The spectrum of the original sound recording is presented in Figure 3.13. The background noise was presented to the participant at three different levels: 65 dBA, 85 dBA, and 92 dBA, measured at the center of the room using the reference microphone. The 65 dBA noise was tested twice, once at the very beginning of the phase (i.e., referred to as 65 $dBA_{test}$)) and at the very end of the sequence (i.e., referred to as 65 $dBA_{retest}$)). This non-randomized sequence was implemented in the test protocol to start and end the test sequence in the 65 dBA background noise with the intention to evaluate the temporal evolution of the $OE_{exp}$. To do this, the experimenter and the participant simulated a factory visit during which they had to hold a fictive conversation at four locations in an industrial workshop. To contextualize the participant, the visit was presented as follows: (i) the beginning of the visit behind the closed doors of the workshop (i.e., 65 $dBA_{test}$)), (ii) touring the workshop, not far from noisy machines (i.e., 85 dBA), (iii) touring the workshop near noisy machines (i.e., 92 dBA), and (iv) the end of the visit in a calm area of the workshop (i.e., 65 $dBA_{retest}$). Although the participant was informed that this phase involved different levels of background noise, the participants conducted the tests blindly (i.e., the participants did not know that the first and last background noises were set at a level of 65 dBA). The test protocol followed during this measurement phase was also slightly different from the other two phases, notably on two specific points. First, since only one pair of earplugs was tested in the four background noises, a single fit of the earplugs was done; sound attenuation was therefore measured twice, at the very beginning to verify the fit (as described in Section 3.3.7.1), and at the end of the sequence to ensure that the plug had not moved even if the participant had to shout. Second, the fictitious conversation described in Section 3.3.4 was mandatory (instead of optional) to force the participant to speak at an appropriate vocal effort level for the background noise to which they were exposed. This measure was introduced following the pretests that highlighted the difficulty participants could have in judging the appropriate vocal effort for noises at

85 dBA and 92 dBA. Finally, although the preferred earplug for this test phase was the CUS due to its ease of insertion, 3 participants tested the RDF earplug; two of them because an adequate fit was difficult to achieved with the CUS earplug, and one for whom the CUS earplugs were not manufactured, as explained in Section 3.3.7.3.

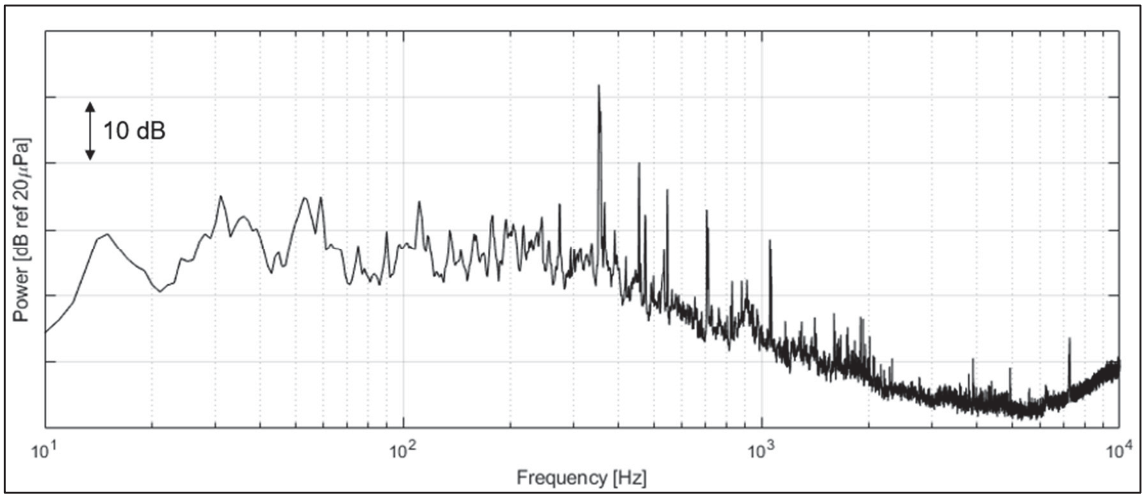



Figure 3.13 Power of the broadband industrial noise sampled in an industrial workshop. Each horizontal line represents a 10 dB power increment Adapted from Valentin et al. (2022)

### 3.3.8 Assessment of the Triad Characteristics

Several physical and psychosocial characteristics of the environment-person-HPD triad, potentially relevant to the degree of $OE_{exp}$, were measured before- and during the study through the questionnaire and laboratory measurements. As explained in Section 3.3.6, the first part of the questionnaire allowed for the assessment of participants' psychosocial characteristics using information collected on age, biological sex, and habits of using HPDs in both work and personal activities contexts. Physical characteristics of the person component of the triad were measured during the eligibility- and earcanal impression sessions to obtain the participants hearing losses and earcanal morphological characteristics from an analysis of the 3D scans of the earcanal impressions. Physical characteristics of the earplugs, measured in a previous research project (Bastien Poissenot-Arrigoni et al., 2022), were compiled for the earplugs tested in this study. Finally, a single physical characteristic of the environment was measured in this study, namely the background noise level, using the reference microphone of the audiometric booth (see Section 3.3.3). No psychosocial characteristic of the earplug nor of the environment were assessed in the context of this study. The data collected throughout the various measurements over the three sessions were stored into a SPSS database and the different characteristics were coded into variables of various types (i.e., continuous, dichotomous, or categorical). Post-processing of the data then allowed for the computation of descriptive statistics of the study sample and for the assessment of the influence of the characteristics on the $OE_{exp}$; statistical tools and procedures are more thoroughly described in Section 3.3.10. The methodology employed to assess and measure the different characteristics of the triad, as well as their coding into variables (indicated between parenthesis) is presented in Sections 3.3.8.1 to 3.3.8.4.

#### 3.3.8.1 Psychosocial characteristics of the Person

Biological, demographic and the usage habits of HPDs were surveyed during the study. The participant's age (Age) was categorized into two categories relative to the median of the sample, namely the age groups of 21-29 years old and 30+ years old. The participants' biological sex (Sex) was categorized as male, female, or other, but all participants declared themselves as either male or female. Subsequently, participants stated whether they had received training on the dangers of noise in the workplace ($Train_{NIHL}$) and on the use of HPDs ($Train_{HPD}$). Participants' naivety regarding their use of HPDs ($Use_{HPD}$) was defined as a dichotomous variable; participants were classified as non-naïve individuals (i.e., users) if they reported using HPDs in the context of work and/or personal activities. Conversely, participants were classified as naïve individuals (i.e., non-users) if they reported not using them. Participants who considered themselves users were asked to indicate whether they used earmuffs ($Use_{ERM}$), earplugs ($Use_{ERP}$), or custom earplugs ($Use_{Customs}$). Finally, two other characteristics were coded as variables: whether the participant knew the experimenter before participating in the study ($XPMTR_{Known}$) and whether they were working within the university (e.g., student, teacher, or staff). These last two variables were added to the analyses to determine if naivety regarding the experimenter, or being affiliated with the institution where the laboratory measurements took place could introduce bias in the assessment of the $OE_{exp}$. The characteristics and their respective variables are summarized in the uppermost part of Table 3.5.

#### 3.3.8.2 Physical characteristics of the Person

The physical characteristics of the "person" component of the triad considered in this study are hearing losses and the morphology of the earcanals. All physical characteristics were measured independently for each ear, which allowed obtaining monaural variables. However, the monaural variables were transformed into binaural variables by calculating the average of the values measured in each ear, respectively. This data transformation not only simplified the analysis process by reducing the number of variables to be post-processed but also facilitated the interpretation of the results. However, the transformation of variables was only performed if the difference in values measured in the two ears was not deemed significant (p-value < 5%); the process used to verify the significance of the difference is presented in Section 3.3.10.4. The characteristics associated with hearing losses are presented first, followed by the characteristics associated with the morphology of the earcanals.

Audiograms allowed measuring the hearing losses of participants at audiometric frequencies between 250 Hz and 8000 Hz in AC, and between 250 Hz and 4000 Hz in BC. The variables associated with hearing losses are noted as $HL_{x\ Hz\ (type)}$, where the index "x" denotes the audiometric frequency in Hz and the index "type" denotes the type of sound conduction used to measure hearing loss (i.e., AC or BC). Additionally, three Pure Tone Averages (PTA) (National Institute on Deafness and Other Communication Disorders, 2025) were calculated, namely (i) the average over the bands from 250 Hz to 1000 Hz ($HL_{PTA3\ (type)}$), (ii) the average over the bands from 250 Hz to 2000 Hz ($HL_{PTA4\ (type)}$), and (iii) over all measured frequencies ($HL_{PTA\ (type)}$); again, the index refers to the type of sound conduction used to measure hearing loss (i.e., AC or BC).

The morphological characteristics of the participants' earcanals were measured from the 3D scans of the impressions of the earcanals using the procedure described comprehensively in (Bastien Poissenot-Arrigoni et al., 2022). To calculate the different morphological indicators, three cross-sections were identified, namely the entrance of the canal (E), the first bend (FB), and the second bend (SB), as depicted in Figure 3.14. The earcanal girth, measured as the circumference (C) in mm, is designated by the variables $C_E$, $C_{FB}$, and $C_{SB}$. The ovality of the earcanal, computed as the isoperimetric ratio (IR), and defined as the ratio between the area and the circumference squared, multiplied by 4 times $\pi$, is designated by the variables $IR_E$, $IR_{FB}$, and $IR_{SB}$. The IR varies between 0 and 1, the latter value indicating a circular cross-section. The length of the canal (L), measured as the length of the curvilinear axis distance between cross-sections E and SB, is designated by the variable $L_{E\text{-}SB}$. The conicity of the earcanal, calculated as the ratio between the area of the cross-sections E and SB, is designated by the variable $F_{E\text{-}SB}$. A ratio close to 1 indicated a non-conical earcanal whereas a higher ratio indicates the shrinking (i.e., funneling) of the earcanal in the medial direction. Finally, the tortuosity, computed as the ratio between the Euclidean- and curvilinear axis lengths between cross-sections E and SB, is designated by the variable $T_{E\text{-}SB}$. A ratio equal to 1 indicates the earcanal is a straight duct whereas a ratio greater than 1 indicates the earcanal is an “S” shaped duct.

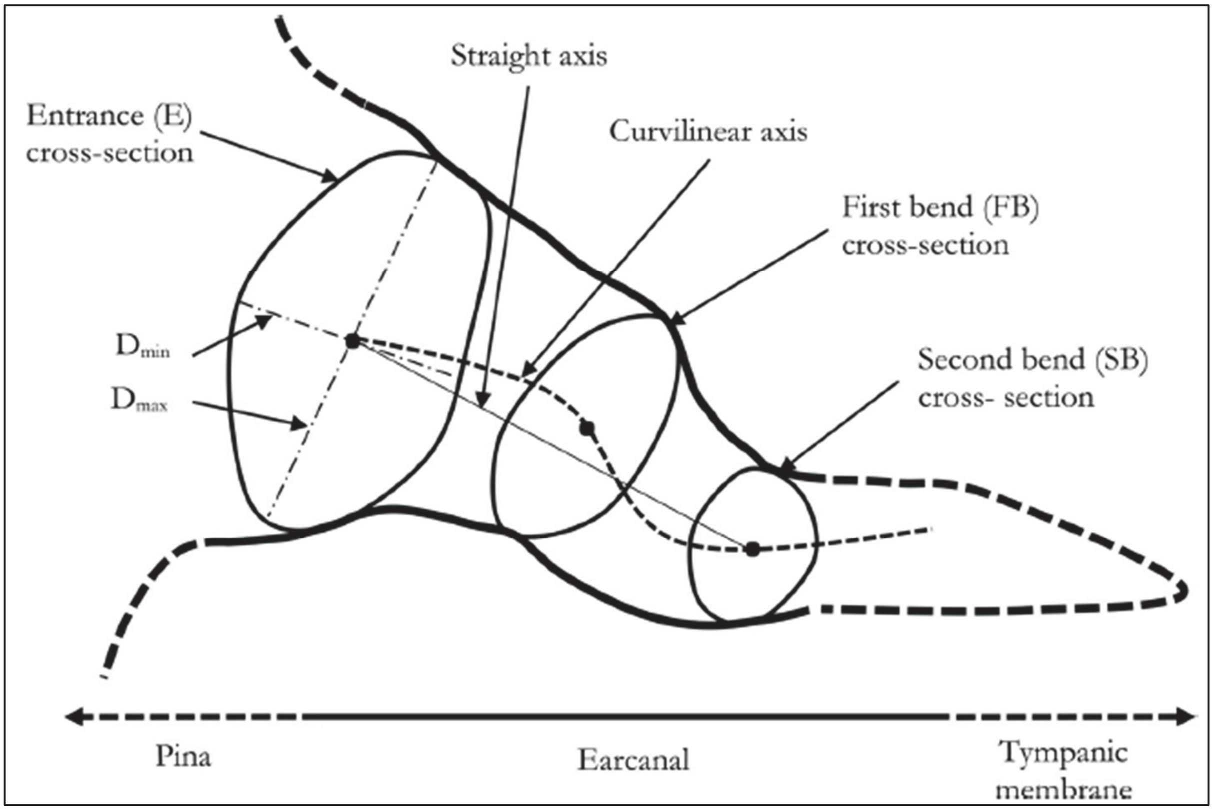



Figure 3.14 Depiction of the earcanal. Thick solid lines depict the earcanal walls of the region of interest to compute the morphological indicators whereas thick dotted lines depict the earcanal regions that are not of interest. Thin solid lines depict the three cross-sections of the earcanal, namely the entrance (E), the first bend (FB) and the second bend (SB). Thin dotted line depicts the curvilinear axis of the earcanal. Thin mixed lines depict the longest and shortest diameter of each cross-section
Taken from Poissenot-Arrigoni et al. (2022)

The physical characteristics of the person and their respective variables are summarized in the lowermost part of Table 3.5.

Table 3.5 Summary of the physical and psychosocial characteristics of the person

| | **Characteristic name** | **Variable name** | **Variable type/values** |
|---|---|---|---|
| Psychosocial characteristics | Age | Age | Categorical : 21-29 or 29+ |
| | Biological sex | Sex | Trichotomous : Male, Female, Other |
| | Training on noise induced hearing loss | $Train_{NIHL}$ | Dichotomous : Yes or No |
| | Training on HPD usage | $Train_{HPD}$ | Dichotomous : Yes or No |
| | Usage of HPD for work | $Use_{Work}$ | Dichotomous : Yes or No |
| | Usage of HPD for personal activities | $Use_{PersAc}$ | Dichotomous : Yes or No |
| | Usage of earmuff-type HPDs | $Use_{ERM}$ | Dichotomous : Yes or No |
| | Usage of earplug-type HPDs | $Use_{ERP}$ | Dichotomous : Yes or No |
| | Usage of custom earplug-type HPDs | $Use_{Customs}$ | Dichotomous : Yes or No |
| | Usage of any type of HPDs (earmuffs, earplugs, or custom earplugs) | $Use_{HPD}$ | Dichotomous : Yes or No |
| | Prior acquaintance of the experimenter | $XPMTR_{Known}$ | Dichotomous : Yes or No |
| | Works at the university | $Uni_{Worker}$ | Dichotomous : Yes or No |
| Physical characteristics | Air- and bone conduction hearing loss (where X takes the value between 250 Hz to 8000 Hz for AC, and between 250 Hz and 4000 Hz for BC) | $HL_{XHz\ (AC)}$ $HL_{XHz\ (BC)}$ | Continuous (dB HL) |
| | Pure tone average air- and bone conduction hearing loss | $HL_{PTA\ (AC)}$, $HL_{PTA3\ (AC)}$, $HL_{PTA4\ (AC)}$ $HL_{PTA\ (BC)}$, $HL_{PTA3\ (BC)}$, $HL_{PTA4\ (BC)}$ | Continuous (dB HL) |
| | Earcanal cross-sections circumferences | $C_E$, $C_{FB}$, $C_{SB}$ | Continuous (mm) |
| | Earcanal cross-sections isoperimetric ratios | $IR_E$, $IR_{FB}$, $IR_{SB}$ | Continuous (0 to 1 ratio) |
| | Earcanal length | $L_{E\text{-}SB}$ | Continuous (mm) |
| | Earcanal conicity | $F_{E\text{-}SB}$ | Continuous (surfaces ratio) |
| | Earcanal tortuosity | $T_{E\text{-}SB}$ | Continuous (lengths ratio) |

#### 3.3.8.3 Physical characteristics of the environment

Two physical characteristics of the "environment" component of the triad considered in this study are derived from measurements taken with the audiometric booth's reference microphone, namely the background noise level during testing (without the participant speaking) ($L_{p,ref\ BNL}$) and the noise level during testing (with the participant speaking) ($L_{p,ref\ BNL+Speech}$). Both are measured as overall levels in A-weighted decibels (dB(A)).

It is important to note that background noise level in the audiometric booth was measured throughout the tests (with- and without the participant speaking), the background noise level was controlled by the experimenter. Consequently, $L_{p,ref\ BNL}$ was imposed by the test protocol to examine its influence on the $OE_{exp}$. Moreover, this variable is treated as categorical in the analyses to determine whether there is a temporal influence of background noise level on the $OE_{exp}$ by comparing any variation in the ratings assigned by participants during the 65 $dBA_{test}$ and 65 $dBA_{retest}$ conditions, as described in Section 3.3.7.5. However, $L_{p,ref\ BNL+Speech}$ is treated as continuous variable in the analyses.

The two characteristics and the associated variables are summarized in Table 3.6.

Table 3.6 Physical characteristics of the environment

| | Characteristic name | Variable name | Variable type/values |
|---|---|---|---|
| Physical characteristic | Background noise level (without speech) | $L_{p,ref\ BNL}$ | Categorical : 20 dBA, 65 $dBA_{test}$, 65 $dBA_{retest}$, 85 dBA, 92 dBA |
| | Total noise level (with speech) | $L_{p,ref\ BNL+Speech}$ | Continuous [dBA] |

#### 3.3.8.4 Physical characteristics of the earplug

In this study, only the physical characteristics of the earplug were considered, describing the physical and mechanical properties of the various earplugs tested, while psychosocial characteristics were not surveyed in the questionnaire (currently considered secondary). It is important to note that the model of the earplug tested was controlled during the study, meaning that the testing protocol was developed around this characteristic to study its influence on the $OE_{exp}$. Although physical properties (i.e., nominal diameter, presence of a stem, mass) and mechanical properties (i.e., friction coefficient, radial force, extraction force) were measured on a tester, redundancy issues among the different characteristics were encountered due to the small sample size relative to the number of earplugs tested and the number of characteristics measured. Indeed, the correlation analysis among the different characteristics revealed that only one characteristic is sufficient to study the influence of the earplug on the $OE_{exp}$. Therefore, to facilitate interpretation, the only characteristic considered in the data analysis is the family of the earplug ($HPD_{Family}$). The characteristic and its variable are summarized in Table 3.7.

Table 3.7 Physical characteristics of the earplug

| | Characteristic name | Variable name | Variable type/values |
|---|---|---|---|
| Physical characteristic | Earplug family | $HPD_{Family}$ | Categorical : Roll-down foam (RDF), Push-to-fit (P2F), Premolded (PM), Custom (CUS) |

### 3.3.9 Objective indicators

Two out of the four indicators computed for the analysis of data from C2 were previously presented in the methodology of campaign C1 (see Section 3.1.5), namely the objective occlusion effect indicator measured according to the NR method ($OE_{obj}^{NR}$) and the attenuation indicator measured according to the NR method (NR), presented in Eq. (3.6) and Eq. (3.3), respectively. In addition to these two, two other sound pressure indicators are also computed, namely the noise level measured by the IEM of the occluded earcanal microphone (denoted $L_{p,occluded}$) as well as the noise level measured by the reference microphone during tests (denoted $L_{p,ref\ BNL+Speech}$) when participants spoke in the background noise. Both indicators are calculated according to Eq. (3.2) presented in Section 3.1.5.

The four indicators were calculated in octave and third-octave bands, but certain specific frequency ranges- and bands are used in analyses aimed at objectivizing the $OE_{exp}$; specifically, the frequency bands chosen for analysis correspond to the audiometric frequencies measured during AC and BC audiometry (see Section 3.3.2). In addition to these indicators, averaged indicators representing low-, mid-, and high-frequencies were also calculated, denoted LF, MF and HF, respectively. These indicators represent the average level (using arithmetic mean) calculated over frequency bands, specifically 250 Hz and 500 Hz for LF, 1000 Hz and 2000 Hz for MF, and 4000 Hz and 8000 Hz for HF. These three indicators were calculated for the $OE_{obj}^{NR}$, NR and $L_{p,occluded}$. Finally, a single indicator was calculated from the reference microphone, namely the overall level measured in the audiometric booth by the reference microphone (in dBA) (denoted $L_{p,ref\ BNL+Speech,\ Ovl}$). All indicators computed and used for the analysis of C2 campaign data are summarized in Table 3.8.

Table 3.8 Summary of the indicators computed for the analyses of data collected in C2

| Indicator | Overall | LF, MF and HF Bandwidths | 250 Hz to 8000 Hz Octave Bands |
|---|---|---|---|
| $OE_{obj}^{NR}$ | - | $OE_{obj}^{NR}{}_{VLF}$ | $OE_{obj}^{NR}{}_{63\ Hz}$ |
| | | | $OE_{obj}^{NR}{}_{125\ Hz}$ |
| | | $OE_{obj}^{NR}{}_{LF}$ | $OE_{obj}^{NR}{}_{250\ Hz}$ |
| | | | $OE_{obj}^{NR}{}_{500\ Hz}$ |
| | | $OE_{obj}^{NR}{}_{MF}$ | $OE_{obj}^{NR}{}_{1000\ Hz}$ |
| | | | $OE_{obj}^{NR}{}_{2000\ Hz}$ |
| | | $OE_{obj}^{NR}{}_{HF}$ | $OE_{obj}^{NR}{}_{4000\ Hz}$ |
| | | | $OE_{obj}^{NR}{}_{8000\ Hz}$ |
| NR | - | $NR_{VLF}$ | $NR_{63\ Hz}$ |
| | | | $NR_{125\ Hz}$ |
| | | $NR_{LF}$ | $NR_{250\ Hz}$ |
| | | | $NR_{500\ Hz}$ |
| | | $NR_{MF}$ | $NR_{1000\ Hz}$ |
| | | | $NR_{2000\ Hz}$ |
| | | $NR_{HF}$ | $NR_{4000\ Hz}$ |
| | | | $NR_{8000\ Hz}$ |
| $L_{p,occluded}$ | - | $L_{p,occluded\ VLF}$ | $L_{p,occluded\ 63\ Hz}$ |
| | | | $L_{p,occluded\ 125\ Hz}$ |
| | | $L_{p,occluded\ LF}$ | $L_{p,occluded\ 250\ Hz}$ |
| | | | $L_{p,occluded\ 500\ Hz}$ |
| | | $L_{p,occluded\ MF}$ | $L_{p,occluded\ 1000\ Hz}$ |
| | | | $L_{p,occluded\ 2000\ Hz}$ |
| | | $L_{p,occluded\ HF}$ | $L_{p,occluded\ 4000\ Hz}$ |
| | | | $L_{p,occluded\ 8000\ Hz}$ |
| $L_{p,ref\ BNL+Speech}$ | $L_{p,ref\ BNL+Speech,Ovl}$ | - | - |

### 3.3.10 Data Analysis & Statistical Tools

The statistical tools and analysis methods are presented in this section, namely (i) the iterative approach employing mixed linear models (see Section 3.3.10.1), (ii) the methodology for statistical analysis to identify influential triad characteristics on the $OE_{exp}$ (see Section 3.3.10.2), (iii) the methodology for statistical analysis to objectivize the $OE_{exp}$ (see Section 3.3.10.3), and (iv) the methodology for statistical analysis for converting monaural variables into binaural variables (see Section 3.3.10.4). The statistical approaches and tools used in the context of this doctoral thesis were validated by two senior statisticians, one affiliated to the Université de Sherbrooke and one to the École de technologie supérieure.

Moreover, the approaches were also used in a previous research project within the research group (B. Poissenot-Arrigoni, Doutres, Negrini, Berbiche, & Sgard, second review on going; Bastien Poissenot-Arrigoni, 2023).

#### 3.3.10.1 Iterative procedure using mixed linear models

IBM SPSS Statistics 28 (IBM Corporation) was used for conducting all statistical analyses in this study. These analyses consisted of: (i) computing descriptive statistics of the variables measured, and (ii) employing mixed linear models (MLMs) to achieve the second and third specific objectives of the project. In the context of the second specific objective, the MLMs are used to identify which characteristics of the environment-person-HPD triad (i.e., independent variables) are influential on the $OE_{exp}$ (i.e., dependent variable). In the context of the third specific objective, the MLMs are instead used to objectivize the OE by identifying which objective indicators presented in Section 3.3.9 (i.e., independent variables) are correlated with the $OE_{exp}$ (i.e., dependent variable). MLMs were deemed suitable for this type of analysis due to the heterogeneous nature of the data, which comprises various types of variables (e.g., dichotomous, categorical, continuous), the presence of missing values, and is derived from repeated measures. Given the considerable number of independent variables to assess, an iterative procedure was adopted. Specifically, a step-wise backward elimination procedure was employed, as illustrated in Figure 3.15.

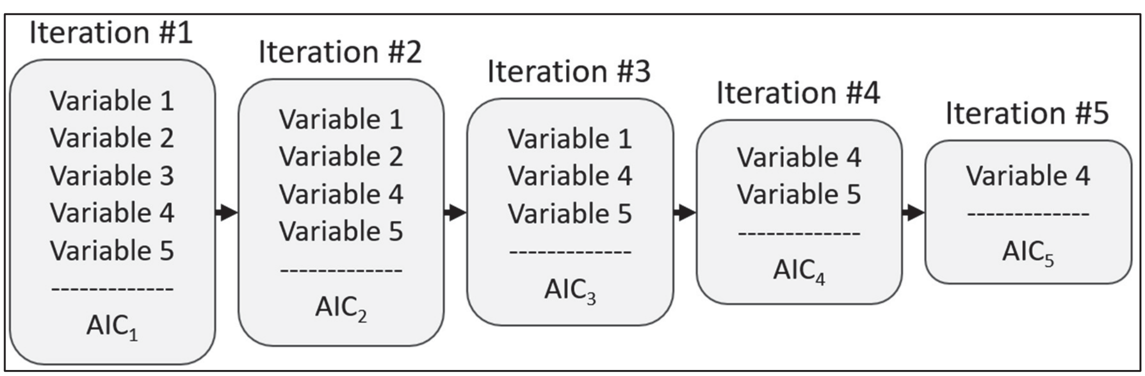



Figure 3.15 Schematic example of the iterative procedure with MLMs applied to a group of variables, during which the variable with the lowest significance (i.e., largest p-value) is eliminated from one iteration to the other

This iterative method begins with an initial iteration in which a first model incorporates all the chosen variables; how variables were chosen for the different MLMs that were computed is explained in Section 3.3.10.2 and 3.3.10.3. Then, in each subsequent iteration, the variable with the highest p-value (i.e., indicating lower significance) is systematically eliminated, while noting the Akaike Information Criterion (AIC). This process continues iteratively until the analysis converges, defined by either all variables exhibiting a strong significance (i.e., p-value $\leq 0.05$) or with a single variable remaining in the model. Upon convergence, the AIC values from each iteration are compared, and the model with the smallest AIC is selected for interpretation. This selection criterion reflects the optimal balance between model complexity (i.e., number of variables) and goodness of fit relative to the observed data. The chosen model can then be computed by Eq. (3.7)

$$\mathrm{Y} = b_0 + \sum b_i X_i + e, \text{with } e \sim N(0, \sigma^2) \tag{3.7}$$

where dependent variable Y is predicted by the intercept $b_0$ plus the independent variables $X_i$ multiplied by a beta estimate of $b_i$, plus a random error *e* that comes from a normal distribution. (van den Berg, 2021). The model's strength was assessed using an intra-sample validation, which consists in computing the Pearson correlation coefficient (r) to verify how the model is correlated with the observed data while using the same data that was used to compute it. Moreover, the model's residuals are displayed in a quartile-quartile plot (i.e., QQplot) to verify that they are normally distributed

The chosen model can then be interpreted as follows: variables with a significance level equal to or less than 0.05 are seen as significantly influencing the $OE_{exp}$, while those with a significance level equal to or less than 0.10 are seen as trends of the $OE_{exp}$. In some cases, a model can include variables with a significance level greater than 0.10; however, these variables are not interpreted in the context of this study as their influence might be weaker or indirect through an interaction with one or more other variables. Nevertheless, these variables are kept within the model.

To interpret the influence of the variables on the $OE_{exp}$, the values of the beta estimates are considered. In the case of dichotomous or categorical variables, the estimated marginal mean indicates which categories of the variable generated the most and the less $OE_{exp}$ (i.e., males rated the $OE_{exp}$ 1.2 points higher on the scale relatively to females). In case of categorical variables with three or more categories, a pairwise comparison following Bonferroni test is employed to compare the categories one against another as to obtain their ranking in terms of $OE_{exp}$ generated by each. For continuous variables, the beta estimates are multiplied by the value of the associated variables. A positive sign of the beta estimate indicates an increase in the $OE_{exp}$ when the considered variable increases (i.e. more discomfort) whereas a negative sign indicates a decrease in the $OE_{exp}$. (i.e. less discomfort) when the considered variable increases. The size (in absolute value) of the beta estimate indicates the magnitude of this effect; a large beta estimate indicates a greater impact than a small one. Since continuous variables may not have the same unit, standardized values (i.e. z-scores) are used in the analyses when comparing the influence of one variable against another.

While both the MLMs and the iterative procedure are employed to achieve the aforementioned objectives (i.e., identifying influential triad characteristics on the $OE_{exp}$ and objectivizing the $OE_{exp}$), the methodologies used in each respective analysis slightly differs from one another. Both methodologies are presented in Sections 3.3.10.2 and 3.3.10.3, respectively.

#### 3.3.10.2 Methodology for statistical analysis to identify influential triad characteristics on the $OE_{exp}$

The process of identifying influential characteristics on $OE_{exp}$ involved two sequential steps: initially analyzing "preliminary" models and subsequently examining a "global" model, as shown in Figure 3.16. Instead of combining all assessed characteristics, the elaboration of preliminary models facilitated pinpointing influential characteristics within specific subgroups, each representing distinct components and dimensions of the triad (i.e., environment-person-HPD and psychosocial-physical, respectively). This division led to the analysis of five preliminary models: (i) psychosocial characteristics of the person, (ii) physical characteristics associated with hearing impairment, (iii) physical characteristics related to earcanal morphology, (iv) physical characteristics related to the environment, and (v) physical characteristics related to the earplug. Subsequently, a global model encompassed all statistically significant characteristics identified in the preceding five preliminary MLMs. While preliminary models allow for an examination of characteristic influence on a smaller scale (e.g., focusing solely on a specific aspect of the triad, such as the psychosocial traits of the individual), the global model, conversely, facilitates a broader assessment of how different components and dimensions of the triad affect $OE_{exp}$ as a whole.

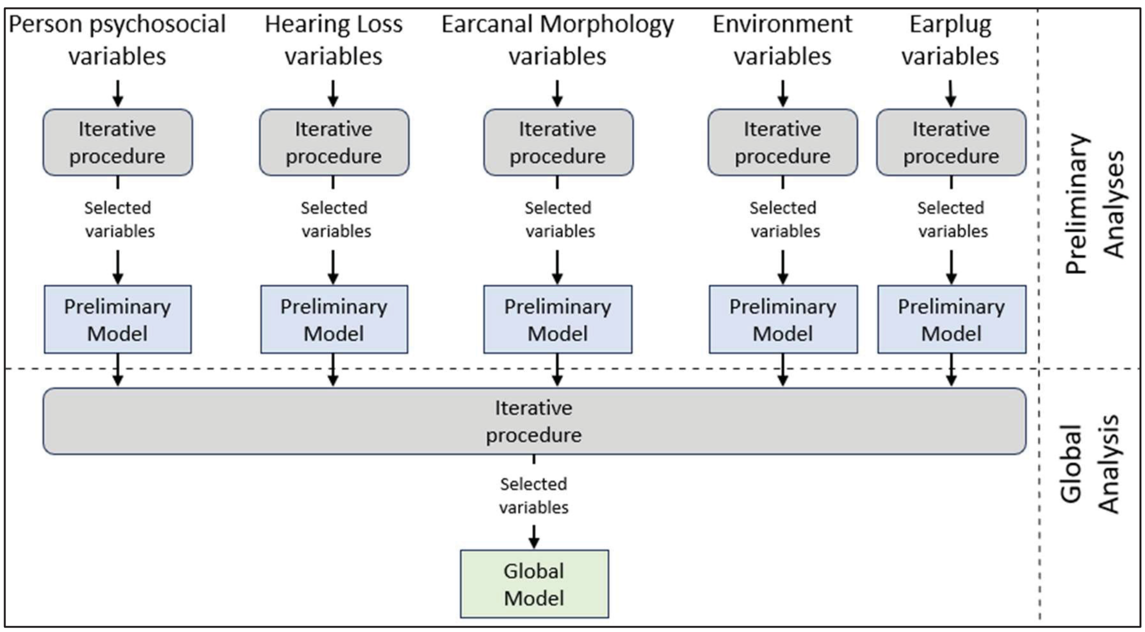



Figure 3.16 Diagram of the iterative procedure with MLMs, adapted from (Bastien Poissenot-Arrigoni, Negrini, Berbiche, Sgard, & Doutres, 2023), consisting of conducting preliminary analyses on subgroups of variables (preliminary models) follow by a global analysis (global model) to identify the characteristics of the triad influencing the $OE_{exp}$

#### 3.3.10.3 Methodology for statistical analysis to objectivize the $OE_{exp}$

The objectivization of OE aims to identify objective indicators that can explain the comfort related to OE (i.e., $OE_{exp}$). In the context of this doctoral thesis, this process is carried out through the same iterative procedure although the methodology to conduct the analyses differed from the methodology outlined in the previous section. It involved analyzing a first

MLM that only included the broadband indicators defined in Section 3.3.9 (i.e., ${OE_{obj}}^{NR}{}_{n}$, $NR_n$, $L_{p,occluded\ n}$, with $n \in$ [VLF, LF, MF, HF]) as to identify which bandwidth of each respective indicators is correlated with the $OE_{exp}$. Once the analysis converged, a new model was analyzed, but this time using the frequency bands that composed the bandwidths found to be significant; for example, if $OE^{NR}{}_{MF}$ was identified as significant, the new model included the indicators $OE^{NR}{}_{1000Hz}$ and $OE^{NR}{}_{2000Hz}$). Additionally, the room's overall noise level, with- and without the participant speaking ($L_{p,ref\ BNL}$, $L_{p,ref\ BNL+Speech}$) as well as the participant estimated vocal effort ($L_{p,ref\ Speech}$) were also included into the model as to consider a potential influence of the environment. The iterative approach was then applied to the new model until the analysis converged. Upon selecting the final model based on the AIC, the model's equation (as given by Eq. (3.7)) is used to calculate the predicted data to evaluate the model's relationship with the observed data, as explained in Section 3.3.10.1. Finally, another iterative procedure is applied to compute what is referred to as a global model, that combines the objective indicators previously identified to objectivize the $OE_{exp}$, and the triad characteristics found to be influential on the $OE_{exp}$ to further objectivize the $OE_{exp}$. Again, the aforementioned methodology is used to assess the model's relationship against observed data. The procedure for this analysis is schematized in Figure 3.17.

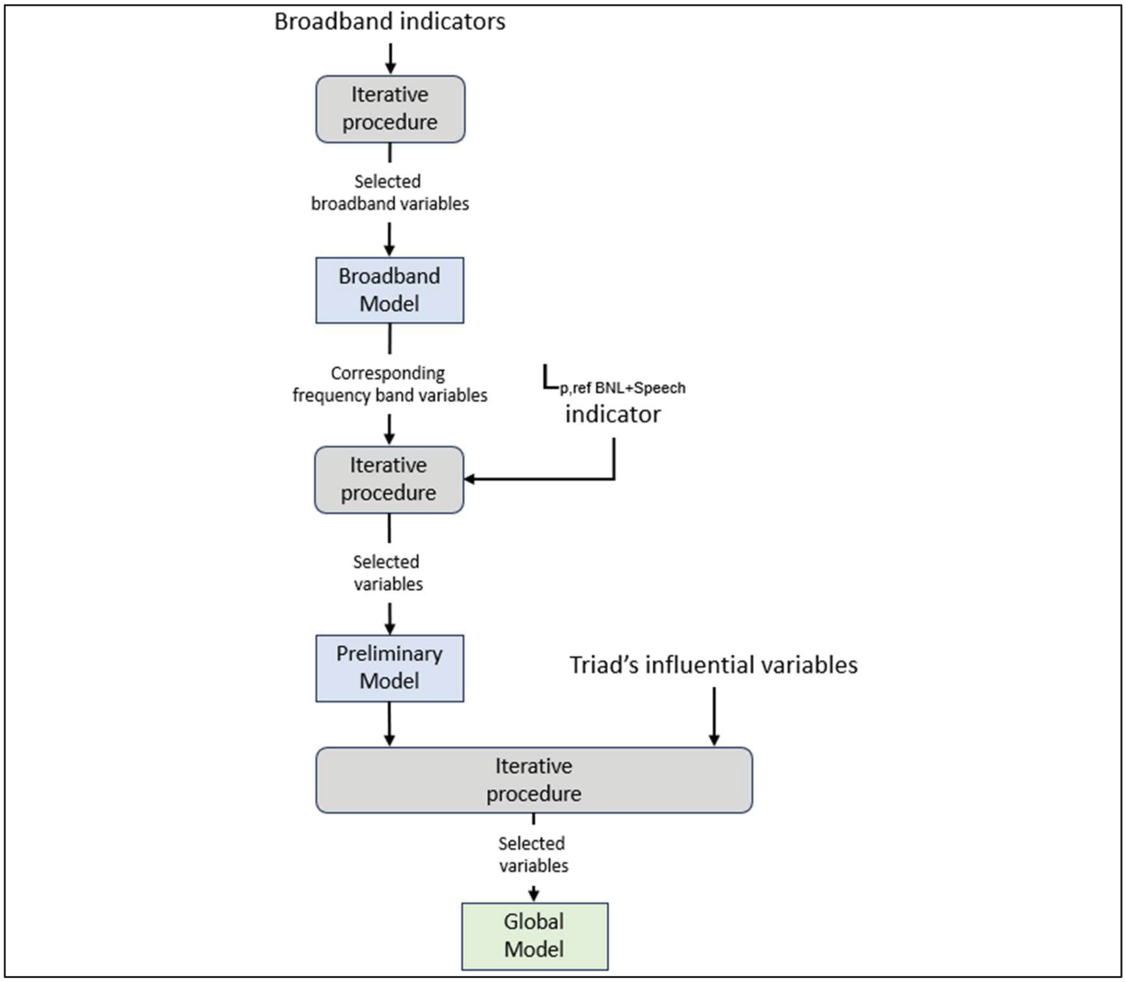



Figure 3.17 Diagram of the iterative procedure with MLMs, consisting of conducting three models, namely a model using broadband indicators, a model using frequency bands indicators and a models combining the objective indicators and the influentials characteristics of the triad to predict the $OE_{exp}$

#### 3.3.10.4 Methodology for statistical analysis for converting monaural variables into binaural variables

Many variables were measured monaurally (i.e. in each ear independently). In order to reduce the number of variables in the statistical models, binaural averages were computed when the left-right differences were not statistically significant. To determine the significance, the distribution of the difference between both variables (i.e., left- and right variables of each characteristic concerned) was assessed using a Shapiro-Wilk test as well as a visual assessment of the quantile-quantile plot (i.e., Q-Q plot) to determine whether it was normally distributed or not. Based on the result, the significance of the difference was verified using the paired Student T-test or the Wilcoxon signed rank test, respectively. If the difference is not significant, the binaural average is computed for this characteristic (e.g., left- and right earcanal entrance circumference computed as the averaged binaural earcanal entrance circumference). By following the procedure described above, most monaural characteristics were replaced with their corresponding binaural averages. An exception was made for a few characteristics in which the Student/Wilcoxon tests indicated a statistically significant difference between the left and right ears. However, because these characteristics were not identified as significant in subsequent analyses, they are not reported further to avoid unnecessary confusion.

# CHAPTER 4

# RESULTS AND DISCUSSION

The results from the analysis of data collected during the C1 and C2 campaigns are presented and discussed in this chapter. To begin, the investigation of methodological aspects related to the measurement of $OE_{obj}$ is detailed in Section 4.1. Next, the results from the pretests conducted to improve the questionnaire on $OE_{exp}$ are presented in Section 4.2. Then, the influence of the characteristics of the triad on the $OE_{exp}$ are discussed in Section 4.3. Finally, the objectivization of the $OE_{exp}$ is conducted in a two-stage approach: an initial model based solely on objective indicators, which then serves as the basis for a refined model integrating socio-demographic indicators. Details are provided in Section 4.4.

## 4.1 Measuring the objective occlusion effect

The results presented in this section aim to address the first specific objective of the project, which is to propose a simple and robust methodology for measuring the $OE_{obj}$. To achieve this, several elements are considered and investigated. First, the influence of the indicator used to quantify the OE is presented in Section 4.1.1. Then, the $OE_{obj}$ and $OE_{subj}$ both derived from measurements using a bone transducer are compared in Section 4.1.2. Next, the influence of the stimulation source used to induce the OE is discussed in Section 4.1.3. Finally, the influence of the method for measuring the SPLs to compute the chosen indicator is presented in Section 4.1.4.

### 4.1.1 Comparison between occlusion effect indicators

Since the OE was measured in various ways during the C1 campaign, $OE_{obj}^{STD}$ data serve as the baseline for calculating the indicators discussed in this section, namely SVIs (single value indicators, as introduced in Section 3.1.5) and the percentile sound levels. To provide a reference for the baseline data used for the analyses, $OE_{obj}^{STD}$ data is plotted as a function of frequency for five stimulation sources (numbers, vowel /i/, vowel /ə/, mastication, and the bone transducer) in Figure 4.1. Additionally, the $OE_{subj}$ measured with the bone transducer is also depicted in the same figure for subsequent analyses. The upper panel shows the average value measured for each stimulation while the lower panel shows the standard deviation. For all stimulations, only the data measured in the ipsilateral ear are plotted. Additionally, only the data measured for the 70 dB(A) vocal effort are plotted for speech-based stimulation (the effect of the vocal effort is presented in Section 4.1.3.1). The magnitude and the variability of $OE_{obj}^{STD}$ depends on the stimulation type (speech-based vs. BC) as well as on the speech content (numbers vs. vowel /i/ vs. vowel /ə/). In accordance with the literature, $OE_{obj}^{STD}$ (and $OE_{subj}$) presents a maximum at low frequency and gradually decreases with increasing frequency (Berger & Kerivan, 1983; M.O. Hansen, 1998; Reinfeldt et al., 2013).

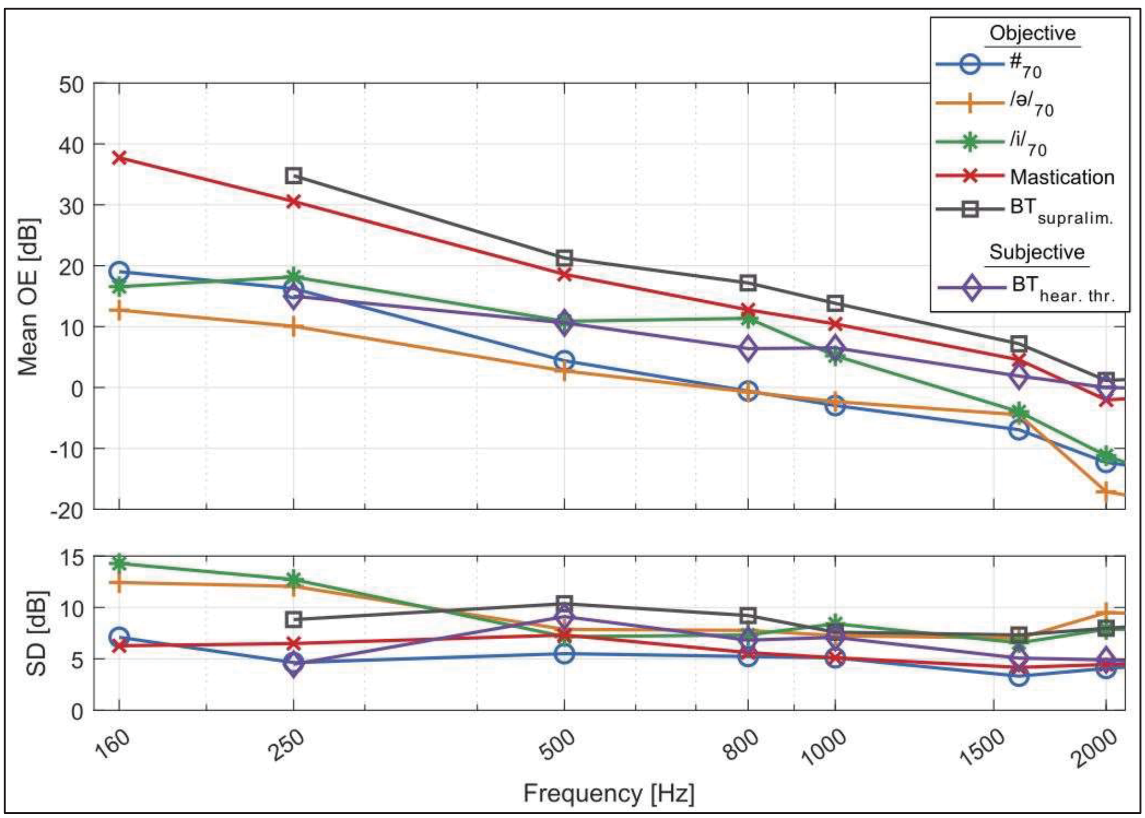



Figure 4.1 $OE_{obj}^{STD}$ and $OE_{subj}$ as a function of frequency for five stimulation sources. The # symbol indicates the enumeration of random numbers. $BT_{supramlim.}$ and $BT_{hear.\ thr.}$ indicates the bone transducer used at a supraliminal level and at hearing thresholds, respectively

The data used to calculate $OE_{obj}^{STD}$ and $OE_{subj}$ as a function of frequency in Figure 4.1 allowed to compute the six SVIs presented in Section 3.1.5. To compare the six SVIs computed for each of the five stimulations (numbers, vowel /i/, vowel /ə/, mastication and the bone transducer), results are presented as clustered boxplots in Figure 4.2. The comparison between the different SVIs highlights that the variability, described here by the interquartile range, depends on the stimulation source (as previously discussed) and on the SVI used. Unsurprisingly, indicators that are average-based ($OE_{AVG}$, $OE_{B-L}$) typically exhibit a smaller interquartile range and fewer outliers than the indicators based on the value in a specific octave band ($OE_{160Hz}$, $OE_{250Hz}$, $OE_{500Hz}$, $OE_{MAX}$). It can also be noted that SVI values differ from one another for each stimulation source since they are computed differently. When considering the relative order between the SVI values for each stimulation, e.g. the ascending order, the lowest magnitude is obtained for $OE_{500Hz}$ while the highest is for $OE_{MAX}$. For the other indicators that are in between (i.e. $OE_{160Hz}$, $OE_{250Hz}$, $OE_{AVG}$, $OE_{B-L}$), their relative order only slightly differs from one stimulation source to another, and their medians are typically close to one another. It suggests that choosing arbitrarily one of the four SVIs to evaluate the OEI (introduced in Section 3.1.5) would not change the interpretation of the results. Moreover, this comforts that the conclusions drawn in a given study should remain the same even if the analyses were conducted with another indicator, e.g. using $OE_{AVG}$ rather than $OE_{250Hz}$. However, great care must be taken when comparing the results from two studies that don't employ the same indicator as a difference between the results could be attributed to how the two indicators are computed. Although these findings (variability and unchanged relative order) help to better understand the influence of an SVI on the results that are drawn from the analysis of a data set, computing and analyzing the results obtained with every indicator is cumbersome and time consuming. Thus, a single SVI is used for the remainder of the subsequent analyses. In the context of this work, which aims at investigating the methodology to assess $OE_{obj}$, $OE_{AVG}$ is chosen based on the low variability it exhibits. Other analyses could also be used to justify the choice of an SVI over another one. For example, the analyses conducted as part of the objectivization of the OE, presented in Section 4.4, will help determine whether a single-value $OE_{obj}$ indicator is correlated with $OE_{exp}$.

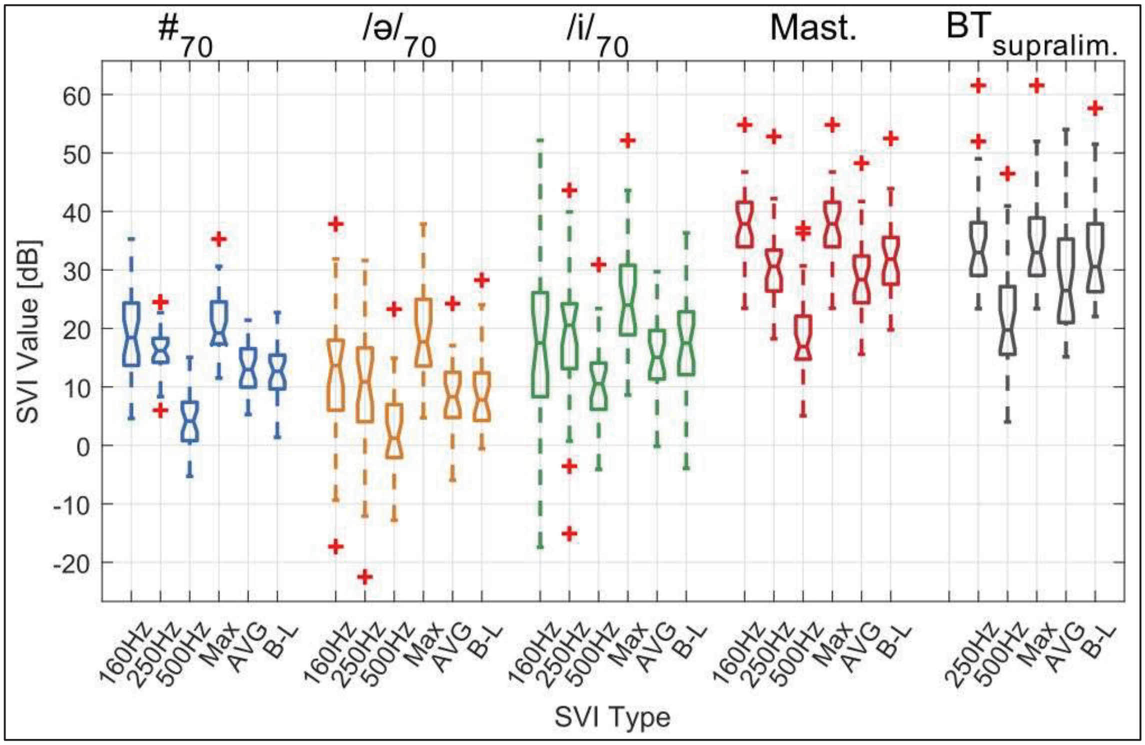



Figure 4.2 SVI Value as a function of different types of SVIs. The label above each boxplot cluster indicates the stimulation source used to induce the OE. The # symbol indicates the enumeration of random numbers and $BT_{supralim.}$ indicates the bone transducer at a supraliminal level. In the boxplot representation, the height of the box represents the interquartile range (Q75%-Q25%). The horizontal bar dividing the box represents the median and the tapered sections on both sides represent the 95% confidence interval around the median. The whiskers represent the minimum and the maximum values of the sample while the crosses represent values determined as outliers

Because of the time fluctuating nature of the voice, $OE_{obj}^{STD}$ was also computed using the percentile sound levels ($L_n$) (Corthals, 2004), a metric typically used for environmental noise, instead of the continuous equivalent sound level ($L_{eq,T}$). The results, not shown here, indicate that in the frequency range where the occlusion effect is maximal (<500 Hz), $L_n$ and $L_{eq,T}$ both lead to similar $OE_{obj}^{STD}$ values for a wide range of percentile n (10 to 90). This finding confirms that using the $L_{eq,T}$ is a valid type of metric to characterize the $OE_{obj}^{STD}$ induced by speech.

### 4.1.2 Objective vs. subjective occlusion effect with a bone transducer stimulation

Large differences can be seen in Figure 4.1 between the $OE_{obj}^{STD}$ and the $OE_{subj}$ with the bone transducer at low-frequency (see grey/square and purple/diamond curves), approximately 21 dB and 12 dB at 250 Hz and 500 Hz, respectively. These differences, already reported in the literature (Huizing, 1960; Reinfeldt et al., 2013; Stenfelt & Reinfeldt, 2007), can be attributed to the different BC mechanisms involved when measuring the occluded and unoccluded low-frequency SPL and hearing threshold levels, respectively. When the ear is occluded, the outer ear BC mechanisms are the main contributors to both BC hearing and earcanal SPL (K. Carillo, Doutres, & Sgard, 2020; Stenfelt & Goode, 2005). When the ear is unoccluded, the outer ear BC mechanisms are the main contributors to the earcanal SPL while the inner and middle ear BC mechanisms are the main contributors to BC hearing (Stenfelt & Goode, 2005; Stenfelt, Wild, Hato, & Goode, 2003). This leads to a smaller earcanal SPL in comparison with the equivalent BC hearing threshold, thus causing an overestimation of $OE_{obj}^{STD}$ compared to $OE_{subj}$. To further analyze the relationship between the two indicators, their correlation is investigated. To do so, $OE_{obj}^{STD}$ is plotted against $OE_{subj}$ in the scatter plot shown in Figure 4.3. Each point represents the data of one participant in a specific frequency band; the horizontal axis represents $OE_{subj}$, and the vertical axis represents $OE_{obj}^{STD}$. Data of the frequency bands of 250 Hz, 500 Hz, 800 Hz and 1000 Hz are pooled together. Based on the Pearson's correlation coefficient, rho (ρ), and the associated p-value, the correlation between $OE_{obj}$ and $OE_{subj}$ is deemed significant ($\rho = .57$, p-value = < .001) and is in accordance with results from previous studies (Fagelson & Martin, 1998; Goldstein & Hayes, 1965). This suggests that measuring $OE_{obj}^{STD}$ with the bone transducer driven at a supraliminal level could allow one to assess $OE_{subj}$, but without the need to conduct cumbersome hearing threshold measurements, which could allow one to simplify future studies on the OE. Additional research is however necessary to further investigate the correlation between $OE_{obj}^{STD}$ and $OE_{subj}$ as the data that could be analyzed in this study is limited. This limitation originates from a methodological problem that was encountered with the audiometer, mostly at low-frequency. To ensure the data was reliable, a rejection procedure was applied to remove data points that could potentially underestimate $OE_{subj}$, but at the cost of significantly reducing the sample sizes. In the 250 Hz and 500 Hz frequency bands, the data of only 6 and 16 out of the 30 participants could be used, respectively.

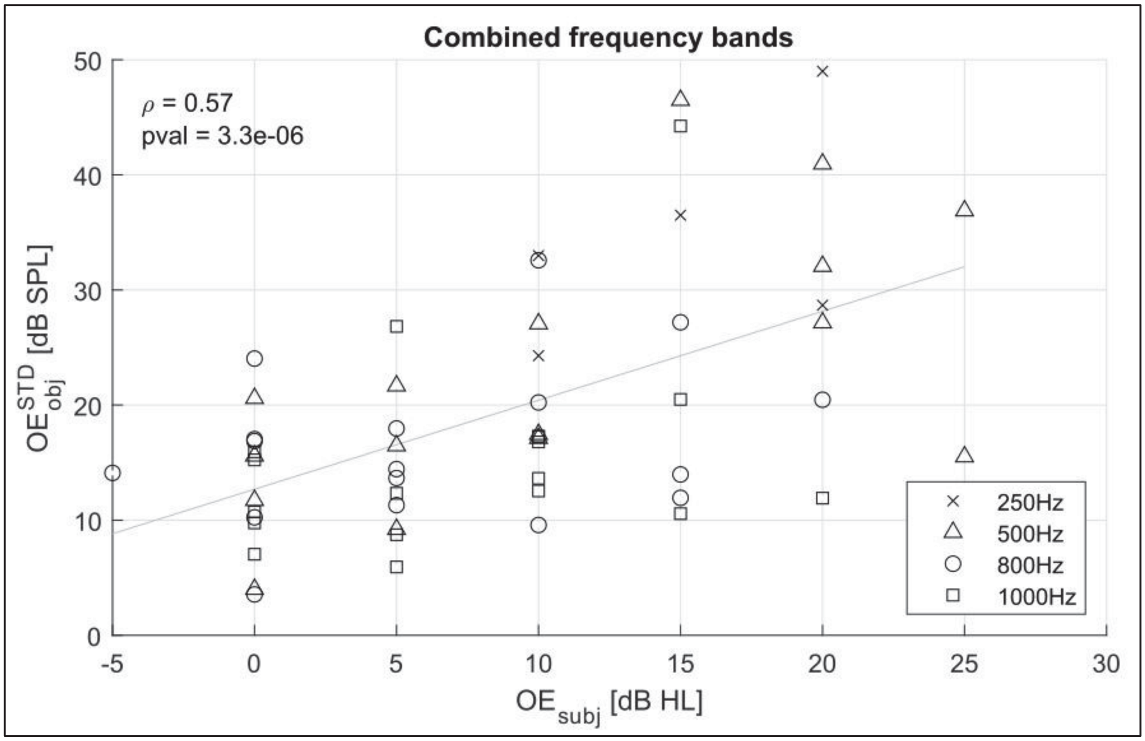



Figure 4.3 Scatter plots of the $OE_{subj}$ against the $OE_{obj}^{STD}$ both obtained with the bone transducer for each participant, at 250-500-800-1000 Hz combined. The Pearson's correlation coefficient (ρ) and the associated p-value is shown in the top left-hand side corner

### 4.1.3 Influence of the stimulation source on the objective occlusion effect

The OEI defined as the average $OE_{obj}^{STD}$ in the 160-500 Hz bandwidth obtained with the two types of stimulations (speech-based, BC) as well as the three vocal efforts for speech-based stimulations (60, 70, 80 dB(A)) are shown in Figure 4.4 in clustered boxplots. Considering that the stimulation produced by the mastication and the bone transducer is asymmetrical, the results are shown in two clusters of boxplots, one for each measurement location (ipsilateral ear, contralateral ear). The differences in speech-based stimulations, BC stimulations as well as the differences between speech-based and BC stimulations are discussed below.

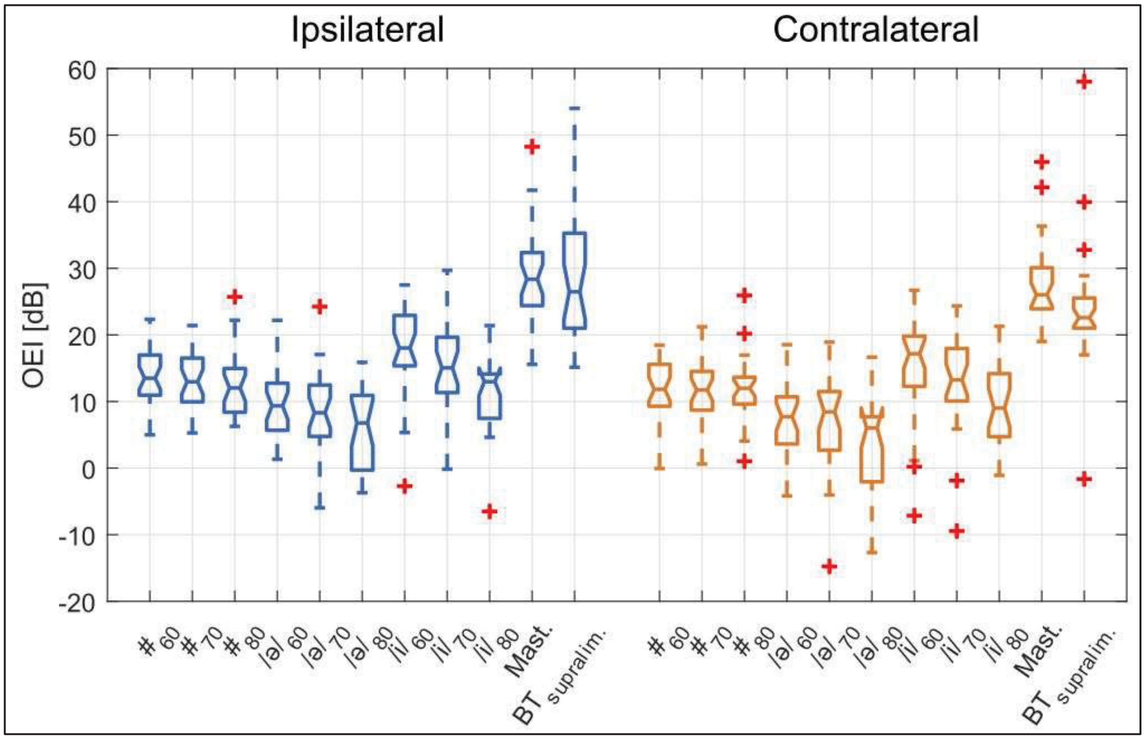



Figure 4.4 OEI, defined as the average $OE_{obj}^{STD}$ in the 160Hz to 500Hz bandwidth, as a function of the ipsi- and contralateral ears, BC stimulations and speech-based stimulations at the three vocal efforts. The # symbol indicates the enumeration of random numbers and $BT_{supralim}$. indicates the bone transducer at a supraliminal level. In the boxplot representation, the height of the box represents the interquartile range (Q75%-Q25%). The horizontal bar dividing the box represents the median and the tapered sections on both sides represent the 95% confidence interval around the median. The whiskers represent the minimum and the maximum values of the sample while the crosses represent values determined as outliers

#### 4.1.3.1 Differences between speech-based stimulation

As shown in Figure 4.4 for $OE_{obj}^{STD}$, the magnitude and variability of the OEI depends on the nature of the sounds produced by the participants when speaking, i.e. continuous speech (random numbers) vs. sustained vowels (/i/, /ə/). This result was somehow expected given their different characteristics and how they are produced in the speech organs, thus resulting in different AC and BC stimulations (M.O. Hansen, 1998). The OEI exhibits more variability with vowels than with numbers at a vocal effort of 70 dB(A). Using the interquartile range ($Q_{75\%}$ - $Q_{25\%}$) to quantify variability associated with the stimulation, it was found to be smaller when numbers were used, ranging from 4 dB to 6.6 dB, in comparison to the vowels, ranging from 6.6 dB to 11 dB. Additionally, using vowels caused outliers to be detected whereas none were found when using numbers. This difference in variability was also found with the vocal efforts of 60 dB(A) and 80 dB(A). The larger variability obtained with vowels is attributed to the difficulty of producing a similar stimulus twice, both in terms of the produced vocal effort amplitude and speech spectrum (M.O. Hansen, 1998). Although the vocal effort amplitude was monitored with the feedback system, a shift in the voice pitch occurred for most participants when occluding the ear. The magnitude of the shift varied from a participant to another, e.g. ranging from less than 5 Hz up to 90 Hz when considering the first formant during the vocalization of the vowel /i/ at a vocal effort of 70 dB(A). In contrast, enumerating numbers instead allows one to measure the signal over longer periods of time (20 sec vs. 5 sec) as the participants can breathe throughout the recording. In addition, the signal integration over the recording time to compute the $L_{eq,T}$ allows to average a large number of vowels and consonants which leads to a more stable, broadband, and more realistic stimulation. Considering these results, numbers are thus considered more robust to measure $OE_{obj}^{STD}$ and OEI. The results shown in Figure 4.4 also suggest that the effect of the vocal effort on the measured OEI is small. Using a repeated measure ANOVA statistical analysis, the three vocal efforts were compared to one another for each stimulation. Statistical results indicate that vocal effort does not statistically influence the OEI obtained with random numbers. With vowels, a 10 dB change in the vocal effort (e.g. 60 vs. 70 dB(A), 70 vs. 80 dB(A)) does not lead to a statistically different OEI, but the larger 20 dB change does (i.e., 60 vs. 80 dB(A)). This suggests that the measurement methodology of the occlusion effect using one's own voice could be simplified: as the influence of the vocal effort is only small, repeated measures at multiple speech intensities seem unnecessary, provided a feedback system is used. Further investigations should be conducted to investigate the influence of speech content on the occlusion effect, e.g. numbers vs. words. Using numbers to obtain the OEI is, however, in accordance with some procedures used with certain hearing aids to control the occlusion effect to improve users' comfort (Høydal, 2017).

#### 4.1.3.2 Differences between BC stimulations

For the two BC stimulations (i.e., mastication and bone transducer driven at a supraliminal level), $OE_{obj}^{STD}$ results obtained were typically similar. In Figure 4.1, $OE_{obj}^{STD}$ measured with mastication was typically 2.5 dB lower than with the bone transducer between 250 Hz and 2000 Hz. The larger variability of $OE_{obj}^{STD}$ can be attributed to the more extreme values the bone transducer produces in some instances. For a closer inspection of the data, $OE_{obj}^{STD}$ obtained with both stimulation sources is plotted as a function of frequency for each individual participant Figure 4.5. The identification number (ID) of each participant is indicated in the bottom left-hand side of each panel. Typically, both $OE_{obj}^{STD}$ are in good accordance, but there are instances where differences are present. These differences can be in specific third octave bands, such as for participants ID18 and ID19, but can also be present over the entire frequency range studied, such as for participants ID5 and ID11. The $OE_{obj}^{STD}$ difference between mastication and the bone transducer are also observed with an SVI. When considering the OEI shown in Figure 4.4, the difference between the two medians is less than 2.5 dB in the ipsilateral ear, and less than 5 dB in the contralateral ear. When considering the variability of the OEI, both stimulation sources yield different results in each ear. In the ipsilateral ear, the standard deviation of $OE_{obj}^{STD}$ is smaller with mastication than with the bone transducer (see Figure 4.1), as previously discussed. When considering the OEI (see Figure 4.4), the interquartile range associated with mastication is smaller than with the bone transducer (respectively 8.0 and 14.3 dB). In the contralateral ear, the interquartile ranges are smaller than in the ipsilateral ear, and the interquartile range obtained with the bone transducer is smaller than with mastication (respectively 4.5 and 6.2 dB). With the bone transducer, the smaller interquartile range measured in the contralateral ear compared to the ipsilateral ear is in accordance with results from (Reinfeldt et al., 2013). As speculated by Reinfeldt et al., the $OE_{obj}^{STD}$ measured in the ipsilateral ear compared to the contralateral ear could be more variable due to the soft tissues' proximity to the stimulation position at the ipsilateral mastoid (Reinfeldt et al., 2013). In contrast, the contralateral ear's soft tissues are excited via the skull and not directly by the bone transducer. With the mastication of a chewing gum, the variability obtained in both ears is comparable. Using the mastication as a BC stimulation source must be investigated further to understand the influence of mastication's characteristics on $OE_{obj}^{STD}$: jaw movement, intensity, duration, food being masticated, background noise, etc. In addition, although the average $OE_{obj}^{STD}$ obtained with both stimulations are similar, their characteristics are very different. Mastication produces the excitation of the teeth, bones, muscles, and soft tissues of the head whereas the bone transducer excites the soft tissues and the skull near the site of the stimulation, i.e. in this study, the mastoid process. Nevertheless, these findings suggest that mastication could be used as a quick alternative to the bone transducer to measure $OE_{obj}^{STD}$, notably because of its compatibility with earmuffs (no physical interference with the headbands), the broadband stimulation it produces, and the lower variability achieved when compared to the bone transducer. Moreover, mastication is simple, straightforward and does not require additional equipment (bone transducer, audiometer), which makes it adapted for a field measurement methodology of the $OE_{obj}^{STD}$, provided that a quiet environment is used to perform the tests. A more thorough investigation is, however, required to validate this approach.

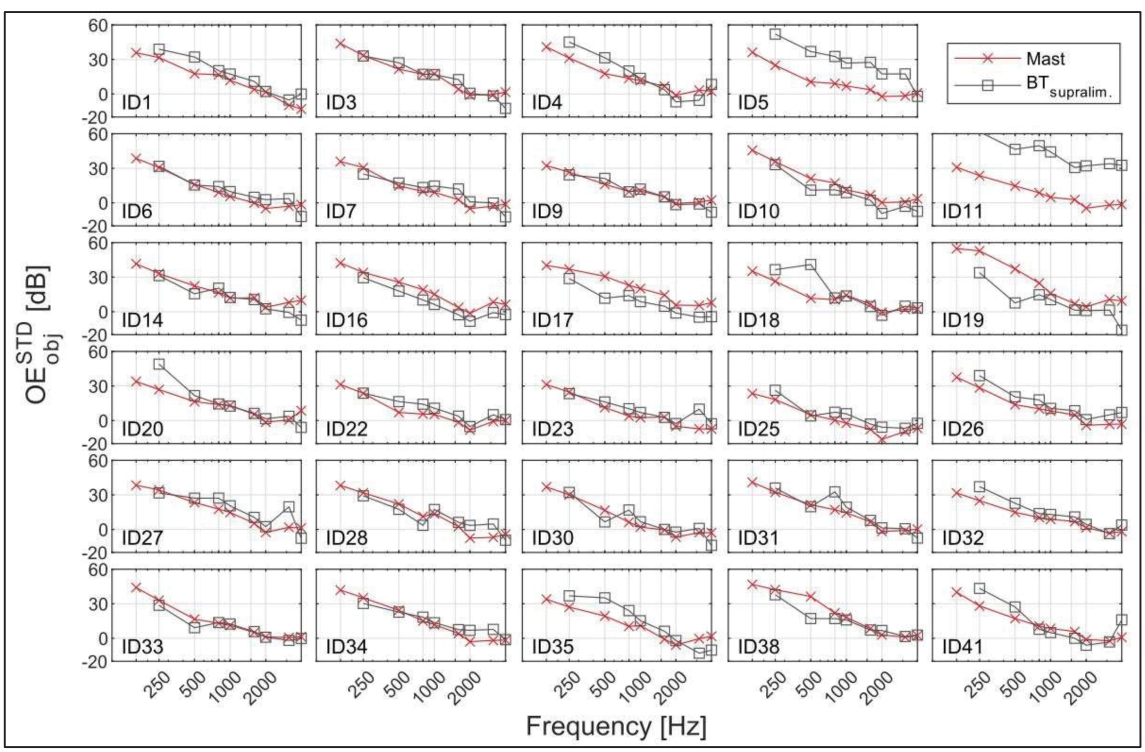



Figure 4.5 Individual comparisons between the $OE_{obj}^{STD}$ obtained with mastication and the bone transducer driven at a supraliminal level ($BT_{supralim.}$)

#### 4.1.3.3 Differences between speech-based and BC stimulation

The difference between the occlusion effect measured with speech-based stimulations and BC stimulations is now highlighted. In Figure 4.4, the median of the OEI obtained with random numbers is 15 to 22 dB less than with the mastication and the bone transducer. This difference can be explained by the AC component of the voice, i.e. the sounds radiated through the lips and nostrils that reaches the ears (Porschmann, 2000), that is more important in the unoccluded ear configuration (open ear). When the ear is unoccluded, the airborne component contributes to the measured SPL in the earcanal. When the ear becomes occluded, this contribution is partly blocked by the occlusion device (Mie Ostergaard Hansen & Stinson, 1998). As the AC contribution is diminished in the occluded ear configuration, the resulting $OE_{obj}^{STD}$ is lower in comparison to the bone transducer. With the latter, the airborne component due to the acoustic radiation of the casing is small; even more in this study as special care was taken to ensure it was minimal. As of now, measuring the $OE_{obj}^{STD}$ with both stimulations (speech, BC stimulation) allows one to characterize the occlusion effect. Using both stimulations provides a method to obtain different values of $OE_{obj}^{STD}$ (or OEI) when using a specific HPD in different situations during a workday. Speech could allow one to measure an $OE_{obj}^{STD}$ representative of when a worker is at their workstation and when verbal communication is needed with colleagues around. A BC stimulation, such as mastication, could allow one to measure an $OE_{obj}^{STD}$ representative of other events occurring during the day while the HPD is worn in a quiet environment, such as in a break room or an office. For the scope of this work, which focuses on earplugs, an approach based on using one's own voice to measure $OE_{obj}$ is preferred over BC stimulation sources (mastication, bone transducer) as speech is more often reported as the main source of $OE_{exp}$ when workers are using HPDs (Berger, 1986; Berger & Kerivan, 1983; Doutres et al., 2019; Terroir et al., 2021). Moreover, because the AC component of the voice is measured by the microphone in the unoccluded ear, it is assumed that $OE_{obj}^{STD}$ could be assessed in a test room with moderate ambient noise level (levels yet to be defined) provided the AC component of the voice dominates the SPL measured in the earcanal. By eliminating the need for a quiet or controlled environment, such approach would be adapted for field assessment of $OE_{obj}$. Nonetheless, the results obtained with BC stimulations are deemed relevant as they could benefit studies on hearing aids or even future studies on HPDs if BC stimulation sources are identified as an important source of $OE_{exp}$. Nevertheless, further investigation would be necessary to study the influence of background noise on the magnitude of the $OE_{obj}^{STD}$ as all measurements were conducted in a quiet and controlled environment during this study.

#### 4.1.4 Comparison between measurements methods of the objective occlusion effect

The results presented up to this section were obtained using the "standard" method (see Figure 3.3a). This method is now compared with the two other methods introduced earlier, i.e. the real-time method (see Figure 3.3b) and the NR-based method (see Figure 3.3c). To compare them one against another, the $OE_{obj}$ obtained with the three methods is shown individually as a function of frequency in Figure 4.6 for the speech-based stimulations at the 70 dB(A) vocal effort and mastication. Only the data obtained in the ipsilateral ear is shown for all stimulation sources. The upper panels display the average values while the lower panels show the standard deviations to evaluate the variability associated with each method. For all stimulation sources, the average $OE_{obj}^{STD}$ and $OE_{obj}^{RT}$ are very similar between 160 Hz and 2000 Hz; the difference is at the most 3.5 dB, but typically less than 2 dB. In addition to providing similar results, measuring the $OE_{obj}^{RT}$ significantly reduces the variability. With random numbers, the standard deviation is slightly less with $OE_{obj}^{RT}$ than with $OE_{obj}^{STD}$, but this improvement is more significant when vowels are used. It corroborates the hypothesis that a part of the variability when measuring the $OE_{obj}^{STD}$ with vowels can be associated with the difficulty of reproducing the same vowels twice (M.O. Hansen, 1998). With mastication, the variability obtained with $OE_{obj}^{RT}$ is however slightly larger below 500 Hz compared with $OE_{obj}^{STD}$.

When considering $OE_{obj}^{NR}$, the NR-based method overestimates the magnitude of $OE_{obj}$ compared to the other two methods. Since the occluded SPL is measured similarly for the three methods (i.e. $Lp'_{EC\ (1)}$ in Figure 3.3), the overestimation is mostly attributed to a difference in the estimation of the unoccluded SPL. By construction, there is no unoccluded condition with the NR-based method. In this method, the unoccluded SPL is rather approximated by the SPL measured at the entrance of the earcanal, just outside of the protected earpiece, using the OEM (see $Lp'_{OUT\,(1)}$ in Figure 3.3). However, by approximating the unoccluded SPL by $Lp'_{OUT\,(1)}$, the contribution of certain AC and BC paths and mechanisms are either blocked or significantly modified by the presence of the protected earpiece. This can lead to an SPL that is lower compared to the SPL measured inside the unoccluded earcanal, thus leading to the overestimation of $OE_{obj}^{NR}$. This overestimation depends on both the frequency and the stimulation source that is used. With speech, the AC component of the voice is the main contributor below 800 Hz for both the SPL measured by the OEM in the protected condition and for the SPL in the unoccluded ear, which leads to similar $OE_{obj}$ values with the three measurement methods. Above 800 Hz, $OE_{obj}^{NR}$ overestimates the OE above 800 Hz with speech. In this case, approximating the unoccluded SPL with $Lp'_{OUT\,(1)}$ fails to capture (1) the earcanal's quarter wavelength resonance (Hammershoi & Moller, 1996), (2) the diffraction of the head, torso and pinna (Hammershoi & Moller, 1996), (3) the acoustic radiation of the earcanal's walls (Stenfelt et al., 2003), and (4) the acoustic radiation of the tympanic membrane (Stenfelt et al., 2003) that are not seen by the OEM due to the presence of the protected earpiece. In the case of mastication, the overestimation is larger and is present over the whole studied frequency range. This is attributed to the fact that the low noise level measured just outside the earpiece is a poor approximation of the unoccluded ear SPL. Indeed, with a BC dominated excitation such as mastication, the main contributions to the unoccluded SPL come from four above-mentioned paths and mechanisms, which are clearly missed when using $Lp'_{OUT\,(1)}$ as an approximation. Moreover, the AC component is minimal (or even inexistent) as the participants kept their mouth shut while chewing. Therefore, using $Lp'_{OUT\,(1)}$ to approximate the unoccluded SPL with BC stimulations is unadvised and limits the usability of the NR-based method for such stimulations.

These findings suggest that measuring $OE_{obj}$ with the real-time and the NR-based methods provides advantages over the widely used standard method. The real-time and the NR-based methods allow one to measure $OE_{obj}$ faster, i.e. both the occluded and unoccluded SPL are measured simultaneously and subject to less variability as the stimulation is produced only once. Furthermore, both methods could lead to an even more simplified measurement methodology when speech is used as a feedback system is not necessary because of the small effect of vocal effort on $OE_{obj}$ (as previously discussed). Therefore, the participant only needs to speak once. This reduces the cognitive workload, i.e. not having to focus on monitoring the feedback system, and therefore makes it possible to use more realistic and complex speech contents, such as a list of words or sentences. When comparing the real-time method to the NR-based method, each offers advantages and disadvantages over the other. The real-time method provides more flexibility, as it can be used with any type of stimulation without overestimating the $OE_{obj}$. However, this comes at the cost of requiring both ears to be instrumented in opposite configurations (i.e., one ear occluded and the other unoccluded), which prevents it from being paired with comfort assessment measures. This is because the asymmetrical ear configuration would not induce discomfort representative of typical earplug use (i.e., with both ears occluded simultaneously), thereby preventing participants from adequately evaluating the $OE_{exp}$. In opposition, the NR-based method provides the advantages of requiring a single ear to estimate $OE_{obj}$, but is not reliable with BC stimulation sources. Moreover, as a single ear is required, this approach allows computing $OE_{obj}$ in both ears simultaneously and independently, thus leading to a more robust $OE_{obj}$ as it is not affected by possible anatomical differences between both ears. Although systems using the NR-based method have already been used ((Bernier & Voix, 2013; Bouserhal, Bernier, & Voix, 2019; Mejia, Dillon, & Fisher, 2008), patented (United States Patent Patent No. 5,577,511, 1996; United States Patent Patent No. 10,357,402 B2, 2019) and commercialized (Audioscan, 2021), the findings in the present study confirm the accuracy and robustness of this method against the standard and real-time methods when speech is used. Moreover, as the scope of this work focuses on the OE induced by earplugs, these results suggest the NR method is the most adapted and the most practical to measure $OE_{obj}$ generated by one's own voice as speech is often reported as the main $OE_{exp}$ by HPD users.

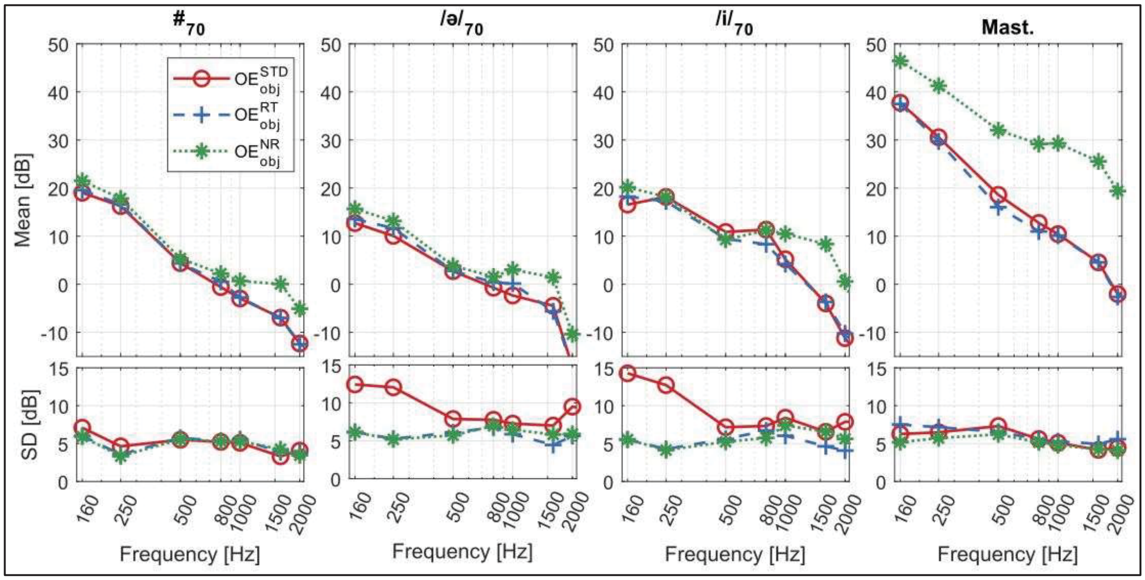



Figure 4.6 $OE_{obj}$ as a function of frequency and measurement method for speech-based stimulations and mastication

### 4.1.5 Synthesis

To summarize, the various aspects related to the objective measurement of the OE have been investigated to identify a simple and robust approach that could eventually be adapted for field conditions.

Regarding indicators, the frequency-based indicator contains the most information, as it allows for an analysis of the phenomenon across different frequency ranges. Among single-value indicators, the $OE_{obj}$ averaged over the 160–500 Hz frequency band was identified as the least variable while remaining simple to compute. However, it was observed that the interpretation of results would have remained the same regardless of the chosen indicator.

Regarding the stimulation source, inducing OE through continuous speech using random number enumeration enables easy and reproducible measurement of the $OE_{obj}$. Compared to BC stimulation source, the $OE_{obj}$ amplitude is lower, primarily due to the AC contribution of the voice, but this method can be applied without specialized equipment and in non-silent environments. Moreover, speech induces an OE that is representative of the discomfort reported by HPD users.

Finally, regarding the measurement method, the three methods investigated each have advantages and disadvantages, but the NR-based approach allows to obtain, from a single measurement and without an open-ear configuration, the $OE_{obj}$ indicator in each ear independently.

Thus, the proposed method for simple and robust OE measurement in laboratory settings is to use a voice-based approach combined with the NR-based measurement method. The choice of indicator can be tailored to specific needs. For instance, researchers may prefer a frequency-based indicator to analyze the phenomenon across different frequency ranges, whereas occupational hygienists may opt for a single-value indicator to facilitate communication of results to workers seeking an HPD suited to their needs.

However, additional measurements are required to validate the method in field conditions.

## 4.2 Formulation of questions about the experienced occlusion effect

The results presented in this section aim to improve the design of questionnaires on the $OE_{exp}$ in response to the challenges related to comfort evaluation raised in Section 1.2.3. Specifically, the investigation focuses on the influence of word choice on participants' understanding of questions about the $OE_{exp}$ induced by HPDs. Based on data collected from the survey (described in Section 3.2), the formulation of questions related to the $OE_{exp}$ is discussed in Section 4.2.1, while the guidance provided to participants to help them answer the questionnaire is addressed in Section 4.2.2. Then, data from the C2 campaign are used to examine the influence of question formulation on comfort evaluation. More precisely, comfort scores obtained for questions addressing the perception of OE (i.e., $OE_{perc}$) and the discomfort related to the OE (i.e., $OE_{exp}$) are compared using statistical tools in Section 4.2.3 to determine whether participants interpret these questions differently.

### 4.2.1 Question formulation in French on the $OE_{exp}$

The survey demonstrated that there is no unanimity among respondents regarding the best formulation to use to evaluate the $OE_{exp}$. Some consider the three formulations presented in Section 3.2.2 to be adequate in the context of the question (i.e., annoyance ("gêne"), discomfort ("inconfort"), inconvenience ("désagrément")), while others have a categorical preference based on specific reasons. Several observations arise from the analysis of survey responses:

- The preference for one of the three words does not seem to stem from the socio-demographic profile of the respondent (e.g., naive vs. non-naive regarding the research project, use of HPDs, male vs. female), except perhaps for the regional variation of French in the case of the word "gêne" (i.e., annoyance in English). Respondents of French origin (n = 3) unequivocally understood the meaning of the word in the context of the question, while respondents of Quebec origin (n = 18) had more difficulty understanding it. This difficulty seems to stem from the fact that the word "gêne" is commonly used in Quebec to refer to shyness (e.g., being embarrassed to speak in public, being embarrassed to be stared at), but rarely to refer to an uncomfortable sensation or discomfort. However, almost all respondents understood the meaning of the question once the word "gêne" was explained and contextualized for them.

- For several respondents, the word "inconfort" (i.e., discomfort in English) refers to a physical state (i.e., pain) while "gêne" rather refers to a mental state (i.e., annoyance, disturbance).

- The word "désagrément" (i.e., inconvenience in English) was preferred by several, but was also judged very inadequate by others in the context of the question; it therefore does not achieve more unanimity than "gêne" or "inconfort".

Based on the fact that there does not seem to be a formulation better understood than the others, and that the word "gêne" was used during a field survey on earplugs comfort (Negrini et al.,2025), the word "gêne" was kept for the C2 campaign's questionnaire to measure $OE_{exp.}$

### 4.2.2 Guidance of the participant

In addition to improving the formulation of the questionnaire, the survey allowed to improve the experimental protocol of C2 to ensure that participants understood the meaning of the word "gêne" in the context of the research project. These improvements are as follows:

- A definition of the word "gêne" was added at the beginning of the questionnaire so that the participant could understand its meaning in the context of the study. In French, the definition given was "sensation désagréable, inconfortable ou agaçante", which translated to English corresponds to "an unpleasant, uncomfortable, or annoying sensation."

- A shortened definition of the word "gêne" was also added at the top of each page where the word was employed so that the participants could be reminded of its meaning throughout the questionnaire.

- A verbal explanation of the word "gêne", as well as an example on how it is used in the context of this study, was given to the participants by the experimenter. More specifically, it was explained that the word refers to 'annoyance' rather than 'shyness,' as it is often interpreted that way by Quebec French speakers.

As there are no published studies in French on the OE, the author believes that the survey conducted during the pretests of the C2 campaign significantly improved the quality of the experimental protocol and questionnaire by adding the three elements mentioned above. These results are particularly important in comfort research as they highlight the relative difficulty in accurately measuring the (dis)comfort induced by HPDs, as well as the precautions that must be taken regarding the translation of questionnaires, which are predominantly published in English in the literature.

### 4.2.3 Differences between the perceived OE and the experienced OE

As explained in Section 3.3.6, participants evaluated the $OE_{perc}$ and the $OE_{exp}$ induced by each tested configuration throughout the measurement session of campaign C2. Although the analyses have so far focused on the $OE_{exp}$, the question regarding the $OE_{perc}$ was included to investigate the potential influence of question formulation related to OE, as discussed in Section 1.2.3.1. More specifically, the objective of the following analyses is to determine whether participants distinguish between the perception of the OE (i.e., $OE_{perc}$) and the discomfort associated with it (i.e., $OE_{exp}$).

To facilitate the comparison between the two types of OEs, the Δscore, calculated as the $OE_{perc}$ score minus the $OE_{exp}$ score, is presented below instead of the $OE_{perc}$ and $OE_{exp}$ scores. However, readers can refer to Section 4.3.3 for the distributions of $OE_{exp}$ scores and ANNEX II for those of $OE_{perc}$. The distributions of Δscore for the comparison of earplug models, insertion depths, and ambient noise levels presented in Figure 4.7, Figure 4.8, and Figure 4.9 can be interpreted as follows:

- A Δscore of 0 indicates that the participant rated the $OE_{perc}$ and the $OE_{exp}$ equally, meaning no distinction is made between the perception of the OE and the associated discomfort.

- A positive Δscore indicates that the participant rated the $OE_{perc}$ higher than the $OE_{exp}$, suggesting that the participant perceives the OE but does not find it as bothersome.

- A negative Δscore indicates that the participant rated the $OE_{perc}$ lower than the $OE_{exp}$, suggesting that the participant perceives less the OE than he/she is bothered by it.

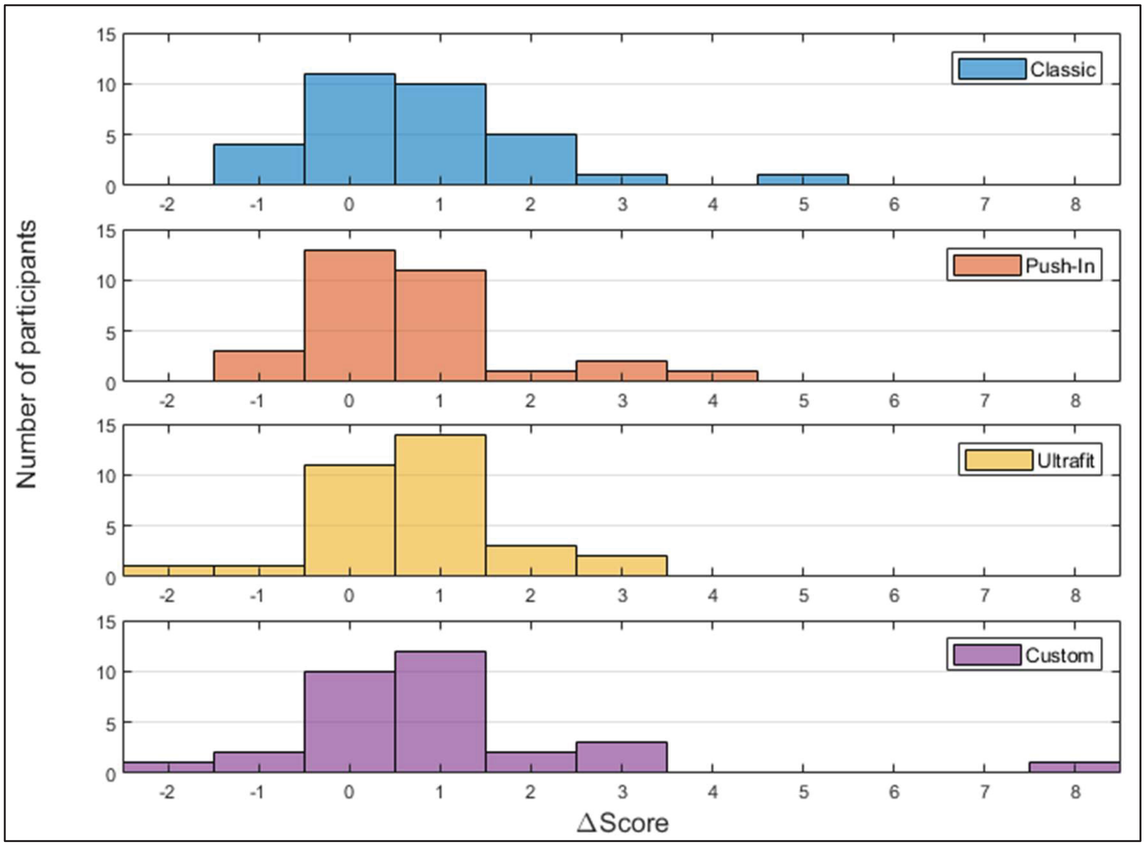



Figure 4.7 Distribution of the Δscores for the four earplugs tested during the earplug models phase of C2, calculated as the $OE_{perc}$ score minus the $OE_{exp}$ score

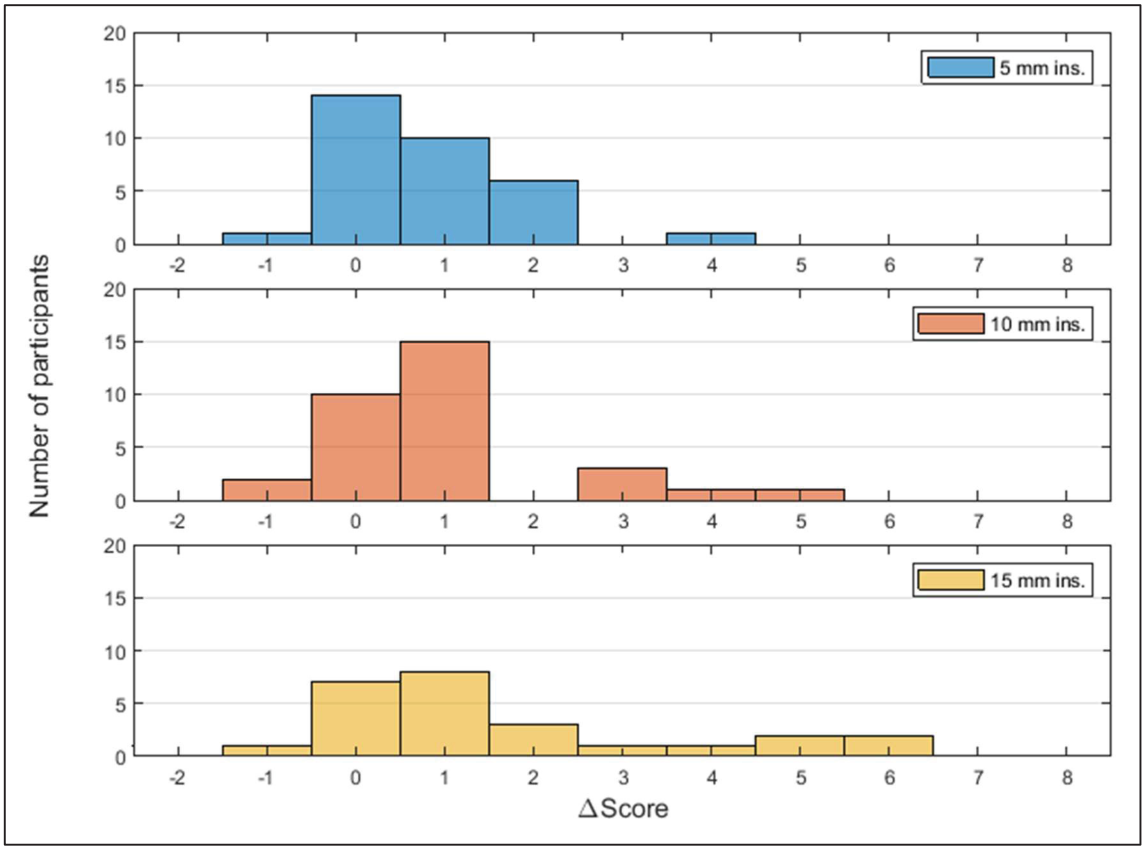



Figure 4.8 Distribution of the Δscores for the three insertion depths tested during the insertion depths phase of C2, calculated as the $OE_{perc}$ score minus the $OE_{exp}$ score

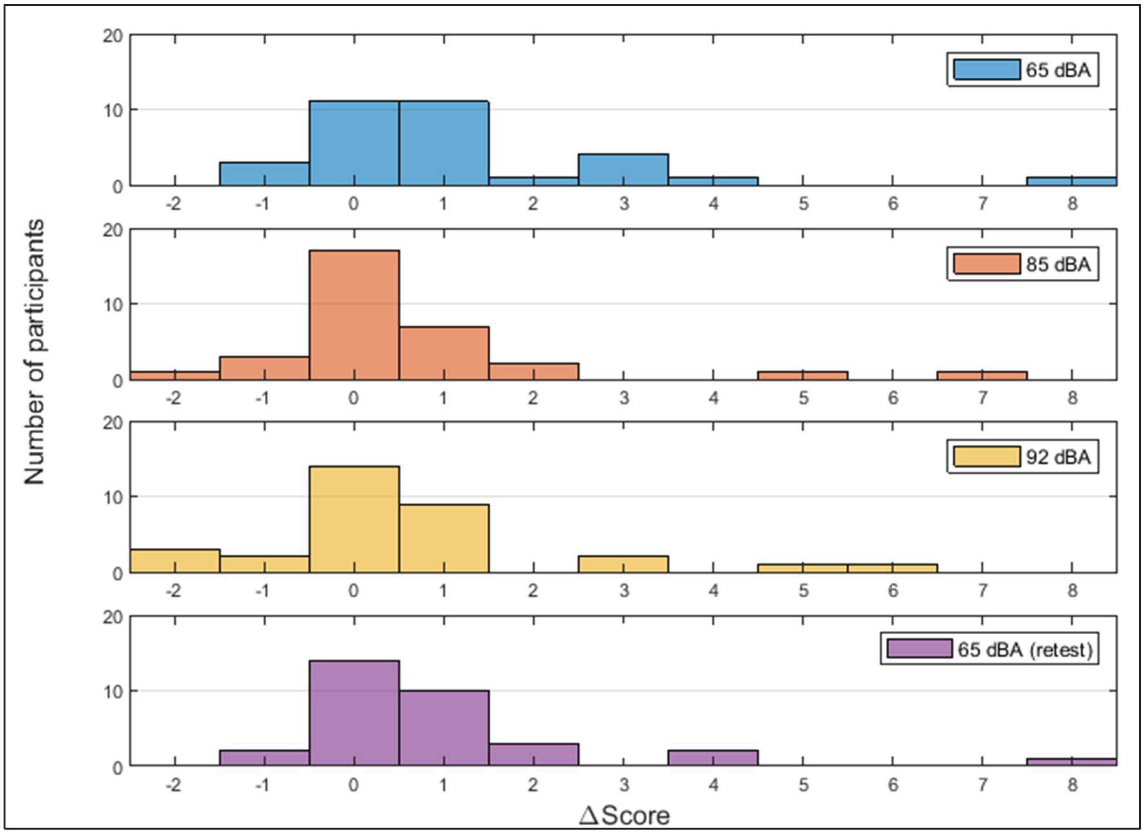



Figure 4.9 Distribution of the Δscores for the four background noise levels tested during the background noise level phase of C2, calculated as the $OE_{perc}$ score minus the $OE_{exp}$ score

A common observation across all tested configurations is the absence of consensus among participants. While a large proportion of participants have a Δscore of 0, the majority exhibit varying Δscores, indicating that they differentiate between the $OE_{perc}$ and the $OE_{exp}$. Typically, Δscores range from 1 to 2 points, though differences of more than 3 points are also observed in some instances. The positive trend in Δscores, shown by the right-hand tail of the distributions, suggests that participants tend to rate the $OE_{perc}$ higher than the $OE_{exp}$; in other words, the discomfort associated with the OE does not necessarily reflect the extent to which it is perceived.

Negative Δscore are also observed across all tested configurations, meaning some participants rated discomfort higher than their perception of the OE. Although the occurrence of negative

Δscores is difficult to explain, several possible explanations can be considered. One is that some participants experienced substantial discomfort related to the OE, even though they reported only limited perception of it. Another hypothesis is that some participants may not have fully understood the explanations provided regarding the OE. Consequently, they might have based their $OE_{exp}$ ratings on other sensations—such as mechanical pressure, temperature, or friction—rather than on the acoustic phenomenon itself. Nonetheless, the frequency of negative Δscores was significantly lower than that of null or positive Δscores. Further investigation of this observation could offer valuable insights into how to improve questionnaire administration in the context of OE assessment.

Although Δscore distributions vary across configurations, an average difference of 0.85 points (relative to the 9-point scale) is observed between the $OE_{perc}$ and the $OE_{exp}$. To determine the significance of this difference, $OE_{perc}$ and $OE_{exp}$ data were gathered and analyzed using an MLM, as presented in Section 3.3.10.2. In this analysis, the dependent variable of the model is the score (ranging from 1 to 9 on the rating scale) as a function of the type of question asked (evaluation of the $OE_{perc}$ vs. evaluation of the $OE_{exp}$) and the tested configuration (11 configurations tested across the three measurement phases). The MLM results indicate that both the type of question and the tested configuration are influential variables affecting the score. In other words, participants differentiate between the $OE_{perc}$ and $OE_{exp}$, but this distinction also depends on the tested configuration.

However, although the difference between the $OE_{perc}$ and the $OE_{exp}$ is statistically significant, its practical significance remains uncertain, as it is less than one point on the rating scale. In other words, the score difference may not be substantial enough to alter the interpretation of the results presented in other sections of this chapter. Nonetheless, the analysis of Δscore highlights the importance of questionnaire design. In light of the results presented above, it is advisable to distinguish between the $OE_{perc}$ and the $OE_{exp}$ and to assess them independently. Moreover, future studies should include rigorous pretesting to ensure that the questions are free from ambiguity, thereby minimizing variability in participants' responses due to differences in comprehension and interpretation.

### 4.2.4 Synthesis

To summarize, pretests conducted with respondents helped identify several key aspects to improve questionnaires aimed at assessing the $OE_{exp}$ induced by HPDs. This need for improvement arises from both the absence of a French-language questionnaire in the literature and ambiguities regarding the use of specific terms to assess discomfort.

Although no consensus was reached on the most appropriate wording, the use of the term "gêne" to describe the experience of discomfort appears to be a suitable choice. However, due to regional linguistic differences, including definitions within the questionnaire help clarify word meanings, ensuring that all participants interpret the questions consistently.

Moreover, the questionnaire used in campaign C2 included two questions to assess OE-related discomfort, based on those used in previous studies. Specifically, participants were asked to evaluate both their “perception” of OE (i.e., $OE_{perc}$) and the “discomfort” associated with the OE (i.e., $OE_{exp}$). The analysis of $OE_{perc}$ and $OE_{exp}$ scores revealed that, from a statistical perspective, significant differences were measurable. Although these differences were small, they highlight the importance of clear, precise, and easily understandable question formulation. Overall, the results presented in this section outline the importance of conducting comprehensive pretests to identify and correct issues related to the wording and administration of a questionnaire.

## 4.3 Triad characteristics influencing the experienced occlusion

The results presented in this section aim to address the second specific objective, which consists in identifying the influential characteristics of the person-environment-user triad on the $OE_{exp}$. First, descriptive statistics of the participant sample as well as questionnaire responses are presented in Section 4.3.1 and 4.3.2, respectively. Next, the five preliminary models (of socio-demographic characteristics, hearing losses, earcanal morphology, environment, and earplug family, see Section 3.3.10.2) are presented in Sections 4.3.4 to 4.3.6.

Then, the overall model, combining all the influential characteristics identified previously, is analyzed and interpreted in Section 4.3.7. Finally, the influence of insertion depth, a characteristic that describes the interaction between the user and the HPD, is investigated in Section 4.3.8. The results presented in this section are derived from the analysis of data exclusively collected in C2.

### 4.3.1 Descriptive statistics of the person characteristics

Although the goal of gender parity was aimed for during participant recruitment, 72% of the participants were men and the average Age = 31 years (SD = 9 years). The sample is nonetheless representative of the field, as men are more likely to hold jobs in noisy environments and more likely to suffer from NIHL (Nelson, Kohnert, Sabur, & Shaw, 2005; Ramage-Morin & Gosselin, 2018). Additionally, participant recruitment was conducted to ensure representation of workers exposed to noisy environments. Although parity was not achieved, 30% of the participants were workers from the construction and performing arts sectors, for whom HPDs are used on a daily basis. Nonetheless, 69% of participants were non-naïve regarding the use of HPDs ($Use_{HPD}$), regardless of the context of use. However, only 47% had received a training regarding their usage ($TRAIN_{HPD}$), and only 53% had received a training on noise-induced hearing loss ($TRAIN_{NIHL}$). However, because of a strong collinearity between $TRAIN_{HPD}$ and $TRAIN_{NIHL}$, only the former was used in the analyses. Regarding their HPD type-dependent usage, 22% reported using earmuffs, 53% using earplugs, and only 9% custom earplugs. Finally, regarding the participant's relationship with the experimenter as well as their relationship to the study's physical location, 38% knew the experimenter beforehand (i.e., $XPMTR_{Known}$) (e.g., colleagues) while 63% worked at the university where the study took place (e.g. students, teachers, maintenance workers).

While all participants were considered to have normal hearing, both AC and BC hearing losses were frequency-dependent, as shown in Figure 4.10. When rather quantified by the PTA3 and PTA4, the average hearing losses are 6.0 and 6.0 dB HL for AC, and 5.3 and 3.6 dB HL for BC, respectively.

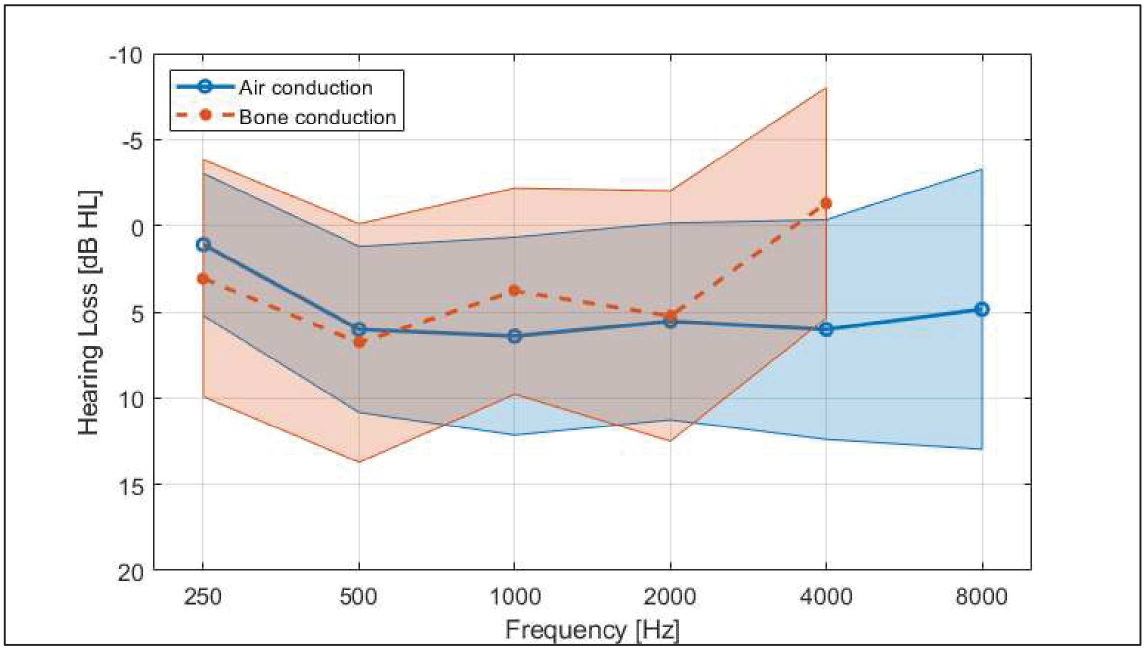



Figure 4.10 AC and BC hearing loss of the participants. Solid/dashed lines represent the averages, while the colored areas represent the variability (i.e., ± one standard deviation)

The earcanal morphological characteristics, extracted using the procedure presented in Section 3.3.8.2, are listed in Table 4.1. On average, earcanals had a length (i.e., $L_{E\text{-}SB}$) of 10.7 mm between the entrance and the second bend. In terms of circumference, earcanals were widest at the entrance ($C_E$ = 35.2 mm) and narrowest at the second bend ($C_{SB}$ = 26.5 mm), with an intermediate circumference at the first bend ($C_{FB}$ = 28.6 mm). The positive conicity ratio ($F_{E\text{-}SB}$ = 1.73) reflects a conical shape, indicating a medial narrowing of the earcanal. Regarding the isoperimetric ratio, earcanals were on average similar across the three cross-sections (i.e., E, FB, SB), with values ranging from 0.86 to 0.92. Finally, earcanals exhibited slight tortuosity, with a tortuosity greater than 1 ($T_{E\text{-}SB}$ = 1.063). In comparison to the morphologies of the workers who participated in a field study (Doutres et al., 2018; Negrini et al., 2025; Bastien Poissenot-Arrigoni et al., 2022), the participants' earcanals in this study are smaller; notably in terms of circumference at the entrance ($C_E$) and at the first bend ($C_{FB}$) of the earcanal (Bastien Poissenot-Arrigoni et al., 2023). Two hypotheses are proposed to explain this (statistically significant) difference: (i) the age difference between the two groups of participants (i.e., 31 ± 9 years in this study vs. 46 ± 10 years in the field study) and (ii) the difference in experience with HPDs (i.e., 34% in this study vs. 77% in the field study have 5+ years of experience, which 50% of those have more than 16 years of experience). Age may play a role in the difference since the morphology of the earcanal changes throughout life (Balouch et al., 2023). Moreover, and it could be hypothesized that the experience in using HPDs may also be a factor influencing the morphology, as an enlargement of the cartilaginous region of the earcanal could result from force exerted by an earplug on the earcanal walls for workers wearing earplug for prolonged periods; however, further research is necessary to verify this hypothesis.

Table 4.1 Descriptive statistics of the participants' earcanal morphological indicators

| **Morphological Indicator** | **Description** | **Average (Std. Dev.)** | **Unit** |
|---|---|---|---|
| $L_{E\text{-}SB}$ | Earcanal length | 10.7 (0.4) | mm |
| $C_E$ | Entrance circumference | 35.2 (0.6) | mm |
| $C_{FB}$ | First bend circumference | 28.6 (0.6) | mm |
| $C_{SB}$ | Second bend circumference | 26.5 (0.7) | mm |
| $F_{E\text{-}SB}$ | Entrance-to-second bend conicity ratio | 1.73 (0.08) | - |
| $IR_E$ | Entrance isoperimetric ratio | 0.86 (0.01) | - |
| $IR_{FB}$ | First bend isoperimetric ratio | 0.92 (0.01) | - |
| $IR_{SB}$ | Second bend isoperimetric ratio | 0.91 (0.01) | - |
| $T_{E\text{-}SB}$ | Entrance-to-second bend tortuosity | 1.062 (0.005) | - |

### 4.3.2 Descriptive statistics of the environment characteristics

Two characteristics of the environment were measured, namely the background noise level with- ($L_{p,ref\ BNL+Speech}$) and without speech ($L_{p,ref\ BNL}$). It can be recalled that configurations tested during the comparison of earplug models and insertion depths were tested in quiet (i.e., 20 dBA), whereas configuration tested during the comparison of background noise levels were tested in the following non-randomized order: 65 dBA (test), 85 dBA, 92 dBA, and 65 dBA (retest). Since the background noise level was imposed by the experimental protocol (as explained in Section 3.3.7.5), the $L_{p,ref\ BNL}$ measured throughout the tests corresponds to the aforementioned nominal values. However, $L_{p,ref\ BNL+Speech}$ was measured when participants spoke; therefore, the average noise level for each tested configuration, with the associated standard deviation, are listed in Table 4.2. Additionally, the two variables can be used to approximate the participant's vocal effort. More specifically, the AC contribution of the participant's voice (denoted as $L_{p,ref\ Speech}$) can be estimated using $L_{p,ref\ BNL+Speech}$ and $L_{p,ref\ BNL}$, using the decibel summation formula, as defined in Eq. (4.1):

$$L_{p,ref\ Speech} = 10 \times log_{10}\left(10^{\frac{L_{p,ref\ BNL+Speech}}{10}} - 10^{\frac{L_{p,ref\ BNL}}{10}}\right) \qquad (4.1)$$

The mean value and standard deviation of $L_{p,ref\ Speech}$ for each configuration tested are also listed in Table 4.2. Observations regarding the inspection of these three variables are discussed below.

Table 4.2 Descriptive statistics of the environmental characteristics, namely the overall noise level measured in the room by the reference microphone without the participant speaking (Lp,ref BNL), when the participant spoke (Lp,ref BNL+Speech), and the estimated contribution of the participant's voice to the overall noise level (Lp,ref Speech). Averaged levels are listed with the standard deviation in parenthesis for each configuration tested. For Lp,ref BNL, nominal values are listed since the noise level in the room was imposed by the experimental protocol

| Configuration tested | | $L_{p,ref\ BNL}$ (nominal) | $L_{p,ref\ BNL+Speech}$ | $L_{p,ref\ Speech}$ |
|---|---|---|---|---|
| Earplug phase | Roll-down foam | 20 | 58.8 (5.3) | 58.8 (5.3) |
| | Push-to-fit | | 57.9 (5.4) | 57.9 (5.4) |
| | Premolded | | 57.7 (5.6) | 57.7 (5.6) |
| | Custom | | 58.1 (5.8) | 58.1 (5.8) |
| Insertion depth | 5mm | | 57.8 (4.9) | 57.8 (4.9) |
| | 10mm | | 58.4 (4.8) | 58.4 (4.8) |
| | 15mm | | 59.3 (5.2) | 59.3 (5.2) |
| Background noise level | 65 $dBA_{test}$ | 65 | 68.3 (2.1) | 64.8 (4.0) |
| | 85 dBA | 85 | 85.8 (0.5) | 76.7 (4.3) |
| | 92 dBA | 92 | 92.7 (0.5) | 82.9 (3.9) |
| | 65 $dBA_{retest}$ | 65 | 70.7 (2.8) | 68.7 (4.3) |

To begin, the participant's vocal effort is the primary source of noise measured in the room for the measurements conducted in a quiet environment. Across the seven configurations tested under these conditions (i.e., various earplugs and insertion depths), vocal effort remains relatively consistent, both in terms of mean value and variability.

Then, although three variables are available, the subsequent discussions in this and the following sections focus on $L_{p,ref\ BNL}$ and $L_{p,ref\ Speech}$. This is for two main reasons: first, the three variables are highly correlated (i.e., $r^2$ greater than 0.8 and significant (i.e., p-value $< 0.05$) across all paired correlations); and second, investigating vocal effort offers valuable insights into OE, as the phenomenon relies on speech production to occur.

As expected, $L_{p,ref\ Speech}$ increases proportionally with $L_{p,ref\ BNL}$, as participants must exert a greater vocal effort to remain intelligible despite the ambient noise. However, the signal-to-noise ratio (SNR) between the voice (i.e., the "signal" in SNR) and the imposed background noise (i.e., the "noise" in SNR) decreases as background noise level increases. In a quiet environment, the SNR exceeds 10 dB, but drops to -10 dB during measurements conducted in the 92 dBA noise. This change in SNR can be explained by the difficulty, or even inability, of the participants to produce a vocal effort that overcomes an increasing ambient noise level when talking to the experimenter, especially when exposed to the 92 dBA noise.

Additionally, it can be observed that vocal effort differed between the two tests conducted in an ambient noise level of 65 dBA (i.e., test and retest). Specifically, $L_{p,ref\ Speech}$ was approximately 4 dB higher during the second trial compared to the first. This suggests that both the background noise level and its variation may have an influence on the $OE_{exp}$, as the second test at 65 dBA was preceded by a test at 92 dBA, whereas the first one was preceded by quiet.

The analysis of the $OE_{exp}$ data in relation to background noise level is discussed in greater detail in Section 4.3.5 to further investigate the influence of these characteristics.

### 4.3.3 Descriptives statistics of the $OE_{exp}$

The distribution of the $OE_{exp}$ ratings obtained during the three phases of the C2 measurement sessions, namely the comparison of earplug models, insertion depths and background noise levels, are depicted in Figure 4.11, Figure 4.12, and Figure 4.13, respectively. Each bar in the figures represents the response frequency for each of the 9 points on the scale (in terms of percentage) with the sample size indicated on the left-hand side in parentheses. Although interpreting the figures provides an overview of the influence the three controlled variables (i.e., earplug model, insertion depth, background noise level) on the $OE_{exp}$, more in-depth statistical analyses using MLMs are discussed in Sections 4.3.5, 4.3.6, and 4.3.8 to determine whether the influence is statistically significant or not. The distributions are nevertheless commented below.

As illustrated in Figure 4.11, there is no consensus regarding the $OE_{exp}$ induced by the types of earplugs tested. In all four cases, the response distributions are similar, and no earplug distinguished itself from the others in terms of comfort, that is by being more- or less comfortable than the others. Although this result is somewhat surprising given the significant differences in $OE_{obj}$ observed in experimental measurements or numerical models (Berger & Kerivan, 1983; M. K. Brummund et al., 2014; Kévin Carillo et al., 2021; M.O. Hansen, 1998; K. Lee & Casali, 2011; Stone et al., 2014), it remains consistent with the results from previous studies in both laboratory and field conditions, in which no difference in $OE_{exp}$ was observed between the various foam and silicon earplug models tested (B. Poissenot-Arrigoni, Doutres, Negrini, Berbiche, & Sgard, 2025; Alessandra G. Samelli et al., 2018). Both low and high $OE_{exp}$ scores are observed, albeit in different proportions; roughly 25% of participants found the $OE_{exp}$ discomfort to be above average (i.e., $OE_{exp}$ score greater than 5), while about 75% of participants found that the $OE_{exp}$ generated by the four earplugs was low or average (i.e., $OE_{exp}$ scores lower or equal to 5). Interestingly, the earplugs tested in the study did not yield maximum $OE_{exp}$, as demonstrated by the absence of scores equal to 9 in all cases.

Regarding insertion depth (see Figure 4.12), fewer participants rate the $OE_{exp}$ as “high” (i.e., with a score of 7 or higher) as the earplug is inserted deeper into the earcanal. With a 5 mm insertion depth, that proportion was 31%, decreasing to 25% with the 10 mm insertion depth and to 20% with the 15 mm insertion depth. This observation is consistent with the recommendation made to earplug- and hearing aid users to decrease the $OE_{exp}$ by inserting the in-ear device more deeply into the ear (Berger & Voix, 2022; H. G. Mueller, 2003; Revit, 1992). Similarly to the results of the earplug model phase, no participant rated the maximum $OE_{exp}$ score for the three tested insertion depths.

Regarding background noise levels, Figure 4.13 outlines two main observations, namely that an increase in background noise level leads to a greater proportion of high $OE_{exp}$ scores, and that testing the 65 dBA noise twice led to different $OE_{exp}$ score distributions. Both observations are discussed below.

Regarding the first element, it is observed that in the 65 $dBA_{test}$ noise, only about 25% of participants rated the $OE_{exp}$ as above average, but this proportion increased to 50% when the background noise level increased to 85 dBA. In the highest noise level (i.e., 92 dBA), not only did this proportion reached 57%, 13% of participants assigned the maximum discomfort score (i.e., 9-point on the $OE_{exp}$ scale). Compared to all other configurations tested in the study, this was the most uncomfortable one. Finally, returning to a quieter level (i.e., 65 $dBA_{retest}$) resulted in a decrease in the discomfort experienced compared to the previous noise level (i.e., 92 dBA). Hence, these results suggest that the discomfort increases with increasing background noise level. Then, regarding the second element, it is observed that the $OE_{exp}$ scores distribution at 65 $dBA_{retest}$ is different from that at 65 $dBA_{test}$. Indeed, the proportion of $OE_{exp}$ scores equal to- or greater than a score of 6 points is not only greater in the 65 $dBA_{retest}$ noise (38% vs. 24%), but 6% of participants still rated the $OE_{exp}$ as maximum during the retest, whereas none had assigned this score during the initial test. Hence, these results suggest that the variation of background noise level may also influence the $OE_{exp}$; this result is discussed in further detail in Section 4.3.5.

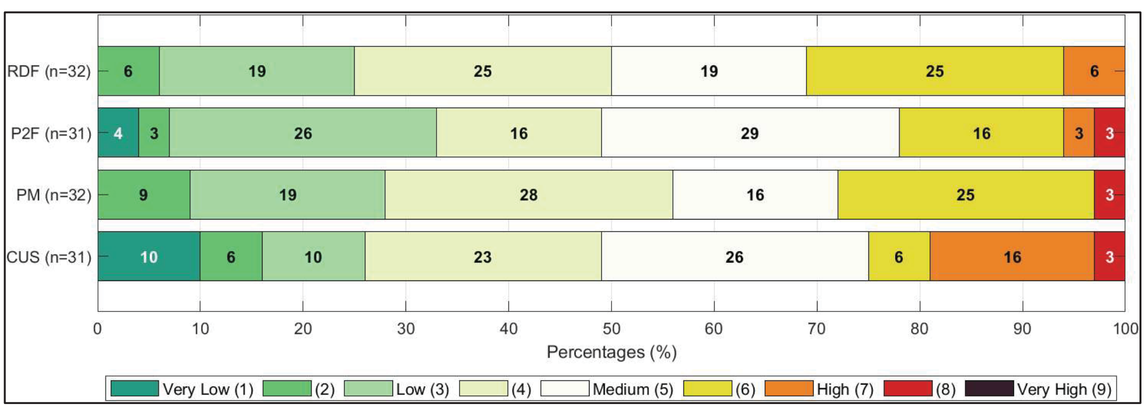



Figure 4.11 Distribution of the $OE_{exp}$ ratings for the four earplugs tested during the earplug models phase of C2, namely the Roll-down foam (RDF), the Push-to-fit (P2F), the Premolded (PM) and the Custom (CUS) earplugs

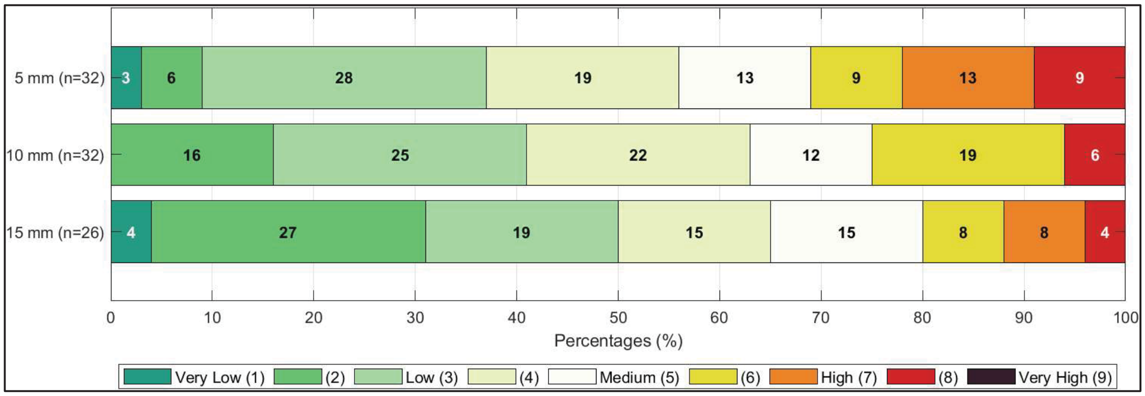



Figure 4.12 Distribution of the $OE_{exp}$ ratings for the three insertion depths tested during the insertion depths phase of C2, namely the 5 mm, 10 mm, and 15 mm insertion

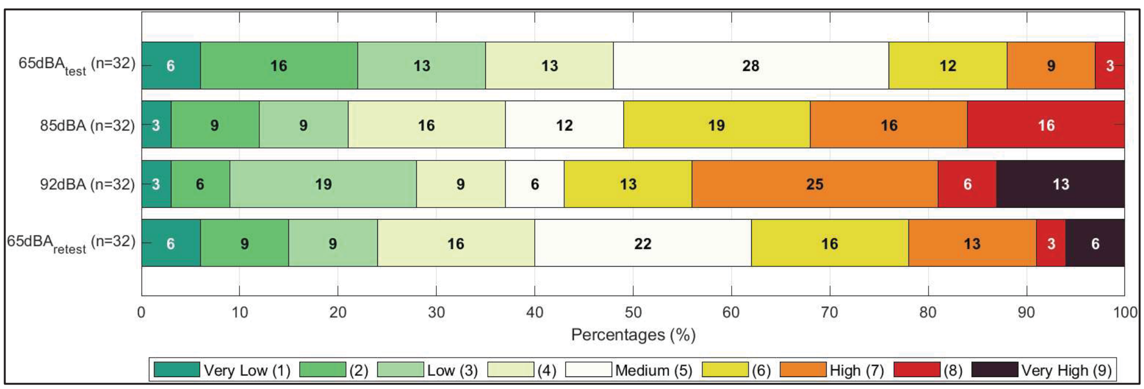



Figure 4.13 Distribution of the $OE_{exp}$ ratings for the four background noise levels tested during the background noise level phase of C2, namely 65 $dBA_{test}$, 85 dBA, 92 dBA, and 65 $dBA_{retest}$

### 4.3.4 Influence of the characteristics of the person

Three preliminary models were built using the characteristics of the person, namely the psychosocial characteristics, the hearing loss characteristics, and the morphological characteristics of the earcanal. Each preliminary analysis is presented below and the results from the three analyses are summarized in Table 4.3.

Following the iterative procedure, four of the five psychosocial characteristics (listed in Table 3.5 in Section 3.3.8.1) were identified as having a significant influence on the $OE_{exp}$, with greater discomfort reported by participants who (i) knew the experimenter ($XPMTR_{Known}$), (ii) had received training on HPD usage ($Train_{HPD}$), (iii) were HPD users ($Use_{HPD}$), and (iv) participants aged 29 and older (Age). Indeed, it was observed that participants who were acquainted with the experimenter were more critical of OE, assigning a higher $OE_{exp}$ score compared to those who did not know the experimenter. This bias is typically referred to as "participant demand" or "good participant effect" (Nichols & Maner, 2008), which leads the participant to desire to validate the experimenter's research hypothesis whom they know. One could criticize the inclusion of a training phase during which the OE phenomenon was explained to the participant and may have emphasized this effect. However, that information was nevertheless included in the documentation participants had to read and sign before taking part in the study as part of the ethics committee’s requirements.

The second and third influential characteristics are having received training on the use of HPD ($Train_{HPD}$), and being an HPD user ($Use_{HPD}$) in the context of work or personal activities. More specifically, participants who had received training related to HPD use ($Train_{HPD}$) experienced more discomfort than those who had not, whereas participants who reported using HPDs ($Use_{HPD}$) experienced less discomfort than those who did not. Although these results are consistent with findings in the literature (i.e., naivety influences discomfort, with non-naïve participants tending to provide extreme evaluations – either highly positive or highly negative – regarding HPD comfort (Doutres et al., 2020)) it remains counterintuitive that effects of these two characteristics are in opposition. However, evaluating a participant's naivety regarding HPDs and their impact on the $OE_{exp}$ proved to be a complex and challenging task. For these reasons, the interpretation of the influence of these characteristics (i.e., $Train_{HPD}$ and $Use_{HPD}$) is made with caution. Indeed, although many psychosocial characteristics describing a person's naivety were assessed with the questionnaire (i.e., use, experience, and number of hours of HPD use in the context of work and personal activities), the analyses conducted with them were laborious and inconclusive (not presented in the document for the sake of conciseness), mainly due to the fact that the results were extremely sensitive to the coding of variables (i.e., continuous vs. categorical variable). Attempts were also made to create new, more comprehensive variables (e.g., estimating the total number of hours of HPD use as the product of experience times the number of hours of weekly use), but the analyses with these variables faced the same problem of non-convergent results.

Finally, the age category of the participant contributes to the $OE_{exp}$, with older participants (part of the 29+ years old group) experiencing more discomfort than younger participants, a finding that is coherent with other studies on HPD comfort (Negrini et al., 2025; B. Poissenot-Arrigoni et al., 2025). However, understanding this influence is not straightforward; it is plausible that its effect intertwines with other characteristics. For instance, considering that the majority of HPD users fall into the 29 and older age group, a potential interaction between the two variables ($Use_{HPD}$*Age) could be occurring. Further statistical analyses could provide clarity on this matter.

As for the physical characteristics related to hearing loss, a significant influence on the $OE_{exp}$ was identified although all recruited participants were considered to have normal-hearing. Of the fourteen frequency bands assessed in total in regards to hearing losses (i.e., eight bands for AC and six for BC), only four were found to be influential; less discomfort is experienced with hearing losses at 250 Hz and 1000 Hz ($HL_{250Hz\ (AC)}$, $HL_{1000\ (AC)}$), but conversely more discomfort is experienced with losses at 500 Hz and 8000 Hz ($HL_{500Hz\ (AC)}$, $HL_{8000\ Hz\ (AC)}$). Considering the hearing loss quantified by a single-value indicator (i.e., PTA, PTA3 or PTA4), none were significant. In terms of relative influence based on the interpretation of normalized beta estimates presented in Table 4.3, the effect of $HL_{500Hz\ (AC)}$ is the largest while the effect of $HL_{8000Hz\ (AC)}$ is the smallest. It is nevertheless difficult to draw conclusions from these results because (i) a large variability is typically associated with the measurement of hearing thresholds, (ii) all recruited participants were considered to have normal-hearing and thus the effect of hearing losses greater than 20 dB HL was not studied and may not be the same, and (iii) the influence that varies in low frequency is counterintuitive (i.e., the inverse effect observed at 500 Hz compared to 250 Hz and 1000 Hz, although the normalized estimators are of a similar order of magnitude). This study therefore allowed us to observe that there could be an influence of hearing losses on the $OE_{exp}$, but additional measurements including hearing-impaired participants would clarify the actual impact of it. However, this objective was not aimed at in the context of this PhD work, as the investigation of hearing losses was well beyond what is presented above and would have required recruiting a larger number of participants to adequately represent different types and magnitudes of hearing losses.

For the physical characteristics related to the earcanal's morphology, six of them are found to be significant, associated with either the entrance (E) or the second bend (SB). Surprisingly, no characteristics of the earcanal's first bend (FB) were found to be influential, contrasting with their influence on physical comfort and sound attenuation as observed in a previous research project (B. Poissenot-Arrigoni et al., second review on going; Bastien Poissenot-Arrigoni et al., 2022, 2023). Nevertheless, the influence of the six significant characteristics is described according to their normalized beta estimates presented in Table 4.3 (in descending order) :

- Earcanals with a small circumference at the second bend ($C_{SB}$) are associated with more discomfort than large ones.

- Non-conical earcanals between the entrance and second bend ($F_{E\text{-}SB}$) are associated with more discomfort than conical ones.

- Earcanals with a large circumference at the entrance ($C_E$) are associated with more discomfort than small ones.

- Earcanals with large isoperimetric ratios (i.e., non-circular) at the second bend ($IR_{SB}$) are associated with more discomfort than circular ones.

- Conversely, earcanals with a small isoperimetric ratios (i.e. circular) at the entrance ($IR_E$) are associated with more discomfort than non-circular ones.

- Tortuous earcanals between the entrance and second bend ($TE_{SB}$) are associated with more discomfort than straight ones.

In terms of relative influence, the most influential characteristic ($C_{SB}$) is approximately six times more influential than the least influential one ($T_{E\text{-}SB}$). Although interpreting these results is challenging and not straightforward, given that the influence of morphological characteristics on the $OE_{exp}$ remains unclear, it is surprising that multiple characteristics emerge as significant in the preliminary model. One hypothesis is that they could play an important role on the velocity field of the earcanal wall and of the earplug, thus leading to an increase in the $OE_{obj}$ (Kévin Carillo, Doutres, & Sgard, 2020). The influence of morphological characteristics on the $OE_{obj}$ has been observed in previous studies using numerical models (Kévin Carillo et al., 2021; Xu, 2019) or human cadavers (Stenfelt et al., 2003), but validating this hypothesis requires the understanding of the correlation between $OE_{exp}$ and $OE_{obj}$; although this correlation is investigated in this PhD, the results presented in Section 4.4 do not allow to validate this hypothesis. Nevertheless, the global model, which considers all characteristics of the triad, will provide a better understanding of their relative importance compared to the others.

Table 4.3 Summary table of the $OE_{exp}$ preliminary analyses; significance of the variables' influence are indicated with the asterisk (*) symbol : significant influence (p-value < 0.05) are flagged by a double asterisk (**), slightly significant influence (p-value < 0.10) are flagged by a single asterisk (*), non-significant effect are flagged by NS ($^{NS}$). The sign of the beta-estimate indicates the direction of the influence on the $OE_{exp}$ : positive signed beta-estimate indicates the effect leads to more discomfort whereas a negative signed beta-estimate indicates the effect leads less discomfort

| Variable | Unit/Level | Normalized beta-estimate | Interpretation of the effect |
|---|---|---|---|
| **Preliminary analysis accounting for the psychosocial characteristics of the "person" component of the triad** | | | |
| $Train_{HPD}$ | Yes<br>No | 0.95*<br>0 | Trained participants experience more discomfort |
| $Use_{HPD}$ | Yes<br>No | -0.89*<br>0 | Participants not using HPDs experience more discomfort |
| $XPMTR_{Known}$ | Yes<br>No | 0.97**<br>0 | Participant acquainted with the experimenter experienced more discomfort |
| Age | 21-29<br>29+ | -0.86**<br>0 | Participants older than 29 years old group age experience more discomfort |
| **Preliminary analysis accounting for the hearing loss characteristics of the "person" component of the triad** | | | |
| $HL_{250Hz\ (AC)}$ | dB HL | -0.81** | No hearing loss at 250Hz increases discomfort |
| $HL_{500Hz\ (AC)}$ | dB HL | 1.18** | Hearing loss at 500Hz increases discomfort |
| $HL_{1000Hz\ (AC)}$ | dB HL | -0.94** | No Hearing loss at 1000Hz increases discomfort |
| $HL_{8000Hz\ (AC)}$ | dB HL | 0.53** | Hearing loss at 8000 increases discomfort |
| **Preliminary analysis accounting for the morphological characteristics of the "person" component of the triad** | | | |
| $C_E$ | mm | -3.40** | Participants with small earcanal at the entrance experience more discomfort |
| $C_{SB}$ | mm | 5.12** | Participants with small earcanal at the 2nd bend experience more discomfort |
| $IR_E$ | [-] | -1.50** | Participants with non-circular earcanal at the entrance experience more discomfort |
| $IR_{SB}$ | [-] | 3.10** | Participants with non-circular earcanal at the 2nd bend experience more discomfort |
| $F_{E-SB}$ | [-] | 4.76** | Participants with non-conical earcanal experience more discomfort |
| $T_{E-SB}$ | [-] | -0.73** | Participants with tortuous earcanal experience more discomfort |
| **Preliminary analysis accounting for the physical characteristics of the "earplug" component of the triad** | | | |
| (none) | | | |
| **Preliminary analysis accounting for the physical characteristics of the "environment" component of the triad** | | | |
| $L_{p,ref\ BNL}$ | 20 dBA | -1.02** | Noisy environments lead to more discomfort. |
| | 65 $dBA_{test}$ | -1.24** | |
| | 65 $dBA_{retest}$ | -0.59* | |
| | 85 dBA | $-0.20^{NS}$ | |
| | 92 dBA | 0 | |

Table 4.4 Lower triangle of the pairwise comparisons between the five background noise levels in the preliminary analysis. The difference between each pair is computed as i – j. Significant differences (p-value < 0.05) are flagged by a double asterisk (**). A negative difference indicates $L_{p,ref\,BNL}$ (i) is more comfortable than $L_{p,ref\,BNL}$ (j) while a positive difference indicates $L_{p,ref\,BNL}$ (i) is more discomfortable than $L_{p,ref\,BNL}$ (j)

| | | (i) $L_{p,ref\,BNL}$ | | | | |
|---|---|---|---|---|---|---|
| | | 20 dBA | 65 $dBA_{test}$ | 65 $dBA_{retest}$ | 85 dBA | 92 dBA |
| (j) $L_{p,ref\,BNL}$ | 20 dBA | 0 | | | | |
| | 65 $dBA_{test}$ | 0.23 | 0 | | | |
| | 65 $dBA_{retest}$ | -0.43 | -0.65 | 0 | | |
| | 85 dBA | -0.82 | **-1.04**** | -0.39 | 0 | |
| | 92 dBA | **-1.02**** | **-1.24**** | -0.59 | -0.20 | 0 |

### 4.3.5 Influence of the characteristics of the environment

As explained in Section 4.3.2, only the background noise level imposed within the room during the test (i.e., $L_{p,ref\,BNL}$) is used to build the preliminary model of the environmental characteristics. As detailed in Section 3.3.7.5, four noise levels were tested (i.e., 20, 65, 85, and 92 dBA), with the 65 dBA noise level tested twice during the BNL phase—once at the very beginning (65 $dBA_{test}$) and once at the very end (65 $dBA_{retest}$). Since this characteristic is treated as a categorical variable, a multiple comparison test was conducted to compare the different levels against one another. The results from the MLM and the multiple comparisons are presented in Table 4.3 and

Table 4.4, respectively.

The main result emerging from the statistical analyses is that background noise level has a significant influence on the $OE_{exp}$. The normalized beta estimates listed in Table 4.3 confirm the interpretation of the $OE_{exp}$ score distributions presented in Section 4.3.3, namely that an increase in $L_{p,ref\,BNL}$ leads to an increase in $OE_{exp}$. Discomfort was highest during the test at 92 dBA, followed by the test at 85 dBA, and was lowest at 65 dBA. However, it should be noted that the two tests conducted at 65 dBA (i.e., 65 dBAtest and 65 dBAretest) yielded slightly different results, which are discussed in more detail below.

The interpretation of these results, combined with the analysis of the vocal effort presented in Section 4.3.2, supports the hypothesis that the increase in $OE_{exp}$ with rising background noise levels may, in fact, be explained by the increase in acoustic pressure within the occluded earcanal due to a greater vocal effort. Since the relative contribution of the AC and BC components of the voice depends on the vocal effort exerted by an individual (Békésy, 1949), it is possible that the amplified and distorted perception of one's own voice (caused by the OE) is more pronounced during intense vocal effort (i.e., shouting). This occurs because greater vocal effort leads to an increased BC component due to the enhanced vibration of the vocal cords.

Furthermore, the results presented above also partially explain the difference in $OE_{exp}$ observed between the two tests conducted in the 65 dBA noise condition (i.e., test and retest). Although it is not possible to fully isolate potential data contamination from an order effect due to the non-randomized sequence (see Section 3.3.7 for details), which may have contributed to the participants' rising vocal effort, two hypotheses could explain this observation. The first hypothesis is that participants' discomfort may have evolved throughout the background noise comparison phase. However, this seems unlikely, as previous research suggests that discomfort remains stable during short-duration tests with earplugs (Park & Casali, 1991). The second, and more probable hypothesis, is that participants spoke louder in the 65 $dBA_{retest}$ condition compared to 65 $dBA_{test}$ because it was preceded by exposure to a very high noise level (i.e., 92 dBA). As a result, participants may have struggled to readjust their vocal effort when returning to a moderate noise environment, leading to the 4 dB increase in vocal effort outlined in Section 4.3.2. Further studies could help clarify this finding. First, by using a randomized test sequence that would eliminate potential data contamination from an order effect. Second, by incorporating measures during which vocal effort is controlled (i.e., using a feedback system for participants to monitor how loud they speak) to assess how the $OE_{exp}$ varies when background noise level changes while vocal effort remains constant.

Despite these findings, the interpretation of the multiple comparison test results presented in

Table 4.4 puts the impact of background noise level variations on the $OE_{exp}$ into perspective. Indeed, the different noise levels tested during the campaign resulted in, at most, a statistically significant mean discomfort difference of approximately 1.24 points on the rating scale (i.e., when comparing 65 $dBA_{test}$ to 92 dBA). Among all other observed discomfort differences, only two additional comparisons are statistically significant: a 1.04-point difference between 65 $dBA_{test}$ and 85 dBA, and a 1.02-point difference between 20 dBA and 92 dBA. Therefore, background noise level has a significant influence on $OE_{exp}$, but only under certain conditions, and leads to discomfort differences of only about one point on the response scale. Nonetheless, this characteristic is thus included in the global model presented in Section 4.3.7.

### 4.3.6 Influence of the characteristics of the earplug

The HPD family ($HPD_{Family}$) is the only physical characteristic of the earplugs that was controlled during the study for a total of 4 tested families of earplugs, namely the roll-down foam (RDF), the push-to-fit (P2F), the premolded (PM), and the custom (CUS) earplugs. Although some earplugs were tested at multiple insertion depths, only data from measurements made with an insertion depth of 10 mm are considered in the analysis of this preliminary model since the influence of insertion depth is primarily investigated in Section 4.3.8. Since $HPD_{Family}$ is the only characteristic investigated, only one iteration of the MLM was necessary to determine that the influence of $HPD_{Family}$ is not significant on the $OE_{exp}$ (i.e., p-value greater than 0.20). Since the characteristic is treated as a categorical variable, a multiple comparison test allowed to observe that the difference in $OE_{exp}$ between the different levels of the variable was typically less than 0.2 point on the rating scale; however, these results are not presented below as $HPD_{Family}$ is found to be not influential. Although previous studies have demonstrated that the $HPD_{Family}$ has a significant influence on the $OE_{obj}$ (M. K. Brummund et al., 2014; M. Brummund, Sgard, Petit, Laville, & Nélisse, 2015; Kévin Carillo et al., 2021; M.O. Hansen, 1998; Kichol Lee, 2011; Stone et al., 2014), this study highlights that the earplugs tested are not different from one another in terms of $OE_{exp}$. Yet, this result is unsurprising as these earplugs were not specifically designed to reduce the OE, but rather to protect the user adequately against noise exposure. However, an important distinction between this- and the previous studies referenced just above must be made, that is the previous ones employ a BC stimulation while speech is used in the present one (i.e., a complex combination of AC and BC sound sources produced by the speech organ). When considering other studies involving hearing aids instead, it was observed that several earmold characteristics were influential on the $OE_{exp}$, namely the material it is composed of, the shape and size of the earmold, and the acoustic mass of the vent, specifically integrated into the device to alleviate the OE (Conrad & Rout, 2013; Denk, Hieke, Roberz, & Husstedt, 2022; Kiessling, Brenner, Jespersen, et al., 2005; F. Kuk et al., 2005; Lundh, 1986; Vasil-Dilaj & Cienkowski, 2011; Winkler et al., 2016). However, comparing the observed results between hearing aids and ear protection plugs remained challenging due to fundamental differences between the two types of devices, as explained in Section 1.4.2.2. Nonetheless, $HPD_{Family}$ is excluded from the global model presented in Section 4.3.7 as its influence on the $OE_{exp}$ was not found to be significant.

### 4.3.7 Global model

The global model presented in this section combines the significant characteristics of the preliminary models presented in Sections 4.3.4 to 4.3.6. The analysis of the global model follows the same methodology as the preliminary analyses and uses the same iterative approach using MLMs. The results stemming from this analysis are discussed below and the influence of the significant characteristics is summarized in Table 4.5. Out of 14 remaining variables, only 6 have a significant influence on the $OE_{exp}$ (i.e., a p-value $< 0.10$). In terms of the magnitude of influence (i.e., absolute value of normalized beta estimates), the isoperimetric ratio at the 2nd bend cross-section ($IR_{SB}$), prior acquaintance of the experimenter ($XPMTR_{Known}$), and background noise level (BNL) are the most influential, while the influence of hearing losses ($HL_{250Hz\ (AC)}$, $HL_{500Hz\ (AC)}$, $HL_{1000Hz\ (AC)}$), although significant, is less in comparison. While the influence of the other 8 variables was not found to be significant, they are nonetheless included in the global model (since they are part of the model, as explained in Section 3.3.10.1) whereas the use of HPD ($HPD_{User}$) is the sole variable eliminated during the iterative approach (as explained in Section 3.3.10.1). As for the sign of the characteristics' beta-estimate (i.e., the direction of their effect on the $OE_{exp}$), the results obtained in the global model are consistent with those found with the preliminary models.

Based on these results, the influence of each significant variable of the global model is discussed below. While several morphological characteristics were influential on the $OE_{exp}$, the only one showing up to be significant in the global model is the isoperimetric ratio at the 2nd bend cross-section ($IR_{SB}$). Although it is difficult to explain its influence, participants with irregular cross-sections (i.e., large $IR_{SB}$) experienced more discomfort than those with circular ones (i.e., small $IR_{SB}$). For the prior acquaintance of the experimenter ($XPMTR_{Known}$), participants who knew the experimenter before the study experienced more discomfort than those who did not know him. As discussed in Section 4.3.4, this could be attributed to the "participant demand" effect (Nichols & Maner, 2008), which leads to a participant bias seeking to validate the experimenter's research hypothesis. In the case of the present study, the OE is presented as discomfort associated with the use of HPDs, so participants would have a negative bias towards the OE they experienced during the various tests. That is, they typically rated the $OE_{exp}$ higher on the rating scale than participants who were not familiar with the experimenter. Finally, the background noise level (i.e., $L_{p,ref\ BNL}$) still exerts a significant influence in the global model. Based on the interpretation of the pairwise comparison using the Bonferroni test shown in Table 4.6, participants rated the $OE_{exp}$ as more unfavorable in the high-level background noise (i.e., 92 dBA) compared to the quiet or moderate-level background noise (i.e., 20 dBA, 65 $dBA_{test}$). However, it is noted that differences are observable compared to the interpretation of the preliminary model. Namely, in the context of the global model combining the effect of all triad components, the difference in $OE_{exp}$ between 65 $dBA_{test}$ and 85 dBA is no longer significant (i.e., whereas it was in the preliminary model). Finally, regarding AC hearing losses, losses at 250 Hz and 1000 Hz result in a decrease in $OE_{exp}$, while losses at 500

Hz, conversely, lead to an increase in $OE_{exp}$. As discussed in Section 4.3.4, it is challenging to explain why the influence of hearing losses on discomfort depends on frequency, especially considering the large uncertainties associated with hearing threshold measurements and the small range of hearing losses obtained (by design) in the context of this study.

The interpretation of the global model ultimately allows us to observe that the $OE_{exp}$ mostly depends on the characteristics of the person when assessed in laboratory conditions. This result is not surprising given the overrepresentation of these characteristics in the analyses; indeed, the influence of 57 personal characteristics was investigated (see Table 3.5), compared to a single characteristic of the environment and the HPD, respectively (see Table 3.6 and Table 3.7). That being said, the lack of influence of the HPD on the $OE_{exp}$ observed in this study is an interesting result that was nevertheless to be expected since the models tested were all commercially available and not designed to reduce the OE, but rather protect adequately the user against noise exposure. Similarly, the influence of background noise on the $OE_{exp}$ is an interesting finding as it highlights that the level of discomfort associated with the OE depends not only on the individual and the HPD used, but also on the work environment in which a person uses it. To the author's knowledge, no other study to date highlighted the influence of these characteristics on the $OE_{exp}$.

Table 4.5 Summary table of the $OE_{exp}$ global analysis; significance of the variables' influence are indicated with the asterisk (*) symbol : significant influence (p-value < 0.05) are flagged by a double asterisk (**), slightly significant influence (p-value < 0.10) are flagged by a single asterisk (*), non-significant effect are flagged by NS ($^{NS}$). The sign of the beta-estimate indicates the direction of the influence on the $OE_{exp}$ : positive signed beta-estimate indicates the effect leads to more discomfort whereas a negative signed beta-estimate indicates the effect leads less discomfort

| **Variable** | **Unit/Level** | **Normalized beta-estimate** | **Interpretation of the effect** |
|---|---|---|---|
| **Global analysis accounting for physical and psychosocial characteristics of all components of the triad** | | | |
| $XPMTR_{Known}$ | Yes | 1.42** | Participant acquainted with the experimenter experienced more discomfort |
| | No | 0 | |
| $HL_{250Hz\ (AC)}$ | dB HL | -0.68** | No Hearing loss at 250Hz increases discomfort |
| $HL_{500Hz\ (AC)}$ | dB HL | 0.90** | Hearing loss at 500Hz increases discomfort |
| $HL_{1000Hz\ (AC)}$ | dB HL | -0.66** | No Hearing loss at 1000Hz increases discomfort |
| $IR_{SB}$ | [-] | 1.58** | Participants with non-circular earcanal experience more discomfort |
| $L_{p,ref\ BNL}$ | 20 dBA | -0.90** | Noisy environments lead to more discomfort |
| | 65 $dBA_{test}$ | -1.06** | |
| | 65 $dBA_{retest}$ | -0.60 | |
| | 85 dBA | -0.17 | |
| | 92 dBA | 0 | |

Table 4.6 Lower triangle of the pairwise comparisons between the five background noise levels in the global model. The difference between each pair is computed as i – j. Significant differences (p-value < 0.05) are flagged by a double asterisk (**). A negative difference indicates $L_{p,ref\ BNL}$ (i) is more comfortable than $L_{p,ref\ BNL}$ (j) while a positive difference indicates $L_{p,ref\ BNL}$ (i) is more discomfortable than $L_{p,ref\ BNL}$ (j)

| | | (i) $L_{p,ref\ BNL}$ | | | | |
|---|---|---|---|---|---|---|
| | | 20 dBA | 65 $dBA_{test}$ | 65 $dBA_{retest}$ | 85 dBA | 92 dBA |
| (j) $L_{p,ref\ BNL}$ | 20 dBA | 0 | | | | |
| | 65 $dBA_{test}$ | 0.16 | 0 | | | |
| | 65 $dBA_{retest}$ | -0.31 | -0.47 | 0 | | |
| | 85 dBA | -0.73 | -0.89 | -0.43 | 0 | |
| | 92 dBA | **-0.90*** | **-1.06**** | -0.60 | -0.17 | 0 |

### 4.3.8 Influence of the insertion depth

Unlike the other characteristics investigated previously, the insertion depth is not part of the person-environment-protector triad, but rather part of the interaction between the protector and the user of the holistic comfort model proposed by Doutres et al. (Doutres et al., 2022). The influence of the insertion depth is thus discussed here separately and not included in the global model since it focused solely on triad's characteristic and not on characteristics derived from the interaction phase.

The influence of the insertion depth was investigated by testing a single earplug inserted at three depths, namely 5-, 10-, and 15 mm, defined as the distance between the entrance of the earcanal and the medial face of the earplug (see Section 3.3.5). Unlike the preliminary models and the overall model discussed in previous sections, only data from the insertion depths phase are considered (i.e., $n_{observations} = 90$) (see Section 3.3.7.4). Since only one characteristic is being investigated, a single iteration of the MLM is performed to determine if the influence of the insertion depth is significant. For the analysis, the characteristic is treated as a categorical variable as to conduct a multiple comparison analysis to compare the $OE_{exp}$ resulting from the different insertion depths one against another. The results of these analyses indicate that the insertion depth has a significant influence on the $OE_{exp}$. On the one hand, fitting an earplug with a deep insertion (i.e., 15 mm) allows to reduce the $OE_{exp}$ by approximately 1 point on the rating compared to a shallow insertion (i.e., 5 mm). On the other hand, the multiple comparison analysis reveals that minor variations in insertion depth yield insignificant discomfort differences, approximately 0.5 points on the rating scale (i.e., 5 mm vs. 10 mm, or 10 mm vs. 15 mm). These results are consistent with the literature and the recommendations given to HPD and hearing aid users; that is to say, the $OE_{exp}$ tends to decrease more as an earplug is inserted deeper into the earcanal (Berger & Voix, 2022; H. G. Mueller, 2003; Revit, 1992). However, this study highlights that, from a statistical standpoint, this difference is significant only when comparing extreme insertions depth (i.e., 5 mm vs. 15 mm), but not when comparing small variations of insertion depths.

Table 4.7 Summary table of the $OE_{exp}$ resulting from various insertion depths; significance of the variables' influence are indicated with the asterisk (*) symbol : significant influence (p-value < 0.05) are flagged by a double asterisk (**), slightly significant influence (p-value < 0.10) are flagged by a single asterisk (*), non-significant effect are flagged by NS ($^{NS}$). The sign of the beta-estimate indicates the direction of the influence on the $OE_{exp}$ : positive signed beta-estimate indicates the effect leads to more discomfort whereas a negative signed beta-estimate indicates the effect leads less discomfort

| Variable | Unit/Level | Normalized beta-estimate | Interpretation of the effect |
|---|---|---|---|
| **Analysis accounting for the characteristic of the interaction phase of the comfort model** | | | |
| $Ins_{Depth}$ | 5 mm | **1.02**** | Inserting an earplug shallowly into the earcanal increases the discomfort |
| | 10 mm | **0.52*** | |
| | 15 mm | 0 | |

Table 4.8 Lower triangle of the pairwise comparisons between the three insertion depths. The difference between each pair is computed as i – j. Significant differences (p-value < 0.05) are flagged by a double asterisk (**). A negative difference indicates $Ins_{Depth}$ (i) is more comfortable than $Ins_{Depth}$ (j) while a positive difference indicates $Ins_{Depth}$ (i) is more discomfortable than $Ins_{Depth}$ (j)

| | | (i) $Ins_{Depth}$ | | |
|---|---|---|---|---|
| (j) $Ins_{Depth}$ | | 5 mm | 10 mm | 15 mm |
| | 5 mm | 0 | | |
| | 10 mm | 0.50 | 0 | |
| | 15 mm | **1.02**** | 0.52 | 0 |

### 4.3.9 Synthesis

To summarize, numerous characteristics of the environment-person-HPD triad were investigated in the laboratory to determine which exert a statistically significant influence on the $OE_{exp}$. This analysis was conducted in two stages using mixed linear models. First, preliminary models were developed to identify influential characteristics within a limited number of features belonging to a specific triad component. Characteristics found to be significant were then combined into a global model, integrating factors from all three components.

Regarding characteristics of the user, participants who were acquainted with the experimenter reported higher discomfort than those who were not. This finding aligns with the "good participant/participant demand" effect, yet it is the first time it has been highlighted in the context of the OE. Additionally, participants with a non-circular earcanal at the second bend experienced greater discomfort than others. While this suggests a potential influence of earcanal morphology on the OE, numerical simulations (given the relationship between the $OE_{obj}$ and $OE_{exp}$ is identified) would be useful to further explain its impact. Furthermore, hearing loss at 250, 500, and 1000 Hz also influences the $OE_{exp}$, although to a lesser extent than the two previous characteristics. However, the inconsistent direction of influence across the three frequency bands complicates the interpretation of this result.

Regarding characteristics of the HPD, the earplug model does not significantly influence $OE_{exp}$. This result is attributed to the low variations in discomfort between the different earplugs tested, hence participants typically had difficulty discriminating one from another. Although this result seems surprising since previous studies have observed a significant influence of earplug properties on the $OE_{obj}$, it is in accordance with previous results regarding the $OE_{exp}$.

Regarding characteristics of the environment, background noise level significantly influences the $OE_{exp}$, with discomfort increasing as noise levels rise. However, it is hypothesized that this effect may be indirectly explained by its impact on participants' vocal effort. As background noise increases, participants need to speak louder to be understood, which in turn increases the BC component of their voice. This leads to higher occluded pressure levels and, consequently, greater discomfort. Nonetheless, additional measurements are required to validate this hypothesis.

Finally, in terms of characteristics user-HPD interaction, insertion depth has a significant effect on the $OE_{exp}$. More specifically, discomfort decreases as insertion depth increases, a result consistent with existing literature. However, this influence is only significant for large insertion variations (e.g., shallow vs. deep) and not for smaller variations (e.g., medium vs. deep).
While some of the findings presented in this section align with those previously discussed in the literature, many had never been documented before. Although further experimental and numerical investigations are needed to better explain the influence of certain characteristics, the results of this study provide a foundation for future research aimed at improving the understanding of discomfort associated with OE.

## 4.4 Objectivization of the experienced occlusion effect

The results presented in this section aim to achieve the third specific objective, which is to objectivize the $OE_{exp}$ using the various indicators and variables measured during the C2 campaign. As explained in Section 3.3.10.3, the objectivization involves using MLMs with an iterative approach to identify significant indicators (i.e., those correlated with the $OE_{exp}$) and derive a linear equation to calculate a predicted $OE_{exp}$ score. This predicted score is then compared to the measured $OE_{exp}$ score to assess the strength of the established model.

### 4.4.1 Objective indicators data overview

The four objective indicators used to objectivize the $OE_{exp}$ are the $OE_{obj}^{NR}$, NR, $L_{p,occluded}$, and the background noise level measured in the booth during the test while the participant was speaking (i.e., $L_{p,ref\ BNL+Speech}$). Unlike the analyses presented in Section 4.3.2, which used only the imposed noise level (i.e., $L_{p,ref\ BNL}$), $L_{p,ref\ BNL+Speech}$ was selected instead, as it considers vocal effort and background noise level. Additionally, the descriptive statistics of $L_{p,ref\ BNL+Speech}$ were previously presented in Table 4.2 in Section 4.3.5.

For the three other indicators—$OE_{obj}^{NR}$, $L_{p,Occluded}$ and NR—the values across the 63 Hz to 8000 Hz octave bands are presented in Figure 4.14, Figure 4.15, and Figure 4.16, respectively.

These values are provided for each tested configuration within the three phases of campaign C2, namely the comparison of earplug models, insertion depths, and background noise levels. To assess trends and variability, the mean values are presented in the upper part of the figures, while the standard deviation is shown in the lower part—both as a function of frequency.

It is important to recall that, as explained in Sections 3.3.7.4 and 3.3.7.5, for tests involving insertion depth and background noise level, not all participants tested the same earplugs. When comparing different insertion depths, 32 participants tested the roll-down foam earplug, while 6 participants tested the push-to-fit earplug. Similarly, when comparing different background noise levels, 29 participants tested the custom earplug, while 3 participants tested the roll-down foam earplug. Additionally, 6 participants did not test the 15 mm insertion depth, as it was either physically impossible to insert the earplug that deep into their earcanals or they could not tolerate the physical sensation. Since the influence of the earplug model on the $OE_{exp}$ was not found to be significant, the data are pooled together (regardless of the earplug model tested) when presenting the averages and standard deviations of the indicators in Section 4.4.1.1 and 4.4.1.2 below, and during the objectivization of the $OE_{exp}$. However, since the influence of earplug properties on the $OE_{obj}$ has been outlined in the literature (as discussed in Section 1.4.2.2), the three indicators ($OE_{obj}^{NR}$, NR, and $L_{p,occluded}$) are also presented in ANNEX III, while the data from the different earplugs are not pooled, and therefore considered as a factor when plotting the data. The key observations regarding the $OE_{obj}^{NR}$ and $L_{p,occluded}$ are discussed in Section 4.4.1.1, and those of the NR in Section 4.4.1.2.

#### 4.4.1.1 Overview of $OE_{obj}$ and $L_{p,occluded}$ data

Data shown in Figure 4.14 illustrate the important variations of $OE_{obj}^{NR}$ across the different configurations tested within the three measurement phases. To better explain these variations, $L_{p,occluded}$ data presented in Figure 4.15 is also interpreted.

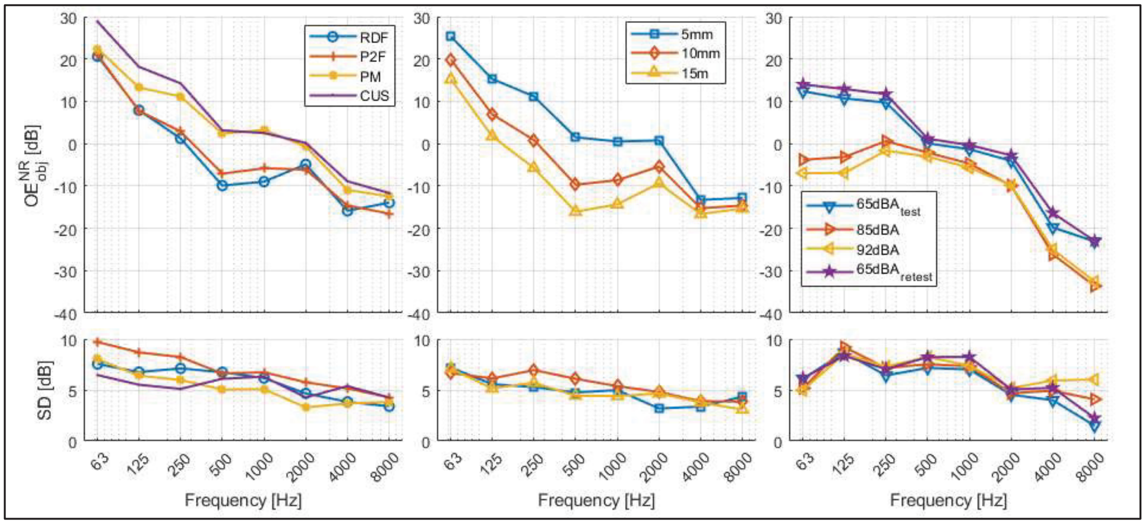



Figure 4.14 $OE_{obj}^{NR}$ as a function of frequency and configuration tested during the C2 campaign, regrouped per testing phase. In the left-hand side column, the comparison of earplug models (Roll-down foam (RDF), Push-to-fit (P2F), Premolded (PM), Custom (CUS)), all tested with a 10 mm insertion depth. In the middle column, the comparison of insertion depths (5mm, 10mm, 15mm). In the right-hand side column, the comparison of background noise levels (65 $dBA_{test}$, 85 dBA, 92 dBA, 65 $dBA_{retest}$). Values averaged across all participants are shown in the top panels while the standard deviations are shown in the bottom panels

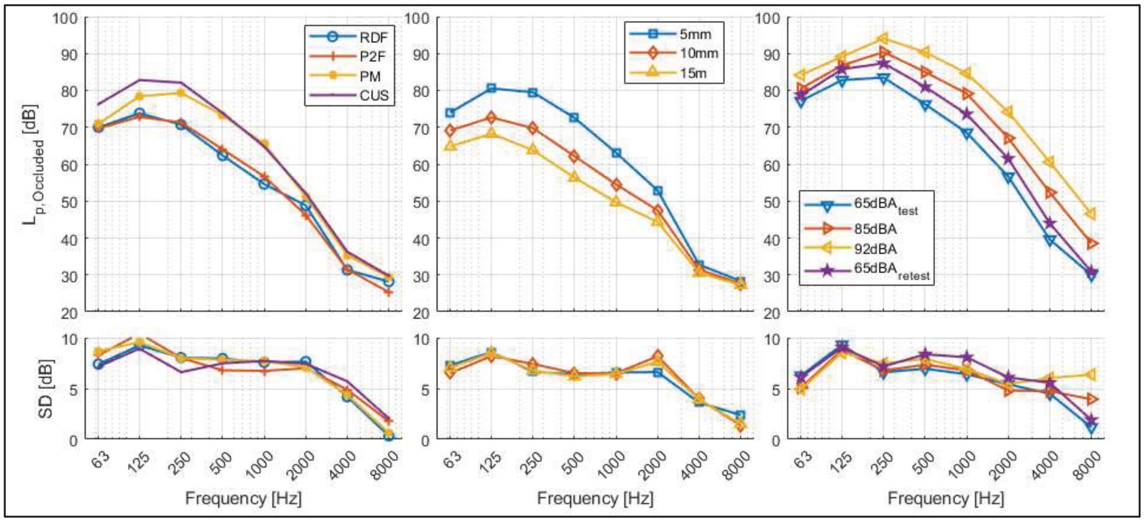



Figure 4.15 $L_{p,occluded}$ as a function of frequency and configuration tested during the C2 campaign, regrouped per testing phase. In the left-hand side column, the comparison of earplug models (Roll-down foam (RDF), Push-to-fit (P2F), Premolded (PM), Custom (CUS)), all tested with a 10 mm insertion depth. In the middle column, the comparison of insertion depths (5mm, 10mm, 15mm). In the right-hand side column, the comparison of background noise levels (65 $dBA_{test}$, 85 dBA, 92 dBA, 65 $dBA_{retest}$). Values averaged across all participants are shown in the top panels while the standard deviations are shown in the bottom panels

From the results of the earplug comparison phase, it is observed that $OE_{obj}^{NR}$ amplitudes are grouped into two categories: roll-down foam & push-to-fit earplugs, which generate less OE than the premolded & custom earplugs. Since $OE_{obj}^{NR}$ is calculated from the SPL measured on either side of the earplug (as explained in Section 3.1.5), this result is attributed to the higher $L_{p,occluded}$ measured inside the earcanal with silicone earplugs compared to those made of foam, as the SPL measured outside the earcanal remain independent of the earplug tested for a given participant. Indeed, several studies have demonstrated that silicone leads to more OE due to material properties (i.e., Poisson ratio (Kévin Carillo et al., 2021)), which can be explained by the greater $L_{p,occluded}$ induced within the earcanal (as explained in Section 1.4.2.2). However, these amplitudes are frequency dependent; the $OE_{obj}^{NR}$ induced by the premolded and custom earplugs is 5 dB to 10 dB higher than that of roll-down foam or push-to-fit earplugs in the low- and mid frequencies (except at 63 Hz), but the gap between the two groups decreases at higher frequencies. Additionally, the highest $OE_{obj}^{NR}$ measured, across all configurations tested, was with the custom earplug, both in terms of peak value and over the entire frequency range. This is attributed to four factors, namely:

i. the silicone material composing the earplug, as discussed above;

ii. the significantly higher weight compared to the other earplugs (i.e., influence of earplug weight, as discussed in Section 1.4.2.2);

iii. the probable shallower insertion observed with some participants, particularly for those with highly tortuous earcanals, for whom the shorter length of the earplug resulted in a reduced insertion depth (i.e., influence of insertion depth, as discussed in Section 1.4.7.1);

iv. the greater vibrational energy transferred to the earplug, as it was in contact with a larger surface area of the cartilaginous portion of the outer ear (i.e., in contact with the entire concha due to its design and manufacturing).

However, despite the significantly higher $\mathrm{OE}_{\mathrm{obj}}^{\mathrm{NR}}$ amplitude observed with the custom earplug compared to other models, this difference does not result in significantly greater discomfort. As illustrated in Figure 4.11 (Section 4.3.3), the distribution of $\mathrm{OE}_{\mathrm{exp}}$ scores for the custom earplug shows that participants experienced slightly more discomfort, but this difference was not statistically significant, as demonstrated by the analyses presented in Section 4.3.6. Finally, it is observed that the push-to-fit earplug exhibits the highest variability. This result is not surprising given its shape (a hemispherical earplug with a rigid plastic stem), which made it particularly difficult to position. The earplug was challenging to insert in smaller earcanals, while in larger canals, it tended to "float" rather than fit securely. The greater variability observed with the push-to-fit earplug is therefore attributed to difficulties in achieving a proper and consistent fit.

From the results of the insertion depth comparison phase, it is observed that the measured $\mathrm{OE}_{\mathrm{obj}}^{\mathrm{NR}}$ amplitudes are consistent with findings in the literature, confirming that the OE decreases with increasing insertion depth. As with earplug models, the variations in $\mathrm{OE}_{\mathrm{obj}}^{\mathrm{NR}}$ amplitude can be explained by changes in $L_{p,occluded}$. Specifically, differences of 5 dB to 10 dB in $L_{p,occluded}$ (and consequently in $\mathrm{OE}_{\mathrm{obj}}^{\mathrm{NR}}$) are observed for every 5 mm increase in insertion depth. In terms of variability, the standard deviations are similar across all three insertion depths tested. Finally, these variations in $\mathrm{OE}_{\mathrm{obj}}^{\mathrm{NR}}$ are well reflected in changes in the $OE_{exp}$. As shown in Figure 4.12 (Section 4.3.3), the discomfort experienced by participants decreased as insertion depth increased.

From the results of the background noise level comparison phase, several observations can be made, but the most striking is the lower $\mathrm{OE}_{\mathrm{obj}}^{\mathrm{NR}}$ amplitude observed during tests conducted in the 85 dBA and 92 dBA noise, compared to those conducted in the 65 dBA noise (i.e., test and retest). While these results cannot be directly compared to previous studies due to the lack of available data in the literature, they were nonetheless expected. These observations are consistent with the way $\mathrm{OE}_{\mathrm{obj}}^{\mathrm{NR}}$ is measured, which is based on the difference between the level measured in the occluded earcanal and the level measured outside the earcanal (or inside the open one when using the standard or real time methods).

More specifically, the decrease in $\mathrm{OE}_{\mathrm{obj}}^{\mathrm{NR}}$ with increasing background noise level can be explained by analyzing the contributions to the noise levels measured inside and outside the earcanal. For measurements outside the earcanal, the relative contribution of the voice is increasingly dominated by that of the background noise as its level rises. This occurs because participants are unable to produce a vocal effort that generates a sound level as high as that of the external noise source, as evidenced by the drop in SNR with increasing background noise levels, despite the observed increase in vocal effort (see Table 4.2 in Section 4.3.2). Regarding the noise level measured inside the earcanal, the voice's BC contribution is outweighed by the combined AC contributions of both the voice and the background noise, which are not fully attenuated by the earplug—particularly in the low frequencies where attenuation is limited (see Section 4.4.1.2). Therefore, these findings underscore a key limitation: the current NR-based

$OE_{obj}$ indicator is inapplicable for measurements conducted in high background noise environments.

Interestingly, the behavior of $OE_{obj}^{NR}$ in response to increasing background noise is opposite to that of $OE_{exp}$. More precisely, its amplitude decreases as background noise increases, whereas $OE_{exp}$ tends to increase (i.e., discomfort worsens) under the same conditions, as illustrated by the distribution shown in Figure 4.13 (Section 4.3.3). Thus, $OE_{obj}^{NR}$ is not an appropriate indicator for the objectivization of the OE when different background noise levels are tested.

Then, $L_{p,occluded}$ data provide an alternative way to visualize the variation in vocal effort between the two tests conducted at 65 dBA (i.e., test and retest). Despite identical conditions (same earplug, same fit, same noise level tested), $L_{p,occluded}$ measured during the retest is typically 2 dB to 4 dB higher compared to the initial test. These results support the hypothesis proposed in Section 4.3.5, suggesting that the slight variation in discomfort (even if not statistically significant) observed between the 65 $dBA_{test}$ and 65 $dBA_{retest}$ noises is due to a variation in vocal effort.

Finally, similar variability is observed in both $OE_{obj}^{NR}$ and Lp,occluded across the four background noise levels tested.

#### 4.4.1.2 Overview of NR data

The data presented in Figure 4.16 show the measured attenuation for the different configurations tested across the three measurement phases.

From the results of the earplug comparison phase, the NR measured for roll-down foam, push-to-fit, and custom earplugs is similar, with the best attenuation observed with the roll-down foam earplug. While these earplugs may be difficult to insert in field conditions by the user, the roll-down foam earplugs were compressed using a Blockwise Model RSS manual crimper (Blockwise LLC, USA) to ensure uniform and reproducible compression while also facilitating their insertion by the experimenter in the context of this study. Conversely, the worst attenuation was measured with the premolded earplug, due to its incompatibility with the morphology of many participants' earcanals. Despite its flanges designed to conform to the earcanal shape, its length and conical shape made it difficult to insert properly in participants with small or tortuous earcanals. Meanwhile, although the push-to-fit earplug was challenging to insert for some participants (as explained in Section 4.4.1.1), it still provided good attenuation. Finally, the similar standard deviations across all earplugs indicate that attenuation variability is of the same order for all earplug models.

From the results of the insertion depth comparison phase, it is observed that NR increases with increasing insertion depth. While this result is well-documented in the literature, the findings confirm that attenuation is greater with deep insertion compared to shallow insertion. In this study, differences of up to nearly 20 dB were measured when comparing the shallow and deep insertions. Although results from both studies cannot be compared directly, the attenuation measured objectively (using microphones) in this study aligns with findings from Berger (2013), who were obtained using a subjective method, namely the Real-Ear attenuation at Threshold (REAT). Finally, the three tested insertion depths resulted in similar variability.
From the results of the background noise level comparison phase, it is important to note that all four noise conditions were tested with a single earplug fit, and that the noise used for attenuation measurement (i.e., broadband white noise) was different from the noise used in the tests (i.e., industrial noise). As a result, a single attenuation curve is displayed for the four background noise levels tested. However, since most participants tested the custom earplugs, it is normal to observe that the attenuation curve is similar to the one measured during the comparison of earplug models, shown in the left-hand side panels of Figure 4.16.

With the data from all four indicators now presented, the next section focuses on objectifying $OE_{exp}$ using these objective indicators.

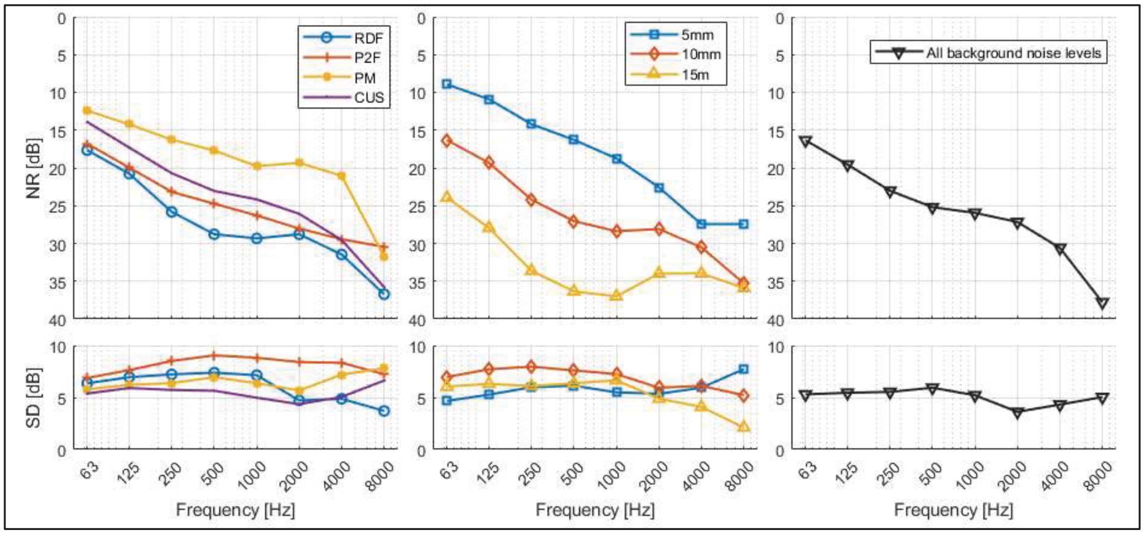



Figure 4.16 NR as a function of frequency and configuration tested during the C2 campaign, regrouped per testing phase. In the left-hand side column, the comparison of earplug models (Roll-down foam (RDF), Push-to-fit (P2F), Premolded (PM), Custom (CUS)). In the middle column, the comparison of insertion depths (5mm, 10mm, 15mm). In the right-hand side column, a single attenuation curve is shown as earplugs were fitted once; thus the NR is the same for all four background noise levels tested, namely 65 $dBA_{test}$, 85 dBA, 92 dBA, 65 $dBA_{retest}$. Values averaged across all participants are shown in the top panels while the standard deviations are shown in the bottom panels

### 4.4.2 Predicting $OE_{exp}$ using objective indicators

The development of the first model was based on the indicators presented in Section 3.3.9 (i.e., NR, $L_{p,occluded}$, $L_{p,ref\ BNL+Speech}$), although $OE_{obj}^{NR}$ was excluded as it is redundant with $L_{p,occluded}$ (explained in more detail below). The objectivization of the $OE_{exp}$ was carried out using an iterative approach divided into two steps, as explained in Section 3.3.10.3. The first step aims to identify the broadband indicators (i.e., VLF, LF, MF and HF, described in Section 3.3.9) correlated to the $OE_{exp}$ as to reduce the number of variables to assess during the iterative approach. Then, the second step aims to identify the frequency band indicators correlated to the $OE_{exp}$ by decomposing the significant broadband indicators identified into those who compose it (e.g., $L_{p,occluded\ MF}$ was decomposed into $L_{p,occluded\ 1000Hz}$ and $L_{p,occluded\ 2000Hz}$).

The use of $OE_{obj}^{NR}$ was omitted from the objectivization analysis, as it is redundant with $L_{p,occluded}$, given that the two indicators are correlated and $OE_{obj}^{NR}$ includes $L_{p,occluded}$ in its calculation. This explains the similar trends observed across the parameters investigated (i.e., earplug model, insertion depth, and background noise level) discussed in Section 4.4.1.1. Moreover, the choice of $L_{p,occluded}$ over $OE_{obj}^{NR}$ is also based on its greater robustness across the different conditions tested. Specifically, $L_{p,occluded}$ enables the measurement of amplitude variations across different background noise levels because it depends solely on the level measured in the occluded ear. In contrast, $OE_{obj}^{NR}$ tends to decrease with increasing background noise due to its mathematical construction (as explained in Section 4.1.4), and therefore behaves inversely to the $OE_{exp}$, which increases with increasing background noise. Hence, $L_{p,occluded}$ is preferred for the objectivization of the $OE_{exp}$ presented in this section and in Section 4.4.3.

Data from measurements conducted during the three comparison phases were used for the analyses (i.e., N = 344 valid samples). Following the first step of the iterative approach using the broadband indicators (NR, $L_{p,occluded}$), only $L_{p,occluded\ VLF}$ was identified as significant. For the second step of the iterative approach, $L_{p,occluded\ VLF}$ is decomposed in the two indicators that composes it (i.e., $L_{p,occluded\ 63Hz}$ and $L_{p,occluded\ 125Hz}$). Additionally, $L_{p,ref\ BNL+Speech}$ was introduced during the second iterative step to determine if the ambient noise could contribute to the discomfort. At the end of the second iterative procedure, the optimal MLM, selected based on the AIC, combined two significant indicators, namely the occluded noise level in the 125 Hz octave band ($L_{p,occluded\ 125Hz}$) and the ambient noise level ($L_{p,ref\ BNL+Speech}$). The equation of the model is given by Eq. (4.2) and the equation with normalized variables (to better understand the weight of each variable) is given by Eq. (4.3).

$$OE_{exp,predicted} = 0.943 + 0.029 \times L_{p,occluded\ 125Hz} + 0.024 \times L_{p,ref\ BNL+Speech} \tag{4.2}$$

$$OE_{exp,predicted} = 4.489 + 0.372 \times L_{p,occluded\ 125Hz(normalized)} + 0.304 \times L_{p,ref\ BNL+Speech(normalized)} \tag{4.3}$$

According to the equations above, the positive beta estimates of both variables indicate that an increase in either $L_{p,occluded\ 125Hz}$ or $L_{p,ref\ BNL+Speech}$ leads to a greater discomfort. When considering the normalized beta-estimates to assess their relative influence on the $OE_{exp}$, both indicators have a similar impact on the discomfort given their similar magnitude (i.e., 0.372 for $L_{p,occluded\ 125Hz}$ vs. 0.304 for $L_{p,ref\ BNL+Speech}$). In order to evaluate the model's predictive performance, the correlation between observed and predicted values as well as the distribution of model residuals are presented in Figure 4.17. These results are discussed in greater detail below.

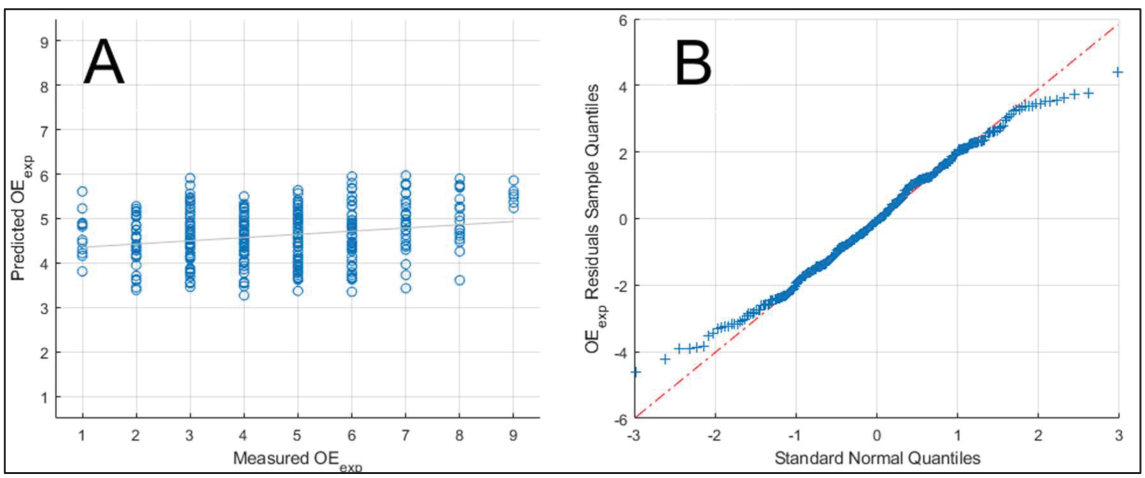



Figure 4.17 (A) Correlation between the predicted $OE_{exp}$ (y-axis) and the measured $OE_{exp}$ (x-axis) using objective indicators only, namely $L_{p,occluded\ 125Hz}$. and $L_{p,ref\ BNL+Speech}$. (B) Distribution of the model's residuals on the quartile-quartile plot (QQ plot)

The model derived from the iterative analyses highlights that the $OE_{exp}$ depends both on the occluded noise level under the protector and on the ambient noise level in which the HPD user is situated. Regarding $L_{p,occluded\ 125\ Hz}$, this result is not surprising, as its amplitude is typically highest at low frequencies, as shown in Figure 4.15. This finding supports the hypothesis that discomfort may, in part, result from the amplification of the low-frequency bone-conducted component of one's own voice, leading to a perception of distortion. Since $L_{p,occluded\ 125Hz}$ is correlated with the $OE_{obj}$ (as it contributes directly to its calculation and similar trends have been observed for both indicators in Section 4.4.1.1), this result is consistent with previous studies that have demonstrated various degrees of correlation between low-frequency $OE_{obj}$ and $OE_{exp}$ (as discussed in Section 1.3).

Furthermore, the second significant variable in the model is $L_{p,ref\,BNL+Speech}$, highlighting that the acoustic environment in which an HPD user is situated influences the $OE_{exp}$. To the author's knowledge, this is the first time ambient noise level has been identified as a contributing factor to OE-related discomfort. This result supports the second hypothesis proposed in Section 3.3.7.5, which suggests that the influence of ambient noise on the $OE_{exp}$ may stem from changes in speech production. Specifically, when in a noisy environment, individuals must increase their vocal effort in order to be understood by others. As explained in Section 1.4.3.1, this increase in vocal effort leads to a stronger BC component of the voice, which in turn raises the occluded acoustic pressure beneath the hearing protector—thereby contributing to increased discomfort.

Unfortunately, an inspection of Figure 4.17 suggests that the results must be interpreted with caution, as the optimal model identified through the iterative MLM approach does not predict an $OE_{exp}$ representative of the measured values. First, the scatter plot comparing measured and predicted $OE_{exp}$ values clearly indicates that the model fails to predict the response amplitude of participants. While $OE_{exp}$ scores are mostly concentrated near the center of the scale (i.e., average $OE_{exp}$ score over the data set used = 4.6, SD = 1.9), scores assigned by participants nevertheless range from the minimum to the maximum of the scale (i.e., scores ranging from 1 to 9). In contrast, the model only produces predicted $OE_{exp}$ scores within a much narrower range, between 3.3 and 6.0, which explains the narrow and vertical shape of the scatter plot presented in the left-hand side panel of Figure 4.17. Additionally, an analysis of the correlation between measured and predicted $OE_{exp}$ scores using Pearson's coefficient confirms this issue. The results indicate a very weak correlation, with $r^2 \approx 0.05$ ($r = 0.23$, $p < 0.05$), which suggests that the model has very little predictive power.

Next, an overview of the model residuals, presented in the right-hand side panel of Figure 4.17, suggests they follow a normal distribution as the residuals plotted on the QQ plot are fairly well aligned with the reference line (i.e., representing a normal distribution), with slight deviations at the tails. However, conducting a Shapiro-Wilk test on the model's residuals indicates that they do not come from a normal distribution. Thus, the non-normally distributed residuals indicate that the model fails to capture important features of the data, potentially leading to biased estimates, and ultimately to a poor predictive power.

However, the poor performance of the model is not surprising given the $OE_{exp}$ data. More specifically, despite testing various configurations (i.e., different earplug models, insertion depths, and background noise levels), which led to significant variations in objective indicators, the variations in discomfort ratings remained relatively small. This was particularly observed in Section 4.3.6, where earplug model was not identified as an influential factor. Additionally, although insertion depth and background noise level were both found to have a significant influence, on average, discomfort differences did not exceed 3 points on the response scale on average (e.g., maximum score minus minimum score when testing insertion depths), although a difference of up to 8 points was possible. Thus, the difficulty in developing a model to objectivize the $OE_{exp}$ based solely on objective indicators is partially attributed to the limited range of discomfort assessed.

An alternative approach would have been to develop the objectivization model using a more restricted data set, selecting only the configurations that induced the largest variations in discomfort (e.g., using only data from the insertion depth and background noise level comparison phases). However, in this study, all available data were considered, as the goal was to explore the objectivization of the $OE_{exp}$ using the MLMs given that no previous studies have conducted similar work, while also increasing statistical power by utilizing a larger sample size. Nonetheless, additional analyses using the data gathered during this study could potentially lead to an improved objectivization model compared to the one presented here.

### 4.4.3 Predicting $OE_{exp}$ using objective indicators and the person-environment-HPD triad's characteristics

The second model developed to objectivize the $OE_{exp}$ combines the objective indicators identified in Section 4.4.2 with the influential characteristics of the environment-person-HPD triad (identified in Section 4.3.7). In total, 7 variables are combined in an MLM and analyzed using the iterative procedure, namely $L_{p,occluded\ 125Hz}$, $L_{p,ref\ BNL+Speech}$, $HL_{250Hz\ (AC)}$, $HL_{500Hz\ (AC)}$, $HL_{1000Hz\ (AC)}$, $IR_{SB}$ and $XPMTR_{Known}$. Although the iterative procedure was applied in an attempt to eliminate non-significant variables, no variables were eliminated from the initial model since it provides the best performance (based on the AIC). However, it can be noted that in this model, the second bend's isoperimetric ratio ($IR_{SB}$) is not significant (in contrast to the global model presented in Section 4.3.7). Nonetheless, the variable is kept within the model when computing the predicted $OE_{exp}$. The equation of the model is given by Eq. (4.4) and the equation with normalized variables is given by Eq. (4.5).

$$OE_{exp,predicted} = -1.346 + 0.032 \times L_{p,occluded\ 125Hz} + 0.024 \times L_{p,ref\ BNL+Speech} - 0.115 * HL_{250Hz\ (AC)} + 0.228 * HL_{500Hz\ (AC)} - 0.166 * HL_{1000Hz\ (AC)} + 1.617 * IR_{SB} + 1.237 * XPMTR_{Known} \tag{4.4}$$

$$OE_{exp,predicted\ (norm.)} = 4.093 + 0.404 \times L_{p,occluded\ 125Hz(norm.)} + 0.308 \times L_{p,ref\ BNL+Speech(norm.)} - 0.450 \times HL_{250Hz\ (AC)(norm.)} + 1.051 \times HL_{500Hz\ (AC)(norm.)} - 0.873 \times HL_{1000Hz\ (AC)(norm.)} + 0.103 \times IR_{SB\ (norm.)} + 1.237 \times XPMTR_{Known} \tag{4.5}$$

The performance of this model is assessed through the correlation between measured and predicted values and the distribution of model residuals, as presented in Figure 4.18. These results are discussed in greater detail below.

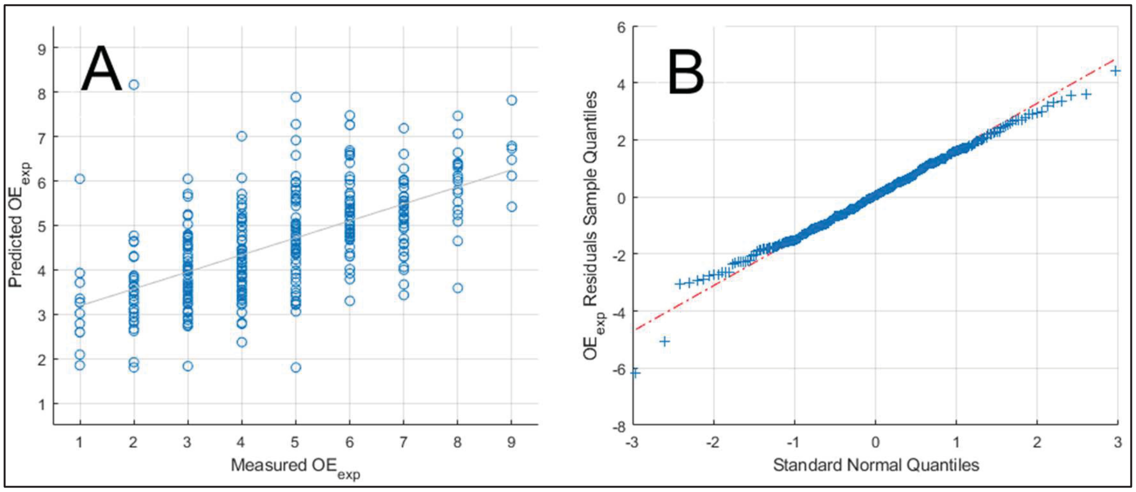



Figure 4.18 (A) Correlation between the predicted $OE_{exp}$ (y-axis) and the measured $OE_{exp}$ (x-axis). using objective indicators and influential triad characteristics (B) Residuals of the model predicting the $OE_{exp}$ based on $L_{p,occluded\ 125\ Hz}$ and $L_{p,ref\ BNL+Speech}$ displayed on the quartile-quartile (QQ) plot

Based on the two equations of the model, the influence of each variable aligns with previous results. Specifically, the direction of influence (as indicated by the sign of the beta estimates) remains consistent with previous models (i.e., triad's global model and the first objectivization model). In terms of relative influence (determined by the magnitude of the normalized beta estimates), the ranking of the variables in descending order of influence is as follows:

- Participant acquainted with the experimenter experienced more discomfort.
- Hearing loss in the 500 Hz octave band increases discomfort;
- Hearing acuity in the 1000 Hz octave band increases discomfort;
- Hearing acuity in the 250 Hz octave band increases discomfort;
- Occluded noise level in the 125 octave band increases discomfort;
- Ambient noise leads to more discomfort;

- Participants with non-circular earcanal at the 2nd bend experience more discomfort, albeit the influence is not statistically significant.

It is observed that the triad variables are the strongest contributors to discomfort, while the objective indicators play a secondary role. Specifically, the participant's prior acquaintance with the experimenter ($XPMTR_{Known}$) remains the most influential variable, supporting the "good participant effect" hypothesis, as explained in Section 4.3.4. Next, hearing loss in the 500 Hz, 1000 Hz and 250 Hz octave bands remains highly influential, though in opposing directions, making the interpretation challenging, as previously discussed. Following this, $L_{p,occluded}$ in the 125 Hz octave band ranks fifth in relative influence. Notably, as in the first objectivization model that included only objective indicators, $L_{p,occluded\ 125\ Hz}$ remains slightly more influential than $L_{p,ref\ BNL+Speech}$. Finally, $IR_{SB}$ is not found to be statistically significant although it remains part of the equation as it improves the model's strength based on the AIC. Compared to the first objectivization model, which relied solely on objective indicators, this more comprehensive model, incorporating the triad's influential characteristics, allows for better prediction of the $OE_{exp}$, although some discrepancies remain. The scatter plot in the left panel of Figure 4.18 reveals a noticeable correlation between measured and predicted $OE_{exp}$ values. Indeed, the Pearson correlation coefficient indicates a $r^2 = 0.37$ ($r = 0.61$, p-value $< 0.05$). While this model does not predict $OE_{exp}$ with high precision, it still captures the main trends. Additionally, it achieves a much broader range of predicted $OE_{exp}$ amplitudes compared to the first model, with predicted scores ranging from 1.8 to 8.2. However, despite this significant improvement, the predictive power of the model remains moderate, as many predicted values still exhibit considerable deviations from the measured values. Yet, considering the subjective nature of the data (i.e., degree of discomfort experienced towards the OE), this model yields interesting results.

Furthermore, an overview of the model residuals, presented in the right-hand side panel of Figure 4.18, indicates that the residuals follow a normal distribution, as evidenced by the alignment of points along the reference line. This result is further confirmed by the non-significance of the Shapiro-Wilk test (not shown here). Thus, unlike the first model, this enhanced model not only provides greater predictive power but is also statistically valid in terms of residual distribution.

All in all, the second objectivization model presented in this section allows for a moderate level of prediction of the $OE_{exp}$ induced by the various configurations tested in campaign C2. Moreover, this model highlights the significant role that psychosocial and physical characteristics of the user have in the context of laboratory measurements, suggesting that these factors may have a greater influence than initially assumed.

### 4.4.4 Synthesis

To summarize, several objective indicators measured during campaign C2 were presented and analyzed to develop two objectivization models for the $OE_{exp}$, namely a first model based solely on objective indicators, and a second model incorporating both objective indicators and the significant triad characteristics identified in Section 4.3.7.

An inspection of the four objective indicators revealed significant amplitude variations for $OE_{obj}^{NR}$, NR, and $L_{p,occluded}$. Some of these variations align with findings in the literature, particularly the dependence of the three indicators on earplug model and insertion depth. However, the results concerning background noise levels are novel, as no similar data are available. More specifically, the analysis of $OE_{obj}^{NR}$ and $L_{p,occluded}$ data raises important questions regarding OE-related discomfort, particularly the low $OE_{obj}^{NR}$ amplitude at low frequencies in the presence of high background noise levels, despite the high discomfort ratings associated with these conditions.

Following the iterative procedure using MLMs, the first $OE_{exp}$ objectivization model was developed using $L_{p,occluded\ 125Hz}$ and $L_{p,ref\ BNL+Speech}$. The inclusion of $L_{p,occluded\ 125Hz}$ is consistent with previous studies on the correlation between the $OE_{obj}$ and $OE_{exp}$. However, the identification of $L_{p,ref\ BNL+Speech}$ was an unexpected result, suggesting that the noise in which an

HPD user contributes significantly to discomfort. This could possibly be explained by the changes in speech production due to the elevated vocal effort required to overcome ambient noise. Despite these findings, the model's predictive power is limited due to statistical validity concerns, including low prediction accuracy and non-normally distributed residuals. Therefore, further analyses are needed to improve the objectivization of the $OE_{exp}$ based solely on objective indicators.

Finally, using the same iterative procedure, a second $OE_{exp}$ objectivization model was developed, incorporating the two objective indicators from the first model ($L_{p,occluded\ 125Hz}$ and $L_{p,ref\ BNL+Speech}$) along with significant characteristics from the global model of the environment-person-HPD triad. Unlike the first model, this enhanced model provides better $OE_{exp}$ predictions while also being statistically valid. Additionally, it highlights the influence of physical and psychosocial user characteristics in comparison to objective indicators.

# CONCLUSION

This doctoral thesis is a continuation of the research conducted within the ICAR laboratory, focusing on the evaluation and understanding of comfort associated with HPDs. More specifically, its primary objective was to gain a better understanding of the OE induced by earplug-type HPDs during speech production. To achieve this, two measurement campaigns involving a total of 63 human participants were conducted to measure, using microphones and questionnaires, the OE induced by various earplugs tested in various conditions.

This chapter concludes the thesis by summarizing the research problematic in Section 5.1 and the main findings in relation to the research questions and specific objectives in Sections 5.2 to 5.5. Finally, the scientific contributions are presented in Section 5.6, followed by the main limitations and perspectives for future research outlined in Section 5.7.

## 5.1 Research problematic

To reduce the risk of hazardous noise exposure, hearing protection devices (HPDs) are commonly used by workers as a last line of defense against noise. However, the use of HPDs often results in discomfort, which can lead to incorrect use or even removal, thereby significantly reducing their effectiveness. One such discomfort related to the acoustical dimension of the comfort model is the experienced occlusion effect ($OE_{exp}$), typically described as a distortion in one's own voice that makes it sound "hollow", "boomy", or "like talking in a barrel". Alternatively, the objective occlusion effect ($OE_{obj}$) has been widely investigated using microphones to measure the increased acoustic pressure inside the occluded earcanal caused by bone-conducted (BC) sound transmitted to the outer ear. Despite extensive investigation of both $OE_{exp}$ and $OE_{obj}$ in the context of HPDs, the discomfort associated with the OE remains poorly understood, hard to describe and difficult to characterize. Moreover, the lack of consensus and standardization regarding the measurement of the $OE_{obj}$ and the evaluation of $OE_{exp}$ renders research on the phenomenon both laborious and time-consuming.

Finally, as the correlation between the $OE_{obj}$ and $OE_{exp}$ has yet to be clearly established, research in this area remains dependent on human subject participation.

In response to these challenges, the research conducted in this doctoral thesis aimed to enhance our understanding of occlusion effect discomforts induced by earplugs during speech production, through an experimental study with human participants under controlled laboratory conditions. This objective was pursued through three specific sub-objectives. The first aimed to propose a simple yet robust methodology for measuring the $OE_{obj}$ using speech-based microphone measurements. The second sought to identify the physical and psychosocial characteristics of the environment-person-HPD triad that influence the $OE_{exp}$. Finally, the third aimed to objectivize the $OE_{exp}$. The findings from this doctoral research were presented at several international conferences and published in a peer-reviewed journal, and are summarized in the following sections.

## 5.2 Measuring the objective occlusion effect

A first measurement campaign was conducted in laboratory conditions with 30 participants to measure the $OE_{obj}$ under various conditions, with the aim of proposing a simple and robust measurement method. During this campaign, a single HPD model was tested across several conditions to compare different excitation sources commonly used in the literature to induce the OE (i.e., speech, mastication, bone oscillator). Additionally, the $OE_{obj}$ was measured using multiple measurement methods (i.e., standard, real-time, NR-based) to identify the advantages and limitations of each. Finally, various single-value indicators (i.e., mean, frequency band, maximum) were compared to determine the most suitable metric for quantifying the $OE_{obj}$. Although this campaign focused primarily on objective measurements, the OE was also assessed through pure-tone bone conduction audiometry to determine the hearing threshold shift (i.e., $OE_{subj}$), a subjective method commonly referred to as the "gold standard" for evaluating HPD-induced OE.

The proposed method for measuring the $OE_{obj}$ involves a speech-based approach combined with the NR-based measurement method. Speech offers a simple and reproducible means of inducing the OE. Compared to BC excitation sources, speech presents the advantage of being usable in non-silent environments, does not require specialized equipment, and more importantly, is more representative of what can be found in day-to-day operations in the workplace. Regarding the measurement method, each of the three approaches presents specific advantages and limitations. However, the NR-based method allows for the independent measurement of the $OE_{obj}$ (referred to as $OE_{obj}^{NR}$) in each ear using a single measurement, thus saving time and reducing variability introduced by excitation sources that are difficult to reproduce. Finally, the comparison of various single-value indicators revealed that similar trends were observed regardless of the indicator used. Nonetheless, mean-based indicators reduced variability compared to others. Despite this, frequency-based indicators remain the most precise, as they offer the greatest depth of information for understanding how the phenomenon fluctuates under changes in parameters such as the excitation source or the measurement method.

## 5.3 Influential characteristics of the environment-person-HPD triad

A second measurement campaign was conducted under laboratory conditions with 33 participants to investigate the influence of the environment–person-HPD triad characteristics on the experienced occlusion effect $OE_{exp}$. Numerous psychosocial characteristics of the participants (e.g., age, familiarity with HPD use) were collected through a questionnaire. Morphological characteristics of different sections of the earcanal were assessed using a method developed by Poissenot-Arrigoni et al. (2022), which enabled the extraction of several earcanal morphological characteristics (e.g., length, circumference, various ratios) from 3D scans of earcanal impressions. Characteristics related to the HPDs (e.g., earplug type) and to the acoustic environment (e.g., background noise level) were also examined. One interactional characteristic between the user and the HPD—the insertion depth of the earplug—was additionally investigated. During testing, participants evaluated 11 different configurations, allowing for the assessment of the $OE_{exp}$ induced by four earplug types, three insertion depths, and three ambient noise levels, one of which was tested twice. After each configuration, participants rated the OE they experienced using a monopolar response scale ranging from 1 to 9, corresponding to "Very low $OE_{exp}$" to "Very high $OE_{exp}$". The identification of the triad's influential characteristics and the evaluation of their relative impact on the $OE_{exp}$ were carried out using a statistical approach based on an iterative mixed linear models (MLMs) analysis. This iterative approach first identified the influential characteristics within each triad component using "preliminary" models and then integrated them into a "global" model that simultaneously considered all three components. Several characteristics were identified as influential, though their relative effects varied in magnitude and direction. The main findings of the analyses are described below.

Participants who were acquainted with the experimenter reported higher levels of discomfort compared to those who were not. This represents a novel observation in the context of the OE, although it aligns with the established "good participant" or "participant demand" effect. In terms of user morphology, participants with a non-circular earcanal at the second bend experienced higher levels of discomfort. Additionally, hearing loss in the 250, 500, and 1000 Hz octave bands was found to influence perceived discomfort, albeit to a lesser extent than the previously mentioned characteristics. However, the directionality of this influence is difficult to interpret, as hearing loss in the 250 Hz and 500 Hz bands increased discomfort, whereas hearing loss at 1000 Hz reduced it. Only one HPD-related characteristic—the specific earplug model tested—was investigated. Although additional variables such as earplugs' weight and material were measured and initially considered, the high number of characteristics relative to the sample size introduced redundancy issues in the statistical models. In the end, the earplug model was not identified as influential on the $OE_{exp}$.

Background noise level was found to significantly influence the $OE_{exp}$. More specifically, discomfort increased with higher background noise levels, likely due to the participants' need to speak more loudly to be understood in noisy environments. It is hypothesized that this increased discomfort results from elevated sound pressure levels within the occluded earcanal, caused by the increased vocal effort required to overcome background noise.

Finally, insertion depth was also found to significantly influence the $OE_{exp}$, with deeper insertions leading to less discomfort. Although this result is consistent with previous findings, the effect was only significant in cases of large variations in insertion depth (i.e., shallow vs. deep insertion).

## 5.4 Objectivization of the occlusion effect

During the second measurement campaign, microphonic measurements were also carried out using the method previously proposed following the first campaign—that is, measuring the $OE_{obj}$ induced by speech and based on simultaneous measurements inside- and outside each earcanal. From these measurements, various indicators were extracted and calculated to be correlated with the $OE_{exp}$ scores obtained for each of the 11 tested configurations. These indicators allowed to quantify the amplitude of $OE_{obj}$ measured using the NR-based method (i.e., $OE_{obj}^{NR}$), the noise reduction provided by the earplug tested (i.e., NR), the occluded sound pressure level underneath the earplug (i.e., $L_{p,occluded}$), and the noise inside the audiometric booth during testing, originating from the background noise and the participant's speech (i.e., $L_{p,ref\ BNL+Speech}$).

The analysis of these indicators confirmed trends previously observed in the literature, particularly with regard to the variation of $OE_{obj}^{NR}$, NR, and $L_{p,occluded}$ depending on the earplug type and insertion depth. Data analysis also confirmed the sensitivity of the $OE_{obj}^{NR}$ indicator to noisy environments, as its value dropped significantly with increasing background noise levels due to its mathematical construction. In contrast, the $L_{p,occluded}$ indicator proved to be suitable for measurements in both silent and noisy environments. When considering that increasing background noise levels leads to greater discomfort and that both indicators are strongly correlated, $L_{p,occluded}$ was preferred for the objectivization of the $OE_{exp}$.

Subsequently, objective indicators correlated with $OE_{exp}$ were identified using the same iterative statistical approach based on MLMs. This approach was used to develop two models aimed at objectifying $OE_{exp}$: a first “preliminary” model based solely on the three objective indicators (i.e., NR, $L_{p,occluded}$, $L_{p,ref\ BNL+Speech}$), followed by a second “global” model combining these objective indicators with the triad characteristics previously identified as influential.

From the analyses of the first model, two objective indicators were identified: $L_{p,occluded\ 125Hz}$ and $L_{p,ref\ BNL+Speech}$. While $L_{p,occluded\ 125Hz}$ is consistent with prior studies on the correlation between $OE_{obj}$ and $OE_{exp}$, the contribution of ambient noise level to the perceived discomfort highlights the role of the acoustic environment in shaping user experience—an influence likely due to speech production changes in noise. Although the model’s very low predictive power represents a clear limitation, its results nonetheless call into question the relevance of the traditionally used $OE_{obj}$ indicator when investigating user discomfort, pointing instead to the importance of the occluded sound pressure level beneath the HPD.

In the second model, both objective indicators ($L_{p,occluded\ 125Hz}$, $L_{p,ref\ BNL+Speech}$), along with the influential triad characteristics, were found to explain the $OE_{exp}$. However, based on their relative contributions, the model showed that the user-related characteristics of the triad had a much stronger influence on discomfort than the objective indicators. This finding is partly attributed to the limited range of discomfort generated by the various conditions tested across the C2 campaign. Hence, it remains difficult to objectivize the $OE_{exp}$ solely through objective indicators with the data collected. Moreover, while the second model demonstrates some improvement over the first, its predictive power remains low from a statistical standpoint.

Although the analyses conducted in this thesis did not yield models capable of accurately predicting OEexp, the importance of the occluded sound pressure level beneath the HPD was clearly demonstrated in relation to OE-associated discomfort—particularly in non-silent environments. While exploratory, these results raise several questions regarding the measurement of objective indicators correlated with $OE_{exp}$. They suggest that future studies should (1) not rely exclusively on $OE_{obj}$ metrics based on the difference in sound pressure with and without the HPD, as is typically done and (2) explore configurations that produce a wider range of discomfort, such as using passive (Kévin Carillo, Sgard, Dazel, & Doutres, 2025) or active earplugs specifically designed to mitigate the OEexp.

## 5.5 Formulation of questions about the experienced occlusion effect

A series of pretests involving 21 respondents was conducted to improve the questionnaire used in the second measurement campaign. This step was deemed necessary, as no French-language questionnaire specifically targeting the OEexp was available in the literature. More specifically, the pretests aimed to refine the wording of questions related to the $OE_{exp}$ and to identify appropriate instructions to be given to participants during the measurement sessions. They also sought to investigate the potential difference between evaluating discomfort (i.e., $OE_{exp}$) and the perception of the phenomena (i.e., $OE_{perc}$), as both formulations have been used in previous studies.

Following the pretests, no consensus emerged regarding the exact wording to use, as respondents associated different meanings with various terms, partly due to regional variations in spoken French. The use of the term "gêne" to describe discomfort was found to be appropriate and consistent with the questionnaire from another research project conducted within the laboratory. To minimize ambiguity, definitions and clarifications were provided to participants both before and during the tests and were also included in the questionnaire itself to support comprehension during completion. Ultimately, the pretests revealed that participants do distinguish between the $OE_{exp}$ and the $OE_{perc}$. While this distinction may be statistically negligible, it underscores the importance of careful question formulation to ensure that participants understand the intended meaning and that researchers measure the variable they actually aim to assess.

Although this investigation was carried out as part of a series of pretest, the results shed light on several critical aspects of administering a questionnaire related to the occlusion effect.

## 5.6 Scientific contributions

The work conducted in this doctoral thesis has contributed to advancing knowledge on the occlusion effect and to proposing methods for better measuring the $OE_{obj}$ and more accurately assessing the $OE_{exp}$ induced by HPDs. These scientific contributions are presented in greater detail below.

Based on the definitions proposed by Hansen, the different types of OE have been established and distinguished even further, helping reduce the ambiguity between the objective, subjective, experienced and perceived occlusion effect. Although these different OE concepts existed in previous work, they have all been measured, compared, and critically examined within the same research project. As a result, it is now easier to understand the advantages and limitations associated with measuring each type of OE. More specifically, the information gathered and the numerous analyses presented in this thesis will enable researchers to better understand the specificities and limitations related to the measurement of the different types of OE in future research.

Then, given the significant methodological differences observed in previous studies and the absence of consensus regarding the measurement of $OE_{obj}$, the research conducted in this thesis offers a simple and robust methodology. The analyses also provided deeper insight into the influence of excitation source, measurement method, and indicator on the measured $OE_{obj}$, as well as a quantification of the variability associated with each of these methodological aspects. Ultimately, the proposed method—based on speech and simultaneous measurement of $OE_{obj}^{NR}$—allows for a simple and reliable quantification of the $OE_{obj}$. As such, this method could be implemented in existing systems already used by occupational hygienists to assist them in helping workers choose the best-fitting HPD, such as the 3M E-A-RFit system. In doing so, the occlusion effect could be considered when choosing and fitting an HPD, in addition to sound attenuation, already assessed using indicators such as the PAR.

Moreover, the investigation of the influence of the environment–person–HPD triad characteristics conducted in this thesis highlights the most critical ones affecting discomfort and identifies those that warrant further examination in future studies. This work also underscores the importance of users' physical characteristics and provides insight into the need to develop measurement benches (e.g., artificial ears) that account for inter-individual variability in earcanal morphology.

Furthermore, the pretest conducted as part of the questionnaire design process contributed to the development of the first French-language tool for assessing OE-related discomfort and deepened the understanding of linguistic constraints associated with the phenomenon. In particular, it highlighted the complexity and ambiguity of describing the sensations it causes, as well as the challenges of word choice when accounting for regional variations in spoken French.

In conclusion, in addition to contributing to scientific advancement on the topic of OE, the results obtained from the work carried out in this thesis have already been applied within studies conducted in the ICAR laboratory. Indeed, the proposed objective measurement method, as well as the questionnaires on $OE_{exp}$ and $OE_{perc}$, have been used in work focusing on the development of meta-earplugs with reduced OE and the design of an acoustical test fixture for assessing the objective occlusion effect (Kévin Carillo, Sgard, Dazel, & Doutres, 2023; Kévin Carillo et al., 2025; Doutres et al., 2025)

## 5.7 Limitations and perspective

The main limitation of the findings presented in this thesis is that the measurement campaigns were conducted in a laboratory setting—that is, in a controlled environment that does not totally reflect real-world conditions. As such, the proposed objective method for measuring the OE was tested under laboratory conditions but must be validated in field settings to assess its potential integration into tools used by occupational hygienists (e.g., the E-A-RFit system for noise attenuation), with the aim of assisting workers in selecting and properly inserting earplug-type HPDs on site. Similarly, further field-based measurement campaigns specifically focused on the OE are necessary to determine whether the trends and findings related to comfort observed in the laboratory hold true in real-world contexts.

Then, certain methodological elements from both measurement campaigns also limit the scope of the results. The first concerns participant recruitment, which was limited to individuals with normal hearing. However, since hearing loss emerged as an influential characteristic, further investigation is necessary to better understand its impact on discomfort—particularly given that a significant proportion of workers (i.e., regular HPD users) develop occupational hearing loss over the course of their careers. Unfortunately, recruiting participants with hearing loss was not feasible within the context of this doctoral thesis due to the complexity of adequately representing the different types and severities of hearing impairment. The second methodological limitation relates to the earplugs used during testing. Although earplug type was not identified as an influential characteristic, it was not possible to assess the potential influence of earplug mechanical properties on discomfort. This is due to the number of variables describing an earplug (e.g., weight, dimensions, material, etc.) relative to the number of earplugs tested and participants recruited. However, it is well documented that these properties significantly influence the $OE_{obj}$. Additional measurements are therefore needed to further investigate these characteristics, particularly by evaluating discomfort induced by different earplugs within the same category (e.g., roll-down foam), but with varying mechanical properties. Finally, the third element concerns the challenges associated with evaluating OE-related discomfort. Results from the pretests on question formulation indicate that it remains difficult to clearly describe the phenomenon to individuals not previously exposed to the OE in a way that allows them to understand and accurately assess the discomfort being measured. This challenge stems in part from the fact that multiple types of discomfort may occur simultaneously when using an HPD (i.e., physical, psychological, or functional), and a person may struggle to distinguish between them if they are rarely exposed to such experiences (i.e., HPD-naïve participants). Additionally, this challenge also stems from the difficulty of properly distinguishing the perception of the phenomenon from the annoyance caused by it, as highlighted during these pretests.

Moreover, another limitation of this thesis lies in the current difficulty of describing participant naivety toward HPD use through measurable indicators. Although two characteristics partially reflecting this naivety were identified as influential (i.e., use of HPDs (UseHPD) and being trained for their use (TrainHPD)), several other indicators were collected through the questionnaire, such as use in personal or professional contexts, number of years of experience, and weekly usage hours. However, these indicators could not be interpreted due to statistical convergence issues encountered during the analyses. As a result, several questions related to the influence of user naivety remain unanswered, such as:

- Does the context of use (i.e., recreational vs. professional) impact the level of perceived discomfort?

- How should experience be quantified: in terms of years or total hours of use? How can we compare the naivety of an individual who has accumulated 25 hours of use over 2 years to someone with 20,000 hours over a 20-year period?

- If the degree of naivety is to be categorized (i.e., low, moderate, high), on what criteria should these categories be based?

Unfortunately, no comparable data or analyses could be found in the literature (i.e., related to the OE, or comfort more broadly) to guide the analyses or help address these questions. It is therefore necessary to further investigate the definition of naivety in the context of the OE (or HPDs more generally) to identify potential indicators that could be integrated into future analyses.

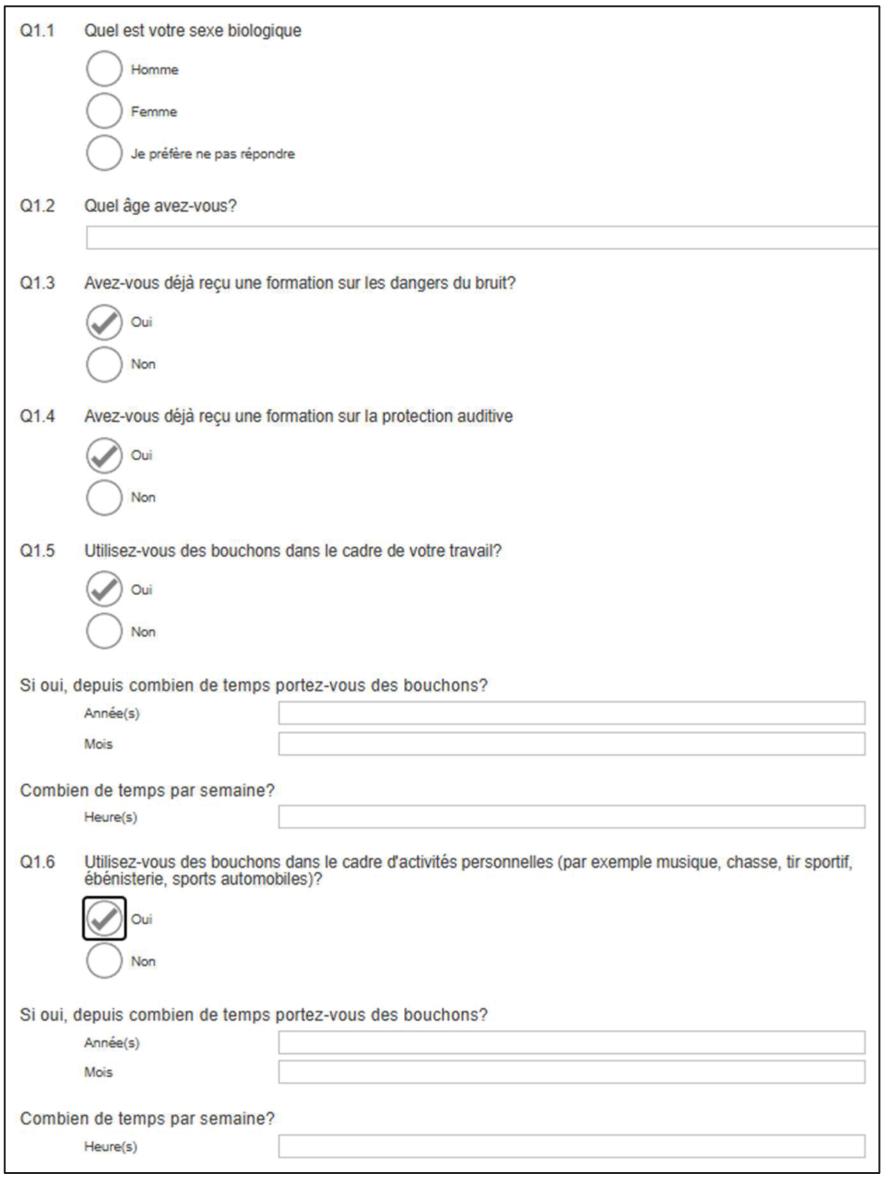
Finally, despite the guidance provided by two senior statisticians, the statistical tools used for the analyses (i.e., SPSS) offered limited automation capabilities for the iterative process of the MLMs, making the procedure time-consuming and restricting the number of models that could be computed and analyzed. Therefore, it is possible that (statistically) stronger models could have been identified to better understand the influence of triad characteristics or to objectivize discomfort through an objective indicator. The use of more powerful and advanced tools (e.g., the R statistical programming language) would have allowed for more comprehensive analyses and potentially the identification of statistically more robust models. However, learning and applying these tools was not realistic within the timeframe of this doctoral work.

Despite the limitations outlined above, the exploratory work conducted in this thesis successfully addressed numerous questions and provided groundwork for future research on the OE. In subsequent studies, it would be relevant to conduct new measurement campaigns focusing on the characteristics identified as influential, in order to better understand their impact on the OEexp while improving the statistical power of the analyses—for example, the impact of hearing loss on discomfort. Alternatively, future studies could further investigate the influence of the HPD and the environment, as few characteristics related to these dimensions were explored in this thesis. Different approaches could also be employed to study OE-related discomfort. One such approach would involve conducting measurements with participants using an open and flexible interview format, in contrast to the rigid and predefined protocol used in this work. Such an approach, combined with continuous microphone signal measurement throughout the session, would allow researchers to associate qualitative descriptors used by participants to describe a discomfort (e.g., own voice sounding “boomy” or “distorted”) with objective indicators. Analyses of such data could enable the correlation of specific words with objective measurements, going beyond a simple response scale, and therefore helping research better understand what causes discomforts associated with the OE. Finally, future studies on the OE could extend the evaluation of comfort through the use of additional sensors. Most existing studies rely on microphone-based measurements, but it would be valuable to examine how the human body responds to the OE beyond the external ear—for example, by measuring brain responses using medical imaging, or by revisiting and enhancing an EEG-based approach such as that proposed by Valentin & Laville (2017).

# ANNEX I

## C2 CAMPAIGN QUESTIONNAIRE

Below are shown the five screens that were presented to the participant during the measurement session of the C2 measurement campaign.



Q1.1 Quel est votre sexe biologique

- Homme
- Femme
- Je préfère ne pas répondre

Q1.2 Quel âge avez-vous?

Q1.3 Avez-vous déjà reçu une formation sur les dangers du bruit?

- Oui
- Non

Q1.4 Avez-vous déjà reçu une formation sur la protection auditive

- Oui
- Non

Q1.5 Utilisez-vous des bouchons dans le cadre de votre travail?

- Oui
- Non

Si oui, depuis combien de temps portez-vous des bouchons?

Année(s)

Mois

Combien de temps par semaine?

Heure(s)

Q1.6 Utilisez-vous des bouchons dans le cadre d'activités personnelles (par exemple musique, chasse, tir sportif, ébénisterie, sports automobiles)?

- Oui
- Non

Si oui, depuis combien de temps portez-vous des bouchons?

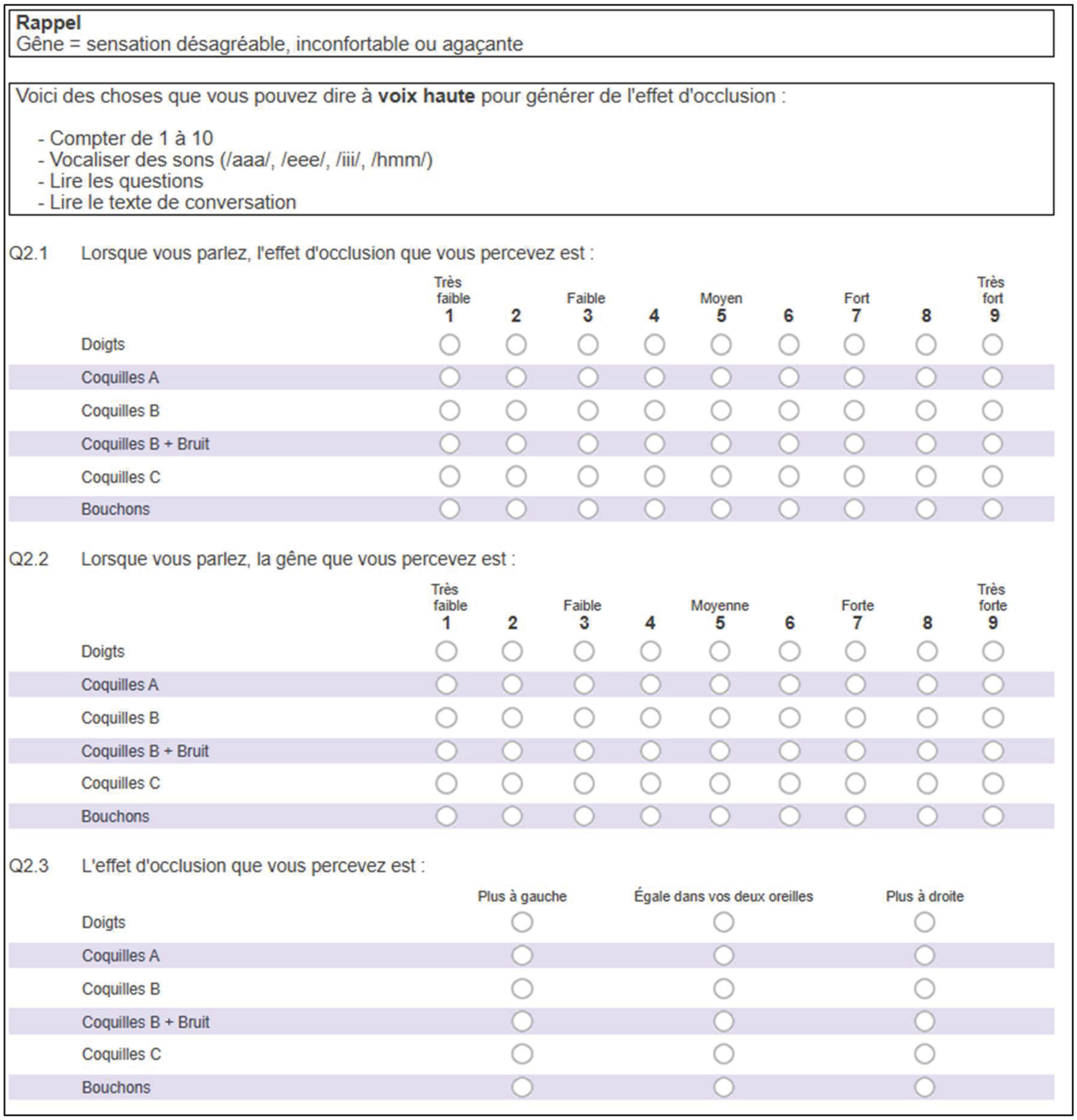
Année(s)

Mois

Combien de temps par semaine?

Heure(s)

Figure-A I-1 Screen 1 – Questions for assessing the participant's profile



**Rappel**
Gêne = sensation désagréable, inconfortable ou agaçante

Voici des choses que vous pouvez dire à **voix haute** pour générer de l'effet d'occlusion :

- Compter de 1 à 10
- Vocaliser des sons (/aaa/, /eee/, /iii/, /hmm/)
- Lire les questions
- Lire le texte de conversation

Q2.1 Lorsque vous parlez, l'effet d'occlusion que vous percevez est :

| | Très faible 1 | 2 | Faible 3 | 4 | Moyen 5 | 6 | Fort 7 | 8 | Très fort 9 |
|---|---|---|---|---|---|---|---|---|---|
| Doigts | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Coquilles A | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Coquilles B | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Coquilles B + Bruit | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Coquilles C | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Bouchons | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |

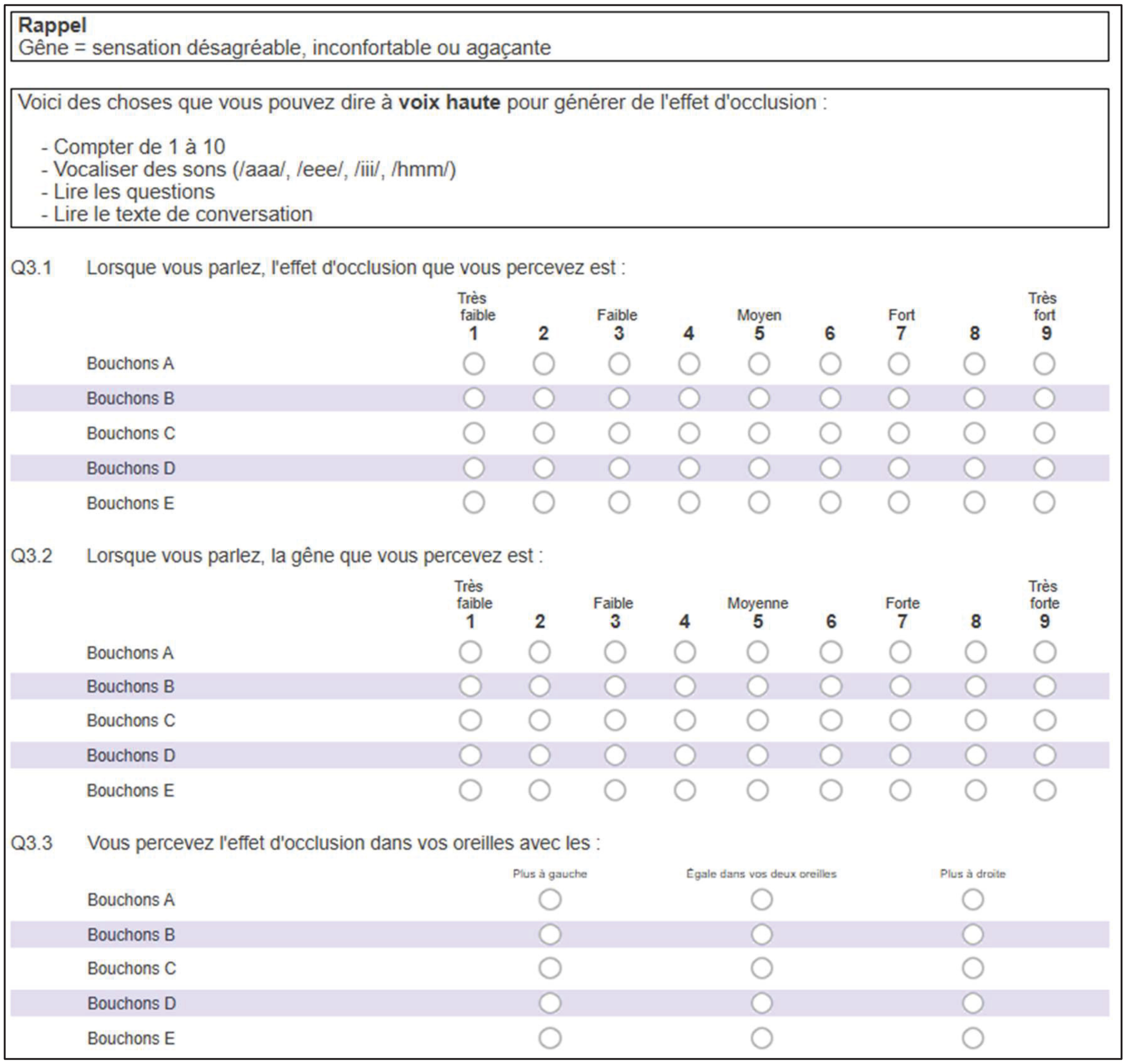
Q2.2 Lorsque vous parlez, la gêne que vous percevez est :

| | Très faible 1 | 2 | Faible 3 | 4 | Moyenne 5 | 6 | Forte 7 | 8 | Très forte 9 |
|---|---|---|---|---|---|---|---|---|---|
| Doigts | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Coquilles A | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Coquilles B | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Coquilles B + Bruit | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Coquilles C | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Bouchons | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |

Q2.3 L'effet d'occlusion que vous percevez est :

| | Plus à gauche | Égale dans vos deux oreilles | Plus à droite |
|---|---|---|---|
| Doigts | ○ | ○ | ○ |
| Coquilles A | ○ | ○ | ○ |
| Coquilles B | ○ | ○ | ○ |
| Coquilles B + Bruit | ○ | ○ | ○ |
| Coquilles C | ○ | ○ | ○ |
| Bouchons | ○ | ○ | ○ |

Figure-A I-2 Screen 2 – Questions of the training phase



**Rappel**
Gêne = sensation désagréable, inconfortable ou agaçante

Voici des choses que vous pouvez dire à **voix haute** pour générer de l'effet d'occlusion :

- Compter de 1 à 10
- Vocaliser des sons (/aaa/, /eee/, /iii/, /hmm/)
- Lire les questions
- Lire le texte de conversation

Q3.1 Lorsque vous parlez, l'effet d'occlusion que vous percevez est :

| | Très faible 1 | 2 | Faible 3 | 4 | Moyen 5 | 6 | Fort 7 | 8 | Très fort 9 |
|---|---|---|---|---|---|---|---|---|---|
| Bouchons A | | | | | | | | | |
| Bouchons B | | | | | | | | | |
| Bouchons C | | | | | | | | | |
| Bouchons D | | | | | | | | | |
| Bouchons E | | | | | | | | | |

Q3.2 Lorsque vous parlez, la gêne que vous percevez est :

| | Très faible 1 | 2 | Faible 3 | 4 | Moyenne 5 | 6 | Forte 7 | 8 | Très forte 9 |
|---|---|---|---|---|---|---|---|---|---|
| Bouchons A | | | | | | | | | |
| Bouchons B | | | | | | | | | |
| Bouchons C | | | | | | | | | |
| Bouchons D | | | | | | | | | |
| Bouchons E | | | | | | | | | |

Q3.3 Vous percevez l'effet d'occlusion dans vos oreilles avec les :

| | Plus à gauche | Égale dans vos deux oreilles | Plus à droite |
|---|---|---|---|
| Bouchons A | | | |
| Bouchons B | | | |
| Bouchons C | | | |
| Bouchons D | | | |
| Bouchons E | | | |

Figure-A I-3 Screen 3 – Questions of the earplug comparison phase

**Rappel**
Gêne = sensation désagréable, inconfortable ou agaçante

Voici des choses que vous pouvez dire à **voix haute** pour générer de l'effet d'occlusion :

- Compter de 1 à 10
- Vocaliser des sons (/aaa/, /eee/, /iii/, /hmm/)
- Lire les questions
- Lire le texte de conversation

Q4.1 Lorsque vous parlez, l'effet d'occlusion que vous percevez est :

| | Très faible 1 | 2 | Faible 3 | 4 | Moyen 5 | 6 | Fort 7 | 8 | Très fort 9 |
|---|---|---|---|---|---|---|---|---|---|
| Profondeur d'insertion A | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Profondeur d'insertion B | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Profondeur d'insertion C | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |

Q4.2 Lorsque vous parlez, la gêne que vous percevez est :

| | Très faible 1 | 2 | Faible 3 | 4 | Moyenne 5 | 6 | Forte 7 | 8 | Très forte 9 |
|---|---|---|---|---|---|---|---|---|---|
| Profondeur d'insertion A | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Profondeur d'insertion B | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Profondeur d'insertion C | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |

Figure-A I-4 Screen 4 – Questions of the insertion depth comparison phase

**Rappel**
Gêne = sensation désagréable, inconfortable ou agaçante

Voici des choses que vous pouvez dire à **voix haute** pour générer de l'effet d'occlusion :

- Compter de 1 à 10
- Vocaliser des sons (/aaa/, /eee/, /iii/, /hmm/)
- Lire les questions
- Lire le texte de conversation

Q5.1 Lorsque vous parlez, l'effet d'occlusion que vous percevez est :

| | Très faible 1 | 2 | Faible 3 | 4 | Moyen 5 | 6 | Fort 7 | 8 | Très fort 9 |
|---|---|---|---|---|---|---|---|---|---|
| Devant les portes de l'usine | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Dans l'usine | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Devant la machine | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Dans un endroit calme | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |

Q5.2 Lorsque vous parlez, la gêne que vous percevez est :

| | Très faible 1 | 2 | Faible 3 | 4 | Moyenne 5 | 6 | Forte 7 | 8 | Très forte 9 |
|---|---|---|---|---|---|---|---|---|---|
| Devant les portes de l'usine | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Dans l'usine | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Devant la machine | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Dans un endroit calme | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |

Figure-A I-5 Screen 5 – Questions of the background noise level comparison phase

## ANNEX II

## PERCEIVED OCCLUSION EFFECT SCORES DISTRIBUTION FOR THE THREE MEASUREMENT PHASES

As explained in Section 3.3.6, the questionnaire administered to participants during the C2 measurement campaign assessed both the experienced occlusion effect ($OE_{exp}$) and the perceived occlusion effect ($OE_{perc}$) for each of the 11 configurations tested, grouped into three phases: earplug model, insertion depth, and background noise level. The differences between $OE_{exp}$ and $OE_{perc}$ discussed in Section 4.2 are based on the $OE_{exp}$ score distributions presented in Figure 4.11, Figure 4.12, and Figure 4.13 of Section 4.3.3, as well as on the $OE_{perc}$ score distributions presented below. More specifically, the $OE_{perc}$ score distributions for the earplug model, insertion depth, and background noise level phases are shown in Figure-A II-1, Figure-A II-2, and Figure-A II-3, respectively.

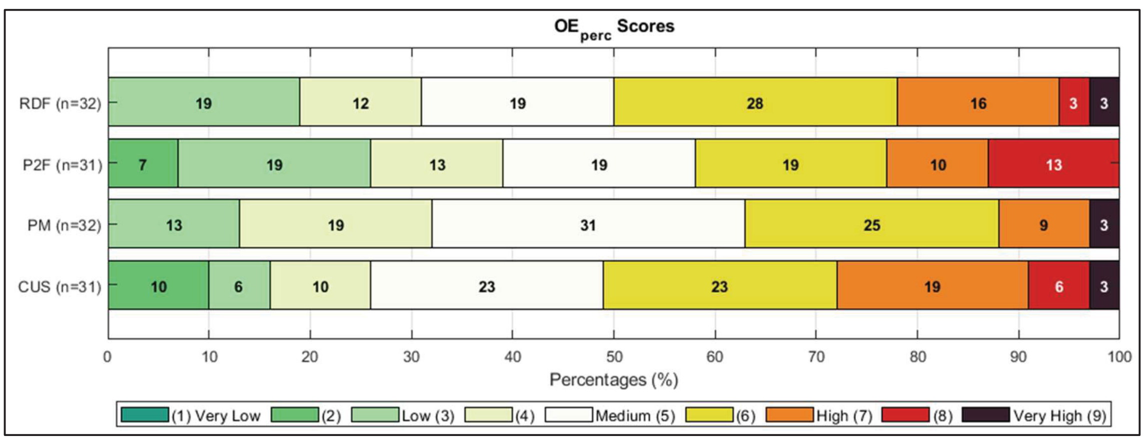



Figure-A II-1 Distribution of the $OE_{perc}$ ratings regarding the four earplugs tested during the earplug models phase of C2, namely the Roll-down foam (RDF), the Push-to-fit (P2F), the Premolded (PM) and the Custom (CUS) earplugs

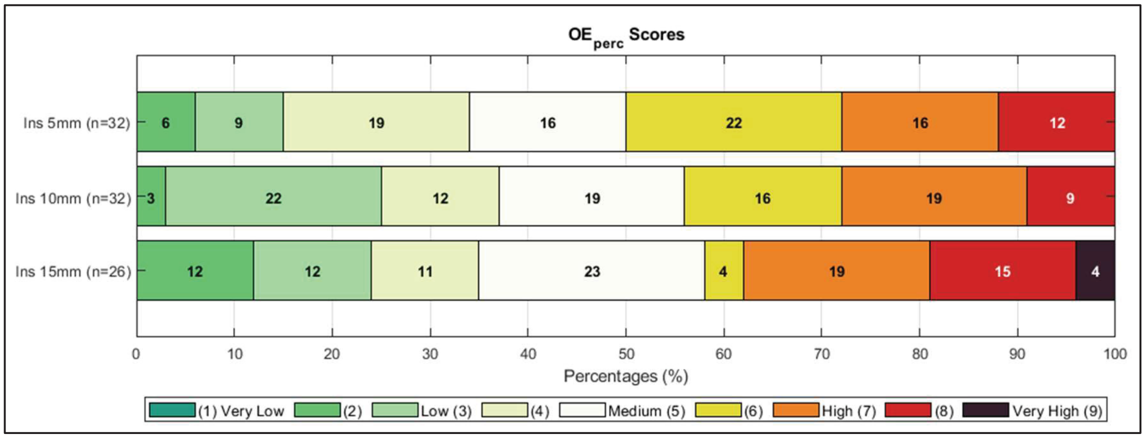



Figure-A II-2 Distribution of the $OE_{perc}$ ratings regarding the three insertion depths tested during the insertion depths phase of C2, namely the 5 mm, 10 mm, and 15 mm insertion

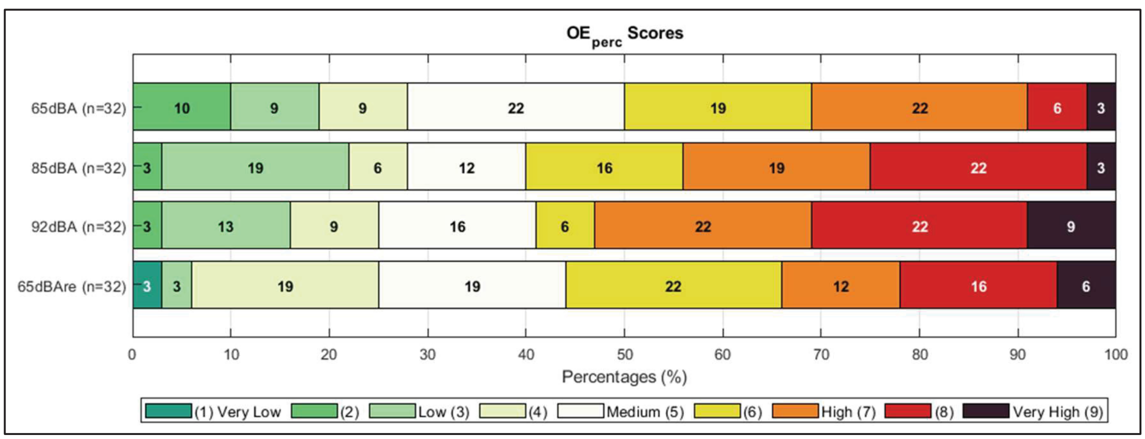



Figure-A II-3 Distribution of the $OE_{perc}$ ratings regarding the four background noise levels tested during the background noise level phase of C2, namely 65 $dBA_{test}$, 85 dBA, 92 dBA, and 65 $dBA_{retest}$

# ANNEX III

## OBJECTIVE INDICATORS AS A FUNCTION OF FREQUENCY AND EARPLUG MODEL

The objective occlusion effect indicators measured using the NR method ($\mathrm{OE}_{\mathrm{obj}}^{\mathrm{NR}}$), attenuation (NR), and noise level measured in the occluded ear ($L_{p,occluded}$) are presented as a function of frequency in Sections 4.4.1 and 4.4.1.2, combining data from all participants without accounting for the earplug model tested. It should be recalled that, in the insertion depth and background noise level phases, not all participants tested the same earplugs due to fit issues. Since it is well documented that earplug properties have a significant influence on the acoustic pressure level measured in the occluded ear (see Section 1.4.2.2), the $\mathrm{OE}_{\mathrm{obj}}^{\mathrm{NR}}$, NR, and $L_{p,occluded}$ data are presented in this annex while accounting for the earplug model used for each configuration tested across the three test phases: earplug model, insertion depth, and background noise level. The $\mathrm{OE}_{\mathrm{obj}}^{\mathrm{NR}}$ data are presented in Figure-A III-1, Figure-A III-2, and Figure-A III-3. The $L_{p,occluded}$ data are presented in Figure-A III-4, Figure-A III-5, and Figure-A III-6. The NR data are presented in Figures Figure-A III-7, Figure-A III-8, and Figure-A III-9.

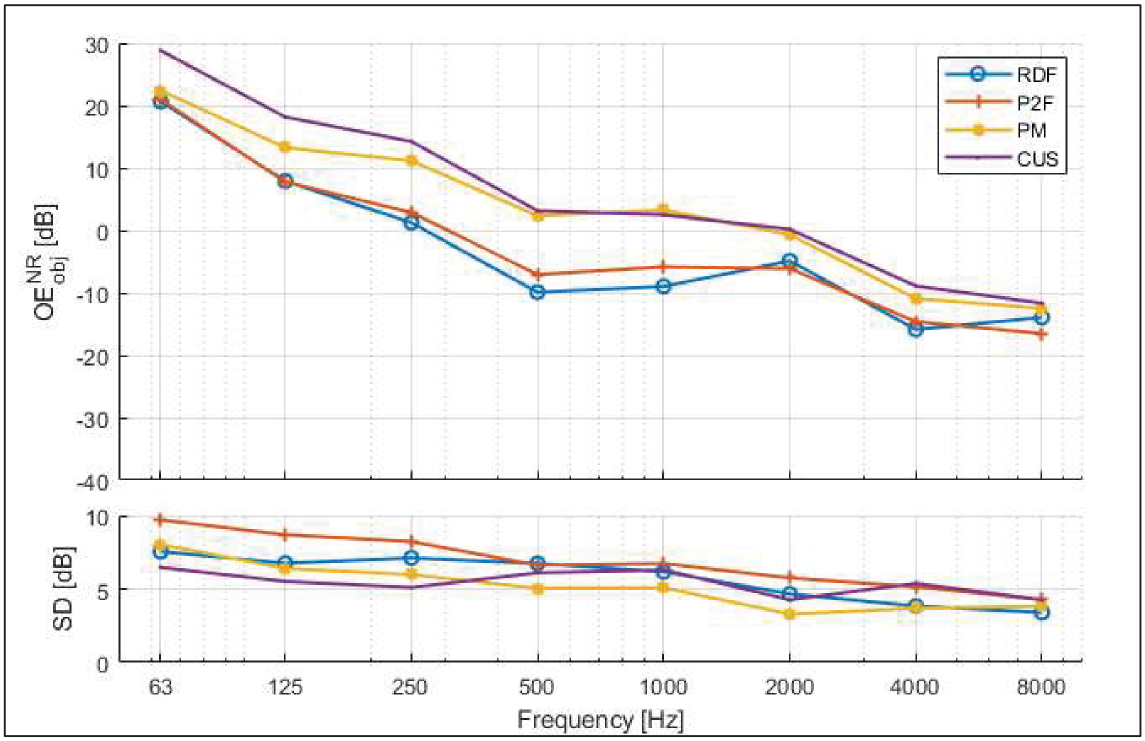



Figure-A III-1 $OE_{obj}^{NR}$ as a function of frequency of the earplug models comparison phase of the C2 campaign. Earplugs are the Roll-down foam (RDF), Push-to-fit (P2F), Premolded (PM), Custom (CUS). Values averaged across all participants are shown in the top panel while the standard deviations are shown in the bottom panel

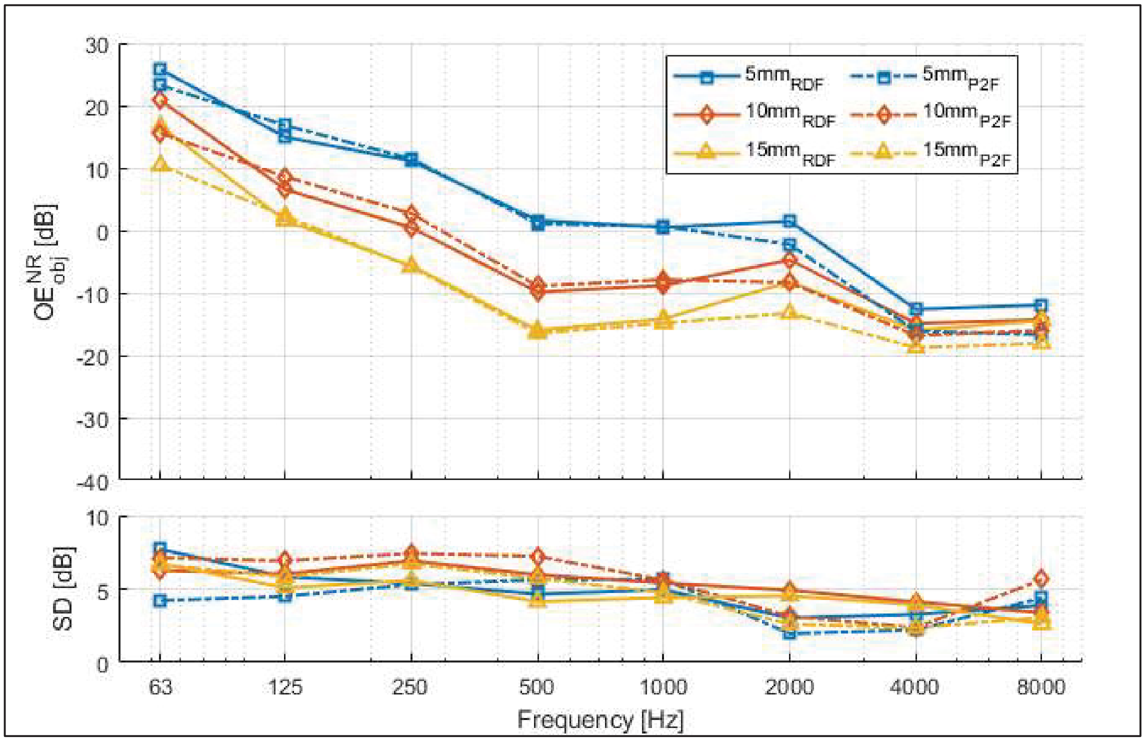



Figure-A III-2 $OE_{obj}^{NR}$ as a function of frequency of the insertion depths comparison phase of the C2 campaign. Insertion depths are the 5 mm, 10 mm and 15 mm. Since two earplug models were tested, namely the Roll-down foam (RDF) and Push-to-fit (P2F), curves are shown for each respective earplug model. Values averaged across all participants are shown in the top panel while the standard deviations are shown in the bottom panel

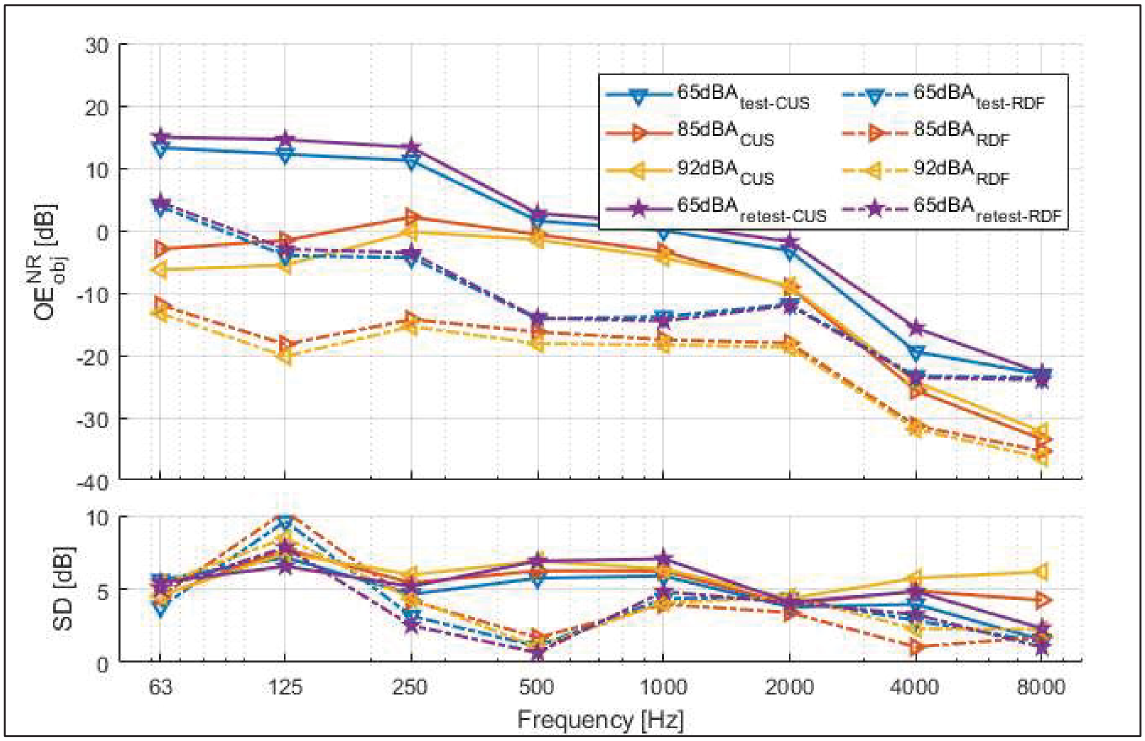



Figure-A III-3 $OE_{obj}^{NR}$ as a function of frequency of the background noise levels comparison phase of the C2 campaign. Background noise levels are the 65 $dBA_{test}$, 85 dBA, 92 dBA and 65 $dBA_{retest}$. Since two earplug models were tested, namely the Custom (CUS) and Roll-down foam (RDF), curves are shown for each respective earplug model. Values averaged across all participants are shown in the top panel while the standard deviations are shown in the bottom panel.

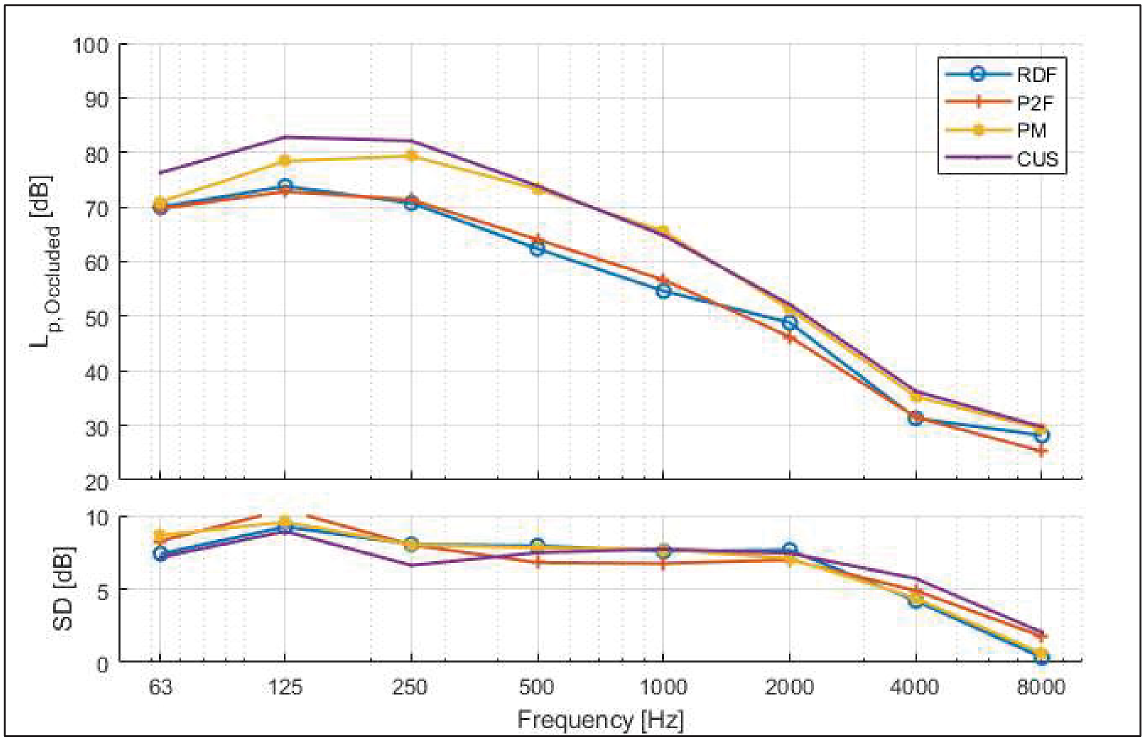



Figure-A III-4 $L_{p,occluded}$ as a function of frequency of the earplug models comparison phase of the C2 campaign. Earplugs are the Roll-down foam (RDF), Push-to-fit (P2F), Premolded (PM), Custom (CUS). Values averaged across all participants are shown in the top panel while the standard deviations are shown in the bottom panel

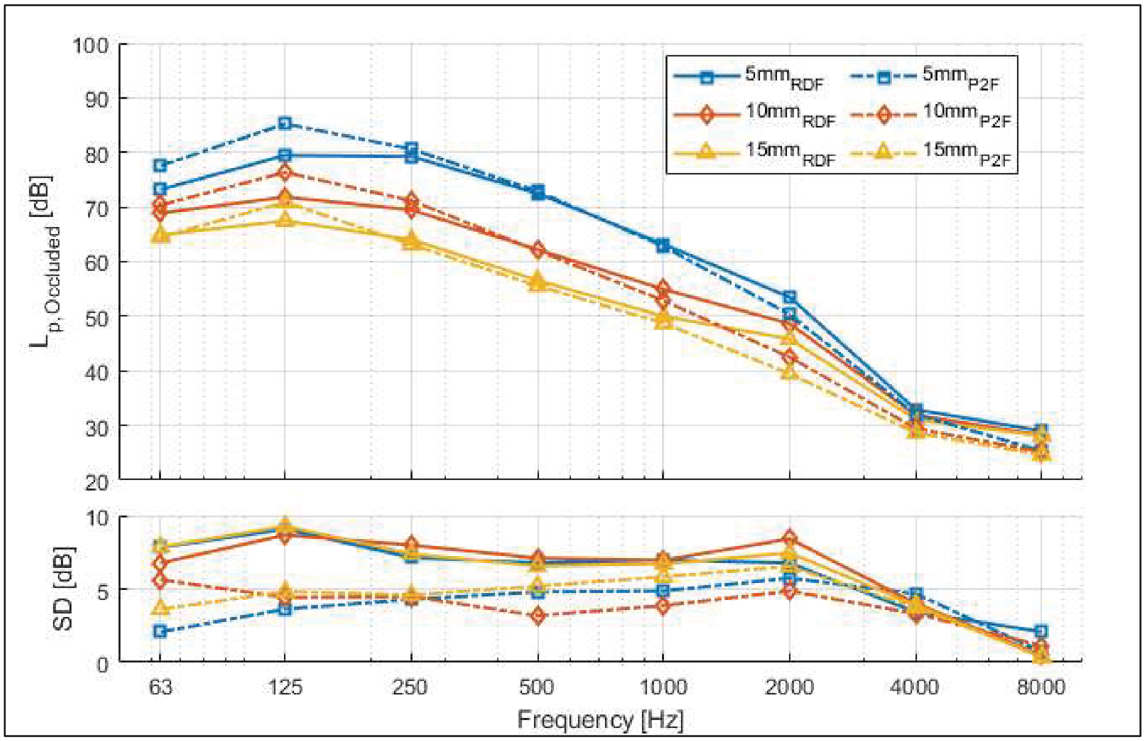



Figure-A III-5 $L_{p,occluded}$ as a function of frequency of the insertion depths comparison phase of the C2 campaign. Insertion depths are the 5 mm, 10 mm and 15 mm. Since two earplug models were tested, namely the Roll-down foam (RDF) and Push-to-fit (P2F), curves are shown for each respective earplug model. Values averaged across all participants are shown in the top panel while the standard deviations are shown in the bottom panel

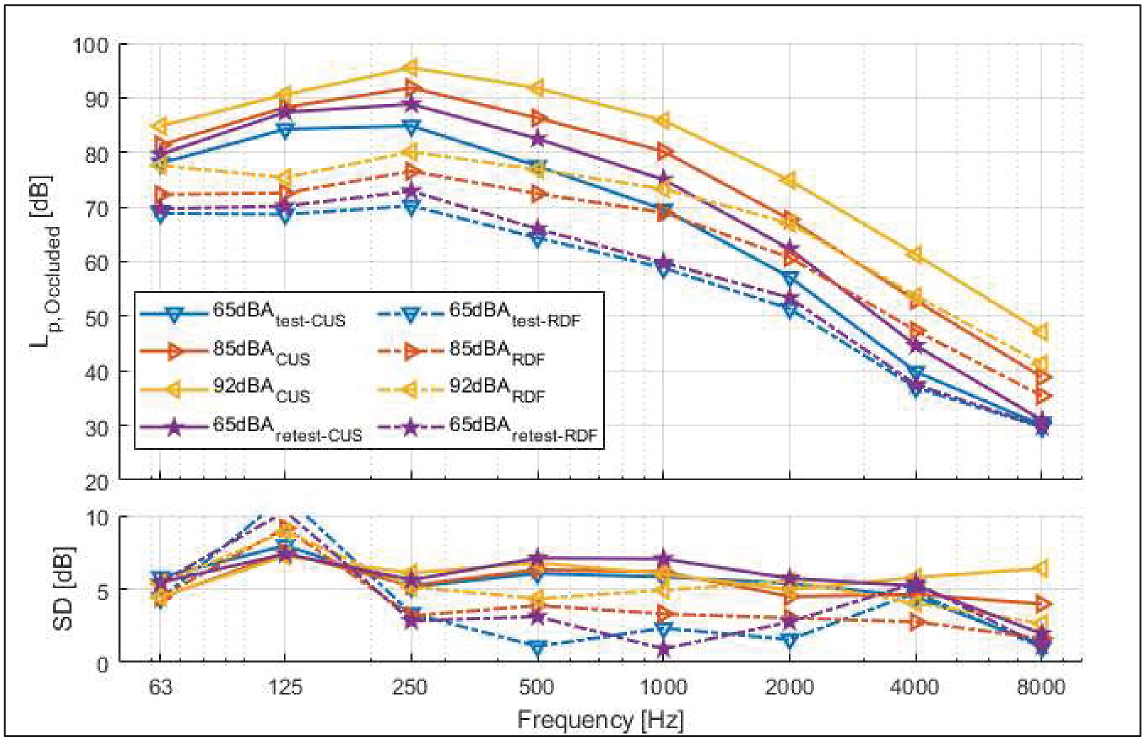



Figure-A III-6 $L_{p,occluded}$ as a function of frequency of the background noise levels comparison phase of the C2 campaign. Background noise levels are the 65 $dBA_{test}$, 85 dBA, 92 dBA and 65 $dBA_{retest}$. Since two earplug models were tested, namely the Custom (CUS) and Roll-down foam (RDF), curves are shown for each respective earplug model. Values averaged across all participants are shown in the top panel while the standard deviations are shown in the bottom panel

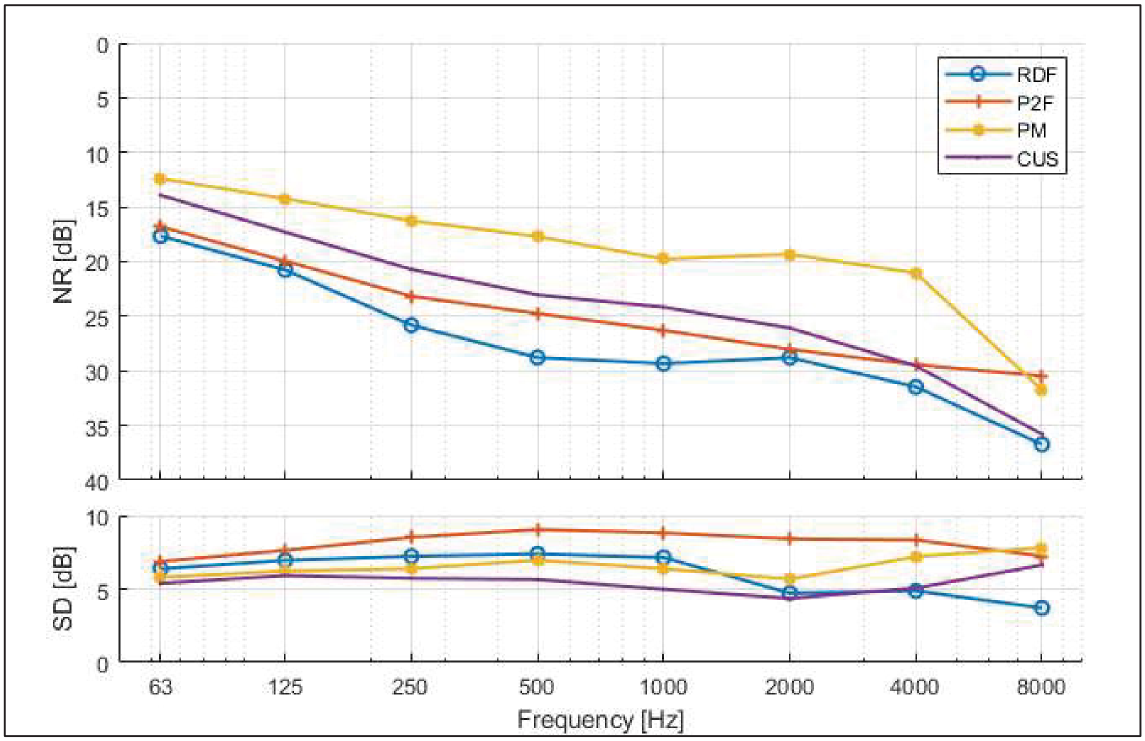



Figure-A III-7 NR as a function of frequency of the earplug models comparison phase of the C2 campaign. Earplugs are the Roll-down foam (RDF), Push-to-fit (P2F), Premolded (PM), Custom (CUS). Values averaged across all participants are shown in the top panel while the standard deviations are shown in the bottom panel

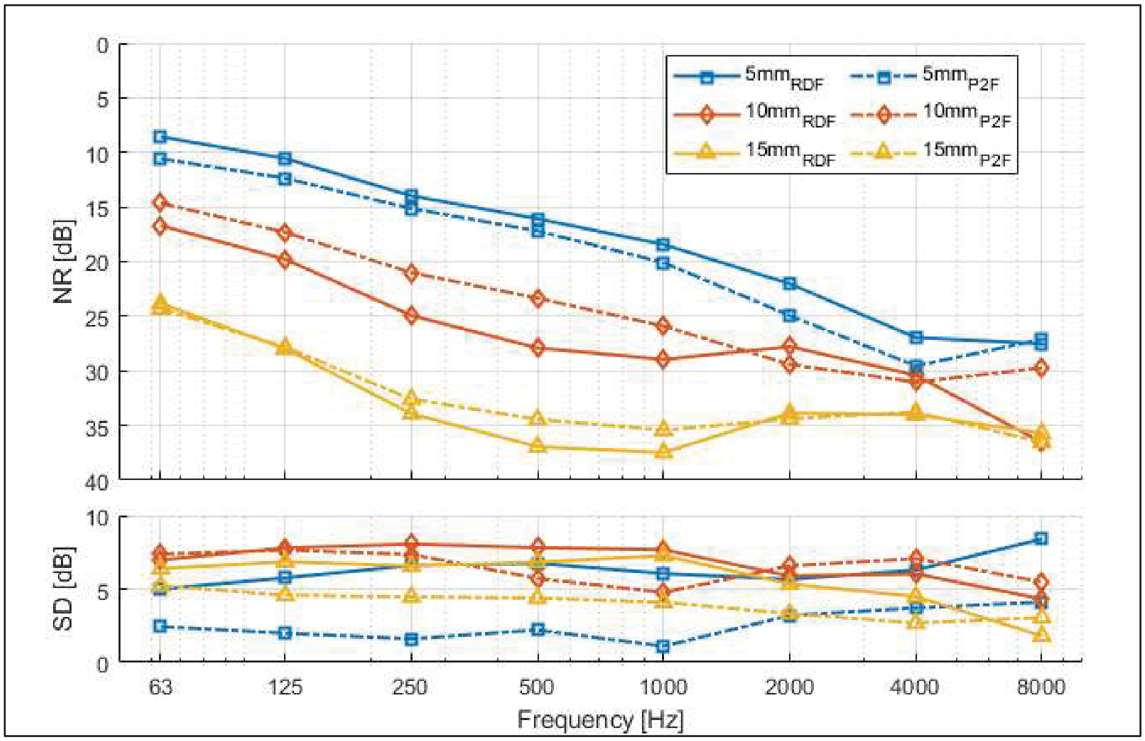



Figure-A III-8 NR as a function of frequency of the insertion depths comparison phase of the C2 campaign. Insertion depths are the 5 mm, 10 mm and 15 mm. Values averaged across all participants are shown in the top panel while the standard deviations are shown in the bottom panel

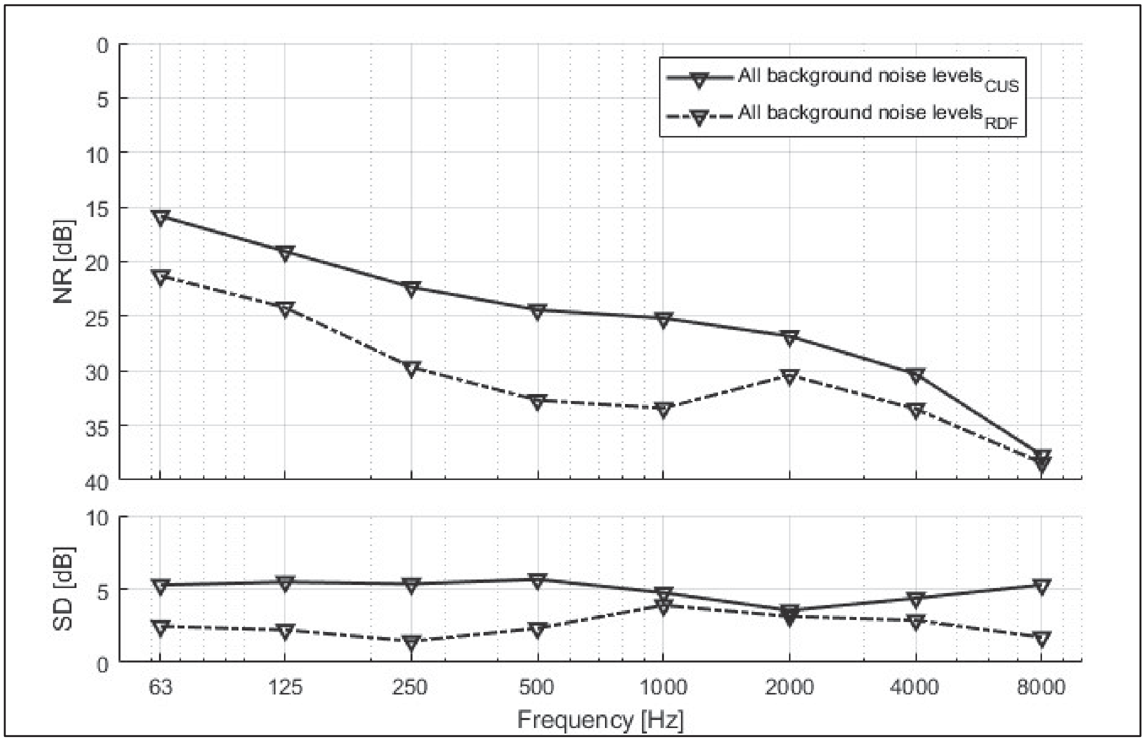



Figure-A III-9 NR as a function of frequency of the background noise levels comparison phase of the C2 campaign. A single attenuation curve for the Custom (CUS) and Roll-down foam (RDF) earplugs is shown, as earplugs were fitted once; thus the NR is the same for the four background noise levels tested, namely 65 $dBA_{test}$, 85 dBA, 92 dBA, 65 $dBA_{retest}$. Values averaged across all participants are shown in the top panel while the standard deviations are shown in the bottom panel

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