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Assessing the multidimensional comfort of earplugs in virtual industrial noise environments

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ABSTRACT

Earplugs' comfort is primarily evaluated through cost-effective laboratory evaluations, yet these evaluations often inadequately capture the multidimensional comfort aspects due to design limitations that do not replicate real-world conditions. This paper introduces a novel laboratory method for comprehensive assessment of the multidimensional comfort aspects of earplugs, combining questionnaire-based evaluations and objective perceptual tests within virtual industrial sound environments replicating *in-situ* noise exposure. Objective perceptual results confirm that the sound environment affect participants' ability to detect alarms in a noisy environment and comprehend speech-in-noise while wearing earplugs. Subjective questionnaire results reveal that the earplugs family has an effect on the primary attributes of the acoustical, physical and functional comfort's dimension. Participants reported the physical dimension as the most important factor they take into account when evaluating earplugs' comfort. The functional dimension was considered the second most important factor by the participants, followed by the psychological dimension, and the acoustical dimension.

1. Introduction

In Québec (Canada), approximately 360,000 workers face daily exposure to noise levels that pose a significant risk to their hearing (Vézina et al., 2011; Arcand et al., 2012). Occupational deafness stands as the most prevalent work-related disease (Duguay et al., 2012), accompanied by considerable economic consequences. In 2019, occupational deafness accounted for nearly 92% of occupational disease cases in Québec (Commission des normes, de l'équité, de la santé et de la sécurité du travail (CNESST), 2020). In addition, ear disorders, including noise-induced hearing disorders, represent staggering costs for the *Commission des normes, de l'équité, de la santé et de la sécurité du travail* (CNESST) (Boucher and Lebeau, 2019). As an example, in 2017, 9730 cases of noise-induced deafness were accepted by the CNESST with a total cost of $210,375 per injury (Boucher and Lebeau, 2019). This issue of occupational deafness extends beyond Québec and affects a substantial number of workers worldwide (Themann and Masterson, 2019).

While addressing the noise issue at its source is undeniably the most effective approach, certain work environments present challenges where this type of noise reduction measure may not be feasible. Examples include industrial sectors where workers operate in close proximity to the noise source, such as steel mills and sawmills, as well as professions like mining, construction, law enforcement, firearm users, and individuals utilizing percussive tools, aircraft guides, baggage handlers, and more. Consequently, the primary safeguard for workers consists in using individual hearing protection devices (HPDs), such as earplugs or earmuffs, which serve as acoustic barriers at the ear to attenuate the acoustic energy from excessively noisy environments.

However, concerns have been raised regarding HPDs efficacy in adequately protecting workers against noise-induced hearing loss (Groenewold et al., 2014). The underlying factors contributing to this apparent inefficiency are well known: HPDs are either not worn at all or not consistently worn and properly fitted (Berger, 2018). Various factors contribute to the improper use or non-use of HPDs but comfort is found

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to be a significant factor influencing HPDs usage (Doutres et al., 2022; Bockstael et al., 2011; Costa and Arezes, 2013; Cramer et al., 2017; Edelson et al., 2019; Hong et al., 2013; Kushnir et al., 2006; McCullagh et al., 2016; Morata et al., 2001; Patel et al., 2001; Reddy et al., 2012; Stephenson, 2009; Stephenson et al., 2011; Svensson et al., 2004).

The assessment of HPD comfort can be conducted through both field studies and laboratories studies. Nevertheless, field evaluations remain particularly challenging, primarily due to the difficulty of ensuring consistent exposure conditions for individuals, as well as the substantial financial and time investments they require. Hence, laboratory studies are favored as they provide a more controlled and cost-effective means of evaluating HPD comfort. Most laboratory studies either focus on assessing the physical and acoustic dimensions of comfort in quiet conditions (Doutres et al., 2019), or investigate the interactions between the acoustical environment and the wearer's ability to perceive sounds in the surrounding environment (e.g., speech intelligibility, sound localization, alarm signal perception) (W.I., 1967; Bockstael et al., 2011; Brown et al., 2015; Giguère et al., 2010; Kryter, 1946; Suter, 1992; Zheng et al., 2007; Zimpfer and Sarafian, 2014). To the authors' knowledge, no laboratory studies have been conducted to evaluate the multidimensional aspect of comfort in noisy conditions that closely mimic *in-situ* noise exposure.

This paper introduces a laboratory-based method for assessing the comfort for three earplugs families (roll-down foam, premolded foam, push-to-fit) using fully immersive industrial sound environments generated via Sound Field Reproduction (SFR) techniques (Valentin et al., 2020), replicating *in-situ* noise exposure. The reported work incorporates objective perceptual tests (i.e., alarm detection tests and speech perception in noise tests), as well as questionnaire-based evaluations of the multidimensional aspects of earplugs comfort (Terroir et al., 2017; Doutres et al., 2019, 2020). More specifically, this research investigates the influence of the acoustic environment and the earplugs family on the acoustical dimension of comfort using both objective perceptual tests and questionnaire-based evaluations. Additionally, this research also investigates the impact of the acoustic environment and the earplugs family on physical, functional and psychological dimensions of earplugs comfort using questionnaire-based evaluations.

This paper is structured as follows: the methodology and experimental protocol are described in Section 2. Section 3 presents the results, followed by their discussion in Section 4. Finally, Section 5 provides the conclusion.

2. Methodology

2.1. Participants

Twenty-four individuals (eighteen males, six females) aged between 22 and 32 and having hearing thresholds below 25 dB HL (pure tone audiometry between 125 to 8000 Hz) participated in this research work. All participants were students from *Sherbrooke University* that were all inexperienced regarding hearing protectors.

2.2. Experimental protocol

Since the control of experimental conditions can be challenging for *in-situ* tests, all experiments were performed in laboratory conditions using a loudspeaker array and spatial sound reconstruction methods to generate virtual sound environments. Participating in this study involved four measurement sessions: a preliminary session and three testing sessions. Twenty participants out of twenty-four completed all the measurement sessions, two individuals completed two measurement sessions, and another two individuals completed only one measurement session. The specific goals of these measurements were: (1) to evaluate how the acoustic environment and the earplugs family affect the acoustical dimension of comfort using objective perceptual tests (alarm detection tests and speech perception in noise tests) and questionnaire-based evaluations (through "comfort assessment" questionnaires), and (2) to investigate how the acoustic environment and the earplugs family impact the physical, functional and psychological dimensions of earplugs comfort using questionnaire-based evaluations. Additionally, a questionnaire entitled "Your ideal earplugs" was used to gather participants' preferences regarding the most and least comfortable HPDs.

Table 1 summarizes the organization of each session, with an estimate of the duration for each activity. During the preliminary session, participants were asked to read and sign the Information and Consent Form. Before inclusion in the study, an air-conducted tonal audiometry was performed for each participant to validate that their hearing thresholds remained within the inclusion criteria. Prior to their auditory checkup, participants were asked to observe a sixteen-hours "acoustical" resting and to avoid any noisy activities, whether professional or personal. Before each session, a visual otoscopy was performed by the experimenter to confirm that no cerumen (earwax) accumulation was blocking participants' ear canal. Over three successive measurement sessions (two hours each), the participants wore the three families of earplugs presented in Section 2.3, in a random order. For each of the two sound environments described in Section 2.4. (noted as #1 and #2 in Table 1), the participants performed a speech perception in noise test and then an alarm detection test while exercising a simulated work activity. The participants also completed the "Comfort Assessment" questionnaires listed in Table 1 on the perceived comfort of earplugs before and after these tests. The questionnaire "Your user profile" administered on Day #1 aimed at collecting demographic information, as well as information on participants' working environment, and their habits related to HPDs. The earplugs were not removed before the end of the two-hour session.

The alarm detection tests and the speech perception in noise tests are presented in Section 2.5 and Section 2.6, respectively. The set of questionnaires used to collect the user profile, the earplugs' comfort evaluations and the participants' favorite model of earplugs are described in Section 2.7. The measurement sessions were organized based on participants' availability, with some individuals completing all three sessions on consecutive days, while others experienced intervals ranging from weeks to months between successive measurements. The experimental procedure was reviewed and approved by the *Comité d'éthique pour la recherche Lettres et Sciences Humaines*, one of the Internal review Boards at *Université de Sherbrooke* in Sherbrooke, Canada (approval no. 2019–1929). Informed consent was obtained from all participants before they were enrolled in the study.

2.3. Hearing protectors and earplug insertion training

The earplugs used for this study (see Fig. 1) were either roll-down foam earplugs (3M™ E-A-R Classic), push-to-fit earplugs (3M™ E-A-R Push-ins), or premolded earplugs (3M™ E-A-R UltraFit). These earplugs were chosen based on their common usage in the field and the availability of a probed version (surrogate) that complies with the ANSI/ASA S12.71 standard (2018) for the measurement of "Personal Attenuation Rating" (PAR) (ANSI/ASA S12.71, 2018).

They were worn in an order randomly chosen prior to the measurement sessions. Participants were individually trained by the experimenter before the beginning of each measurement session for one 20 min session. At the beginning of the training, the experimenter recalled the different steps of the session, how to insert the earplugs to be worn during the whole session, and how to check if the fit was proper. Then, participants watched a short video about the use of different earplug families (INRS, 2013). After the video, participants were invited to insert their earplugs for a first PAR measurement using the 3M™ E-A-Rfit™ Dual-Ear Validation System (Berger et al., 2007).

The 3M™ E-A-Rfit™ Dual-Ear Validation System is based on field microphone in-real ear (F-MIRE) technology (Voix and Laville, 2009),

Table 1
Summary of the research activities conducted during each measurement session.

	Description	Duration (HH:MM)
Day #1: Preliminary session	Preliminary interview	00:15
	Visual otoscopy	00:05
	Tonal audiometry	00:20
	Questionnaire “Your user profile”	00:15
	Total	**00:55**
Day #2 to #4: Measurement sessions (one earplug family tested per day)	Welcome and explanations	00:15
	Earplug insertion training	00:05
	Earplug insertion	00:05
	Pre-task questionnaire “Comfort assessment”	00:10
	Speech perception in Noise Test #1	00:20
	Break	00:05
	Alarm detection test #1 during a simulated work task	00:15
	Post-task questionnaire #1 “Comfort assessment”	00:10
	Snack break	00:10
	Speech perception in noise test #2	00:20
	Break	00:05
	Alarm detection test #2 during a simulated work task	00:15
	Post-task questionnaire #2 “Comfort assessment”	00:10
	Debriefing	00:10
	Day #4 only: questionnaire “Your ideal earplugs”	00:05
	Total	**02:40**

which uses two miniature microphones (one internal and one external) to perform simultaneous sound pressure measurements at two locations across the earplugs. The system includes a specially designed loudspeaker equipped with a digital signal processor that allows for a consistent presentation of the test signal and real-time communication between the microphones, speaker and software. Thanks to this system, it is possible to objectively measure earplugs attenuation without the need of a response from the person being tested. The output given by the E-A-Rfit™ system is the “Personal Attenuation Rating”, or PAR (Berger, 2010), which is an estimate of the attenuation provided by the tested earplugs. To compute the PAR, the E-A-Rfit™ system simultaneously measures the SPL inside and outside the earplugs and then applies compensation factors derived from laboratory testing (Voix and Laville, 2009).

A criterion was set on the PAR value measured after the insertion of the earplugs performed by the participant as a way to validate the training received. If a floor PAR value of 15 dB was reached for both ears, the participant was considered adequately protected and the individual training was considered successful. If not, the participant was asked to adjust the earplugs for another PAR trial as many times as needed to get a good fit. The value of 15 dB was chosen because such level of attenuation ensures the participants were not unintentionally exposed to an excessive noise level for a long period of time when performing the tests. The binaural PAR values without compensation factors (sometimes refereed as the PAR50 (Kulinski and Brungart, 2022) value) for each earplug model are reported in Section 3.1.

2.4. Virtual industrial sound environments

The laboratory reproduction of industrial sound environments was conducted using a square loudspeaker array. During the measurement sessions, participants had to perform tasks that required them to move within the area bounded by the loudspeaker array, therefore the sound environment had to vary as little as possible in this area to avoid a bias in the alarm detection tests and speech perception in noise tests. Therefore, Acoustic Background Spectrum (ABS) was chosen as a synthesis method since this approach provides a spatially homogeneous stationary sound environment over a wide area (Valentin et al., 2020).

2.4.1. *In-situ recordings*

Prior to generating the virtual industrial sound environments, two monophonic *in-situ* recordings were necessary. These recordings were made at two separate industrial workstations (specifically, a granulator and a stacker) using an Edirol R09 portable recorder paired with a FG-23652 condenser microphone (Knowles Electronics). Before starting the measurements, the microphone was calibrated with a Larson Davis CAL200 SoundLevel Calibrator. All *in-situ* recordings were captured at a sampling rate of 48 kHz.

2.4.2. *Sound field reproduction using ABS-synthesis*

The sound field reproduction was performed using a room equipped with a square array of 96 loudspeakers of approximately 4 m by 4 m,

Fig. 1. Earplugs used during the experiments: (a) roll-down foam (3M™ Classic), (b) push-to-fit (3M™ Push-ins), and (c) premolded (3M™ E-A-R UltraFit) earplugs.

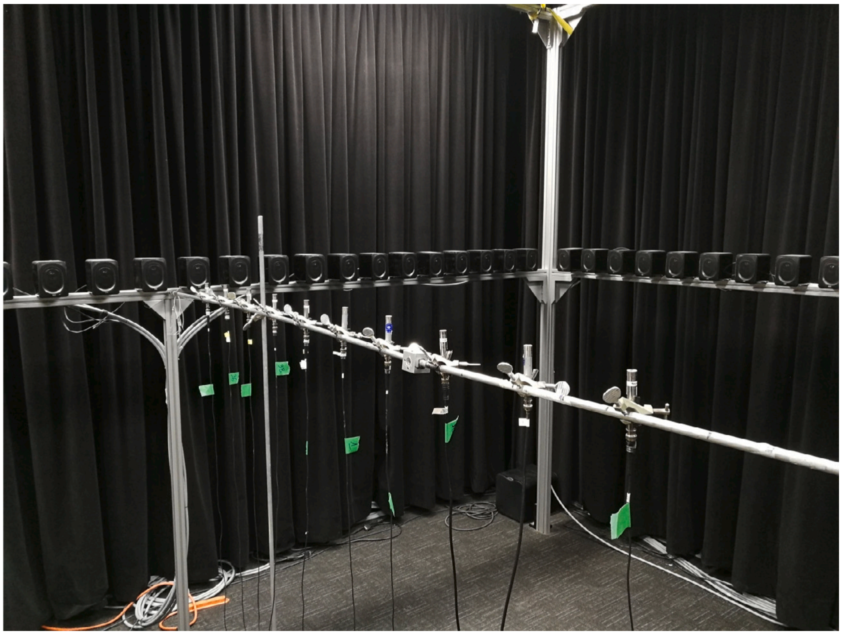


Fig. 2. Experimental setup for the objective evaluation. The sound environments were generated with the loudspeaker array (black loudspeakers, background) of the *Groupe d'Acoustique de l'Université de Sherbrooke.* The microphones are shown in forefront.

1.55 m above the ground, which is typically used for Wave field Synthesis (see Fig. 2) (Ahrens, 2012). Adjacent loudspeakers are separated by a distance of 16.25 cm, corresponding to a Nyquist frequency of approximately 1 kHz. Above this frequency, artifacts such as timbral coloration and source localization bias occur in the reproduced sound field, but the impact of these artifacts on the perception of the reproduced sound field are usually regarded as small (Ahrens et al., 2014). Four subwoofers, used to generate the frequency content below 120 Hz, located in the four corners of the square loudspeaker array. Therefore, it is not expected that the reproduction will be spatially accurate below 120 Hz. The subwoofer signals are derived as a downmix of the corresponding four 24-loudspeaker bars.

Spatial sound synthesis was used to generate the two virtual industrial sound environments that served as background noise during all the laboratory tests performed in this study. These virtual industrial environments were generated using multichannel Acoustic Background Spectrum (ABS) Synthesis inspired from Tarzia's work (Tarzia et al., 2011) on acoustic fingerprints, multichannel uncorrelated noises, and the two *in-situ* monophonic recordings. In this research work, ABS-Synthesis involved filtering 96 uncorrelated random white noise signals with the spectral envelope of the monophonic *in-situ* recordings from which the ABS was obtained using Tarzia's approach. This signal processing step extracts the stationary, background spectrum of the initial recording and removes transient sounds. The outputs are 96 uncorrelated signals with the same stationary timbre as the monophonic *in-situ* recording. When projected over the 96 loudspeakers of the reproduction system, these signals provide a spatially homogeneous sound field with the same frequency content as the monophonic recording.

2.4.3. Sound field objective evaluation

The spatial homogeneity of the two reproduced industrial sounds was measured in the Wave Field Synthesis facility. A microphone array, consisting of ten 1/2" prepolarized condenser microphones (seven 378B02 models from PCB Piezotronics and three TYPE 4189 models from Brüel & Kjær) spaced 19 cm apart, was used to objectively evaluate the reproduced sound fields (see Fig. 2).

This microphone array was placed at a height of 1.64 m and passed through the center of the loudspeaker array, aligning with the geometric center of the woofers of the reproduction loudspeakers. The reproduction loudspeaker aligned with the microphone array is approximately 30 cm from the closest microphone. Each microphone was calibrated before conducting measurements using a Br`uel & Kjær 4230 Sound Level Calibrator. The BK Connect sound and vibration software (Br´uel & Kjær, Denmark) was used for both calibration and measurement processes. All measurements involved 30 averages of 10.67 s each, using a Hanning window with 66.7% overlap, a frequency resolution of 1 Hz, and a sampling rate of 48 kHz. The frequency spectra of the two environments, generated using ABS-synthesis and measured in dB SPL by the microphone array as a function of distance from the loudspeaker array center is presented on Fig. 3. It was noted afterwards that microphone No. 3 (the one positioned at 38 cm from the center of the room) was problematic. If the measurement with microphone No. 3 is omitted, results from Fig. 3 indicate that both reproduced environments are spatially homogeneous in terms of SPL. This aligns with our targeted application, where users of HPD must simulate a work task and move within the area bounded by the loudspeaker array.

2.4.4. Virtual sound environment calibration

The virtual sound environments were level-calibrated with a Bruel & Kjaer 4230 Sound Level Calibrator placed at the centre of the room at a global sound pressure level of 90.9 dB(SPL) for the first environment (the stacker) and 93.0 dB(SPL) for the second environment (the granulator). This approach ensured that the 8-hour time weighted average sound level remains within a safe limit of 75 dB(SPL), preventing participants from any unintentional exposure to excessive noise levels over an extended period, in case of suboptimal fitting of the HPDs. The frequency spectra of the two environments before calibration are reported on Fig. 4.

The average fluctuation strength (Fastl, 1982), i.e. the hearing sensation related to loudness modulations at low frequencies, computed using ArtemiS SUITE with Psychoacoustics Module (HEAD acoustics, Herzogenrath, Germany) was 10.7 mvacil for the environment #A and 70.9 mvacil for the environment #B, confirming that the first environment is more stationary (i.e., with less fluctuations) than the second environment.

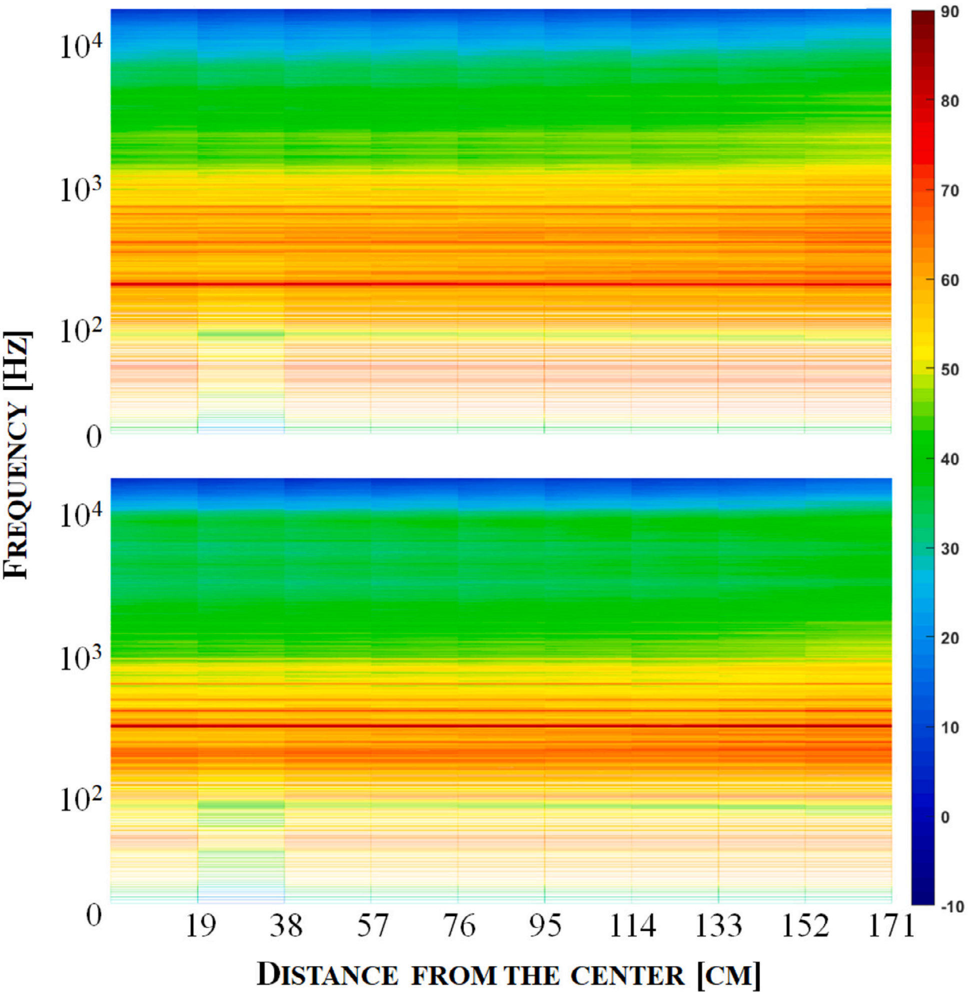


Fig. 3. Spectrum of the two environments generated by ABS-Synthesis, in dB SPL (top: environment #A, stacker. Bottom: environment #B, granulator).

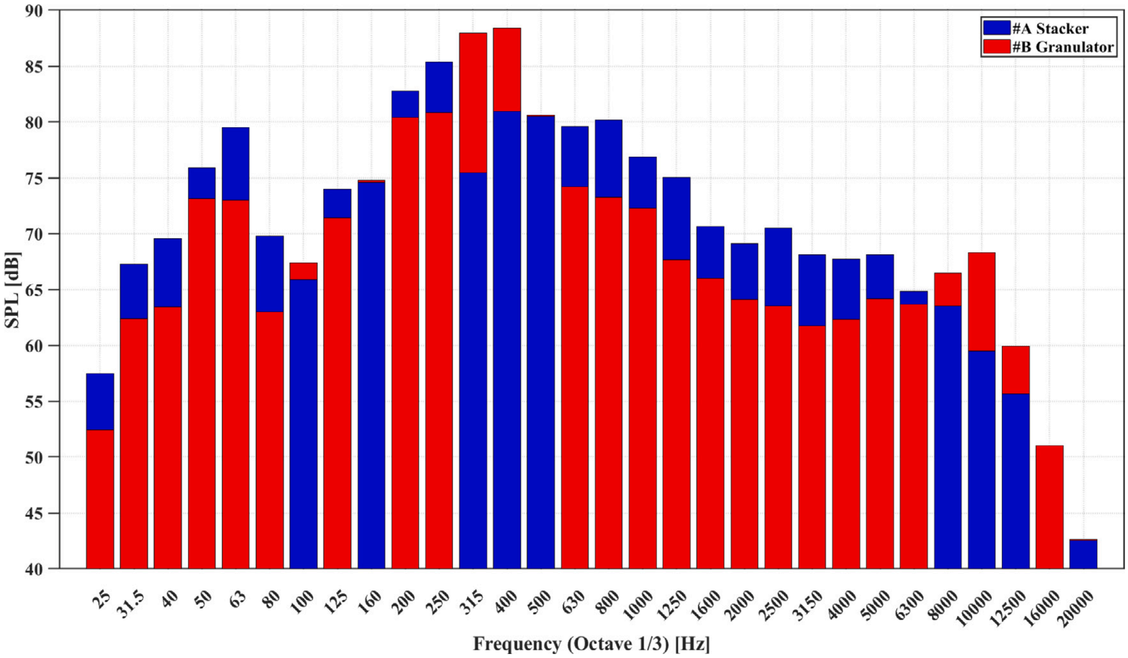


Fig. 4. 1/3 octave band frequency histogram of the two virtual industrial sound environments measured at the center of test room, before calibration.

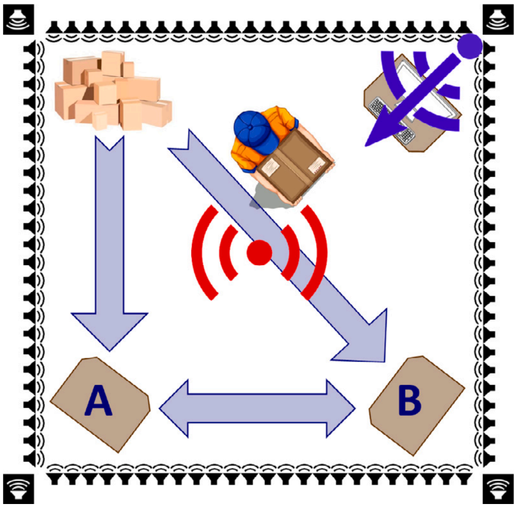


Fig. 5. Illustration of the simulated work task performed by the participant during the alarm detection tests #1 and #2 of Table 1. In a given scenario, the participant had to move a box from the stack of cardboard boxes on or under the table A or B, depending on the instruction.

2.5. Alarm detection tests

In real-life situations, individuals are rarely remaining in a stationary position while waiting for an alarm to sound. Therefore, the alarms detection task was conducted while participant were engaged in a simulated work task. The simulated work task (see Fig. 5) consisted in moving cardboard boxes according to the instructions that were indicated on a written note randomly drawn by the participant from the instruction box (“Pick a box from the stack and put it on Table A”, “Pick a box from the stack and put it under Table B”, “Pick a box from Table A and put it on Table B”, etc.). In Fig. 5, the square array of 96 loudspeakers of approximately 4 m by 4 m, 1.55 m above the ground is represented by the black square of loudspeakers. The supertweeter used to play the alarms, represented in red, was placed at the top center of the zone. The cardboard boxes were filled with biodegradable packaging peanuts and their weight was below the allowable load (25 kg or 55 lbs) as defined in ISO-11228-1:2003 “Ergonomics — Manual handling — Part 1: Lifting and carrying” (International Organization for Standardization, 2003). Participants were asked to read the instructions aloud before performing the described task to induce the deformation of the ear canal and thus of the earplugs.

The two virtual industrial sound environments were played sequentially in a random order as a background noise during the entire alarm detection test. Participants were informed that alarms would be played from time to time during the work task prescribed. They were asked to stop their task when they were able to hear an alarm and to push a button at the center of the touchscreen computer monitor placed in the corner of the room and to rate alarm urgency on a scale of 0–100, with a rating of 0 indicating that the alarm was heard, but evoked no sense of urgency and 100 being most urgent. Participants were asked to not focus to the alarm detection task but rather to concentrate on doing the simulated work task as seriously as possible.

The signal used for the alarm detection tests was a tonal gateway alarm captured at an industrial workstation using an Edirol R09 portable recorder with a FG-23652 condenser microphone (Knowles Electronics). Background noise was removed from the recording using Reaper v6.02 and the plugin “ReaFir”. Each alarm detection test included a total of fifty alarms (5 signal-to-noise ratios × 10 repetitions) with a duration of 10 s each. The alarms were presented at five different signal-to-noise ratios (SNRs) (−15, −10, −5, 0, +5 dB) using a Motorola piezo supertweeter CTS KSN1188. The most favorable SNR (+5 dB) was chosen based on a previous research study that aimed to identify the minimal SNR required to achieve a 100% score for alarm-in-noise detection (Rabau et al., 2014). The 5-dB step was chosen as a compromise between precision and practical time constraints, aligning with common practices in audiometric testing. Each SNR was computed relatively to the background noise SPL measured at the center of the test room. The interval between consecutive alarm signals was randomly set between five and ten seconds. The 1/3 octave spectrum of the alarm signal is illustrated on Fig. 6.

2.6. Speech perception in noise tests

During the speech perception in noise tests, participants remained standing in front of the computer in the corner of the room, as shown in Fig. 5, mirroring a real-life scenario where they would stand facing the person communicating with them. The speech perception in noise tests were conducted using the *Test de Phrases dans le Bruit* developed by J. Lagacée, B. Jutras, C. Giguère and J.-P. Gagné (Lagacé et al., 2010). Stimuli consist of sentences pronounced in French, randomly picked-up from a database of 324 sentences. Each sentence contains a subject, a verb and a color to be identified by the participants from a list displayed on the touchscreen monitor placed in front of them. For example, if the stimulus was *Les amis cherchent des ballons jaunes* (The friends are looking for yellow balloons) the correct answers to pick using the touchscreen monitor were *Les amis* for the subject, *cherchent* for the verb and *jaune* for the color. The stimulation levels were calibrated to 62.4, 68.3, 74.9, and 82.3 dB(SPL), which correspond to the level of normal, raised, loud and shouted voice as defined in ANSI S3.5 1997 (Pavlovic, 1997). A total of sixty (4 stimulation levels × 15 sentences) stimuli were presented to the participants using a supplementary M-Audio loudspeaker Studiophile DX4 placed in frontal incidence for the purpose of this task (see Fig. 5 where the loudspeaker is indicated by the dark blue dot and arrow in the top right corner). Since participants were wearing earplugs during this task and since they were exposed to relatively high sound pressure levels (90.9 dB(SPL) or 93.0 dB(SPL), depending on the virtual industrial sound environment used as background noise), the percentage of word recognition for the raised voice and the normal voice conditions were expected to be low due to the attenuation induced by wearing earplugs and the masking effect coming from the background noise (Olsen, 1998).

2.7. Comfort questionnaires

Three questionnaires were developed as part of a wider research project on HPDs comfort and adapted to the objectives and phases of this laboratory study (Doutres et al., 2019; Terroir et al., 2021). All these questionnaires were presented to participants using a touchscreen computer monitor and their responses were collected using a custom MATLAB script.

- The first questionnaire, entitled “Your User Profile” aimed to gather demographic information (e.g., age), and their level of familiarity regarding the use of HPDs. This questionnaire was completed by participants at the end of the preliminary session (see Table 1).
- The second questionnaire, entitled “Comfort Assessment” aimed to collect the comfort evaluations of the HPDs tested by participants. This questionnaire is derived from the “Comfort of hearing protection devices – North America Questionnaire” (COPROD-NAQ) in which participants express their opinion about the four dimensions of earplug comfort described in Terroir et al. (2017), Doutres et al. (2019) (physical, functional, acoustical and psychological, see Table 2). The COPROD-NAQ is the North American companion of the “Comfort of hearing protection devices (COPROD) questionnaire” validated in France by Terroir et al. (2021). 5-level Likert scales were used to measure each comfort attributes

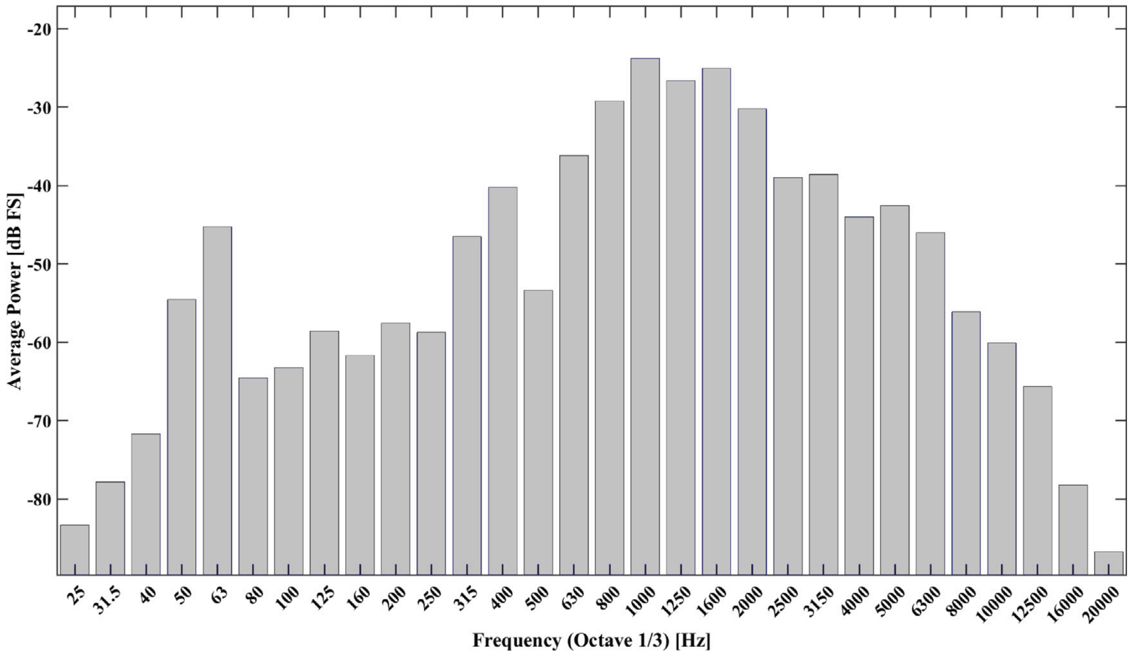


Fig. 6. 1/3 octave band frequency histogram of the alarm signal, in decibels relative to full scale (dB FS). The maximum of energy is reached at 1100 Hz. The spectrum was computed using a dimensionless digital audio signal (wav file).

with responses ranging from 1 (strongly disagree) to 5 (strongly agree). The overall comfort was also measured using a 5-level Likert scale with responses ranging from 1 (very poor) to 5 (very good). This questionnaire was completed by participants before and after each series of alarm detection tests and speech detection tests (see Table 1).

- The third questionnaire, entitled "Your Ideal Earplugs", was designed with the objective of collecting participants' preferred earplug models, identifying which earplugs' features should possess to be "ideal", and gathering participants' feedback and comments. This questionnaire was completed by participants at the conclusion of the study (see Table 1).

2.8. Statistical analyses

Objective measurement results (PAR values, alarm detection scores, and speech perception in noise results) were analyzed using Wilcoxon signed-rank tests (Wilcoxon, 1945) and MATLAB R2015b program (Mathworks, Natick, MA, USA).

To account for the correlation between observations on the same individual resulting from repeated measurements over time, Linear Mixed Models were employed using IBM SPSS Statistics for Windows, version 28.0.1.1 (14) (IBM Corp., Armonk, N.Y., USA) to assess the effect of the earplug family and the sound environment on each comfort attribute, as evaluated in the comfort questionnaires. Linear Mixed Models are a generalized form of matched data models or, more specifically, repeated-measures ANOVA, for continuous dependent variables. One of the strengths of these models is their ability to incorporate measures related to an individual, even if some of them are missing (due to premature disappearance, non-response, etc.) at a given time. In contrast, conventional procedures typically exclude individuals with incomplete responses. Since the Linear Mixed Model analyses consider the number of valid data based on the data structure rather than the number of participants, the power of the study is increased. The standard significance level for determining statistical significance in this study is set at 0.05. In other words, the maximum *p*-value to reject the null hypothesis (the sound environment or earplug family has no effect on a given comfort attribute) is 0.05.

3. Results

The PAR values, results of the alarm detection and speech perception in noise detection tests, results of the questionnaire-based comfort evaluations are presented in this section. These results are further discussed in Section 4.

Table 2
Items of the "Comfort Assessment" questionnaire for each comfort attribute and dimension, as well as for the overall comfort.

Dimension	Attribute	Explanatory items
Acoustical	Intelligibility of alarm signals	*Do these earplugs allow you to hear the alarm signals?*
	Discomfort due to internal noises	*When you wear these earplugs, are you bothered by the sounds of your body (swallowing, stomach, heartbeat, breathing...)?*
Physical	Physical discomfort	*Do these earplugs cause physical discomfort?*
	Pain	*Do these earplugs cause pain?*
Functional	Functionality	*Are these earplugs functional (good fit, intuitive fitting...)?*
	Effectiveness	*Are these earplugs effective?*
Psychological	Satisfaction	*Generally, are you satisfied with these earplugs?*
	Well-being	*Do you feel good when you wear these earplugs?*
Overall comfort		*Overall, how would you rate this earplug model?*

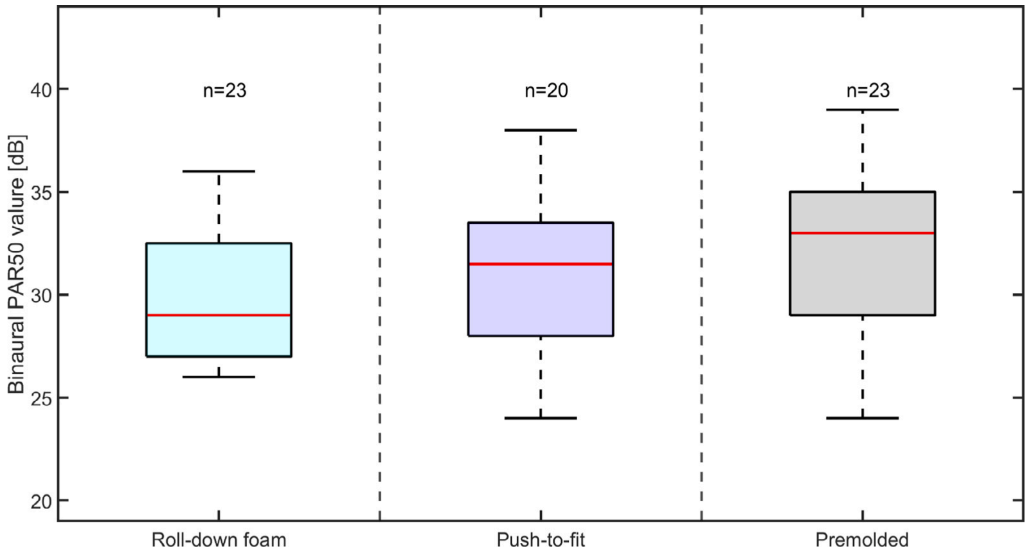


Fig. 7. Binaural PAR values without compensation factors for each model of earplug. The number of participants are indicated above each boxplot. The red central mark indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.1. Personal attenuation ratings

Fig. 7 presents the binaural PAR values without compensation factors (PAR50) for each earplug class (roll-down foam, premolded and push-to-fit) and for the whole pool of participants. The slight differences that can be observed on Fig. 7 across the different classes of earplugs remain non-significant as Wilcoxon unpaired tests failed to reject the null hypothesis at a 0.05 level.

3.2. Alarm detection tests

Fig. 8 presents the average percentage of alarm detection for the three types of earplugs and for each sound environment.

Results shown on Fig. 8 reveal that alarm detection results are influenced by the sound environment when the task is difficult (SNR = −15 dB), regardless of the earplug model worn by the participants. This observation is confirmed by Wilcoxon paired tests: for SNR values of 5, 0, −5 and −10 dB, Wilcoxon paired tests failed to rejected the null hypothesis, indicating no significant difference. However, for an SNR value of −15 dB, Wilcoxon paired tests rejected the null hypothesis, indicating a significant difference in results, regardless of the type of protectors. Additionally, results displayed in Fig. 8 indicate that the earplug family does no impact the alarm detection results. This observation is confirmed by Wilcoxon unpaired tests which failed to rejected the null hypothesis (no significant difference) when comparing each HPD against one another across all SNR conditions.

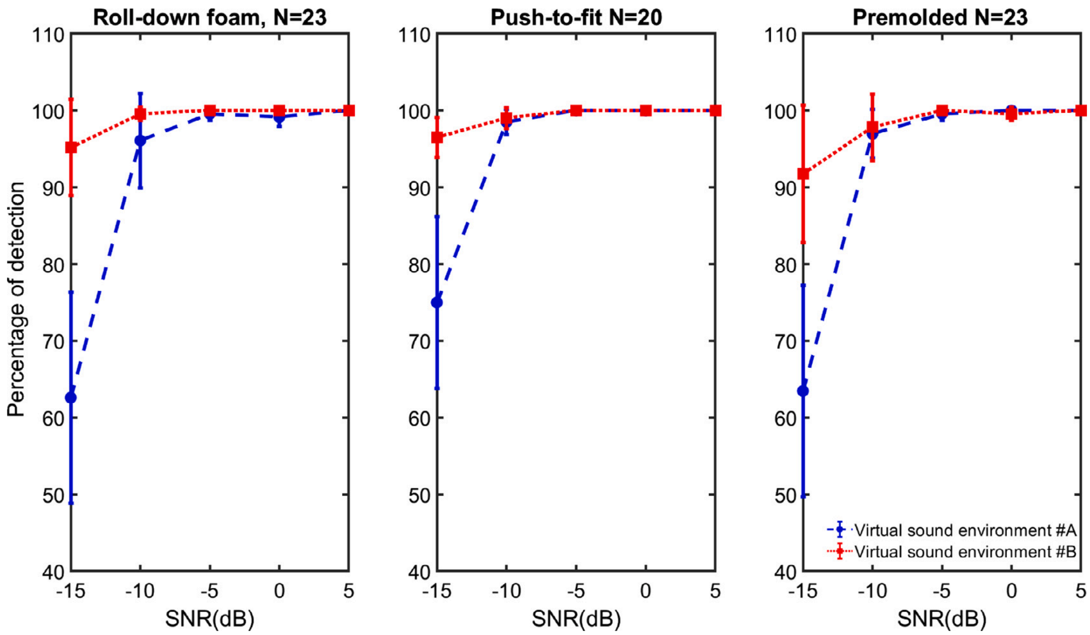
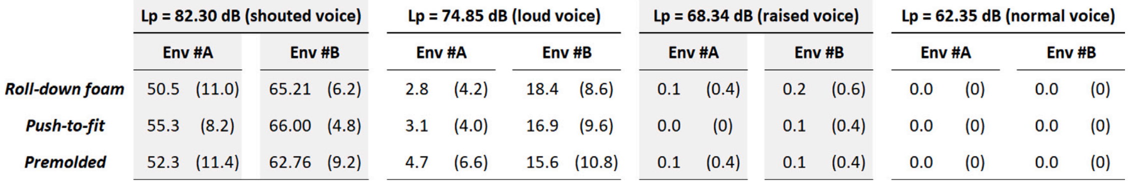


Fig. 8. Average percentage of alarm detection obtained for each model of earplug and for each sound environment. No statistical differences were found for SNR values of 5, 0, −5, and −10 dB ($p > 0.05$). However, for an SNR value of −15 dB, Wilcoxon paired tests rejected the null hypothesis, indicating significant differences regardless of the type of earplug (roll-down foam: $p = 0.0002025$, push-to-fit: $p = 0.001012$, premolded: $p = 0.004701$).

Table 3
Average percentage of word recognition with standard deviation, for each model of earplugs and each speech condition (shouted, loud, raised, and normal voice). The number of assessments performed were respectively 23 for the roll-down foam, 20 for the push-to-fit, and 23 for the premolded. Participants were unable to discriminate speech from noise in the “normal voice” condition. Wilcoxon paired tests revealed that speech-in-noise results are influenced by the sound environment for the “shouted voice” condition, regardless of the type of earplug (roll-down foam: p = 9.042e−05, push-to-fit: p = 0.0001104, premolded: p = 0.0003472). Similar results were observed in the “loud voice” condition (roll-down foam: p = 2.822e−05, push-to-fit: p = 0.02627, premolded: p = 0.0002182).



	Lp = 82.30 dB (shouted voice)				**Lp = 74.85 dB (loud voice)**				**Lp = 68.34 dB (raised voice)**				**Lp = 62.35 dB (normal voice)**			
	Env #A		**Env #B**		**Env #A**		**Env #B**		**Env #A**		**Env #B**		**Env #A**		**Env #B**	
Roll-down foam	50.5	(11.0)	65.21	(6.2)	2.8	(4.2)	18.4	(8.6)	0.1	(0.4)	0.2	(0.6)	0.0	(0)	0.0	(0)
Push-to-fit	55.3	(8.2)	66.00	(4.8)	3.1	(4.0)	16.9	(9.6)	0.0	(0)	0.1	(0.4)	0.0	(0)	0.0	(0)
Premolded	52.3	(11.4)	62.76	(9.2)	4.7	(6.6)	15.6	(10.8)	0.1	(0.4)	0.1	(0.4)	0.0	(0)	0.0	(0)

3.3. *Speech perception in noise tests*

Table 3 presents the average percentage of word recognition for the three types of earplugs and for each sound environment. As expected, participants were not able to discriminate speech from noise when the stimulation level is the lowest (“normal voice” condition), due to the masking effect induced by the virtual industrial sound environments, and due to the attenuation induced by earplugs. However when the task is easier, speech-in-noise scores for environment #B are somewhat higher than for sound environment #A (despite the fact that the SPL is larger for environment #B).

Results shown on Table 3 reveal that speech-in-noise results are influenced by the sound environment for the “shouted voice” and “loud voice” conditions, regardless of the model of earplug worn by the participants. This observation is confirmed by Wilcoxon paired tests: for the shouted voice and loud voice conditions, Wilcoxon paired tests rejected the null hypothesis, indicating a significant difference in results, regardless of the type of protectors. However, for the “raised voice” condition, Wilcoxon paired tests failed to rejected the null hypothesis, indicating no significant difference.

Wilcoxon unpaired tests were conducted to assess the impact of the earplug family on speech-in-noise results across various voice conditions. The results revealed that the earplug family does not significantly impact speech-in-noise outcomes (p-value > 0.05) when comparing the roll-down foam earplugs to the premolded earplugs. However, in the loud voice condition with environment #A, the roll-down foam earplugs showed a significantly lower word recognition compared to both the push-to-fit earplugs (p-value < 0.001) and the premolded earplugs (p-value < 0.01). These findings suggest that while the choice of earplug type generally did not lead to significant differences, there were notable exceptions under specific conditions.

3.4. *Questionnaires-based evaluations*

The aim of the questionnaire-based evaluations is to quantify the various comfort attributes of Table 2 as perceived by the participants. The effect of the earplug family and the sound environment on the perception of these comfort attributes is evaluated. The results of the statistical analyses of these questionnaires is presented in the following subsections.

3.4.1. *“Comfort assessment” results*

Figs. 9 and 10 report the perception of the main comfort attributes when only considering the earplug family and the sound environment as a factor, respectively.

Fig. 9 and the results of the multivariate analyses show that the earplug family has a significant effect on the perception of : discomfort due to internal noises (p-value = 0.001), physical discomfort (p-value = 0.03) and pain (p-value = 0.001), functionality (p-value = 0.02), and satisfaction (p-value = 0.014). According to the experience of the group of participants:

- Push-to-fit and pre-molded earplugs cause less annoyance due to internal noise than roll-down foam earplugs. Additionally, participants perceived that pre-molded earplugs cause less annoyance than push-to-fit foam earplugs.
- Participants perceived that roll-down foam and push-to-fit earplugs cause less physical discomfort and pain compared to pre-molded earplugs.
- Functionality is perceived higher with push-to-fit earplugs than with roll-down foam and pre-molded earplugs.
- The differences are statistically significant only between pre-molded and push-to-fit foam earplugs, with higher satisfaction reported for the push-to-fit foam earplugs.

With regards to the influence of the sound environment, only the acoustical dimension of comfort (intelligibility of alarm signals and discomfort due to internal noises) is reported in Fig. 10 since one may conjecture that acoustical comfort is primarily influenced by the sound environment. However, the results of the multivariate analyses show that the sound environment has no effect on any of the comfort dimensions, including acoustical comfort.

3.4.2. *“Your ideal earplugs” results*

The purpose of this questionnaire, conducted at the end of day #4, was to provide additional subjective data on the perceived comfort of the various earplug families tested. This questionnaire investigated two key aspects: (1) participants’ preferences regarding the most/least comfortable HPDs, and (2) the essential features that HPDs should possess to be considered “ideal”. Tables 4 and 5 respectively present the average preference rank (1 = best, 3 = worst) for each tested HPD and the average preference rank (1 = most important, 4 = least important) assigned by participants for each comfort dimension. These results should be considered with caution, given the small size of the pool of participants.

Five out of twenty participants (25%) ranked the roll-down foam earplugs as the best choice, whereas seven out of twenty participants (35%) ranked these earplugs as the worst choice. Five out of twenty participants (25%) also rated the premolded earplugs as the best choice, whereas ten out of twenty participants (50%) considered them as the worst choice. Finally, participants seem to have preferred the push-to-fit as these earplugs obtained the first rank for ten out of twenty participants (50%) and only three out of twenty participants (15%) ranked them as the worst choice among the earplugs available.

Table 4
Average preference rank for each tested HPD.

	Average rank
Roll-down Foam (3M™ Classic)	2.1
Push-to-fit Foam (3M™ Push-ins)	1.65
Premolded (3M™ UltraFit)	2.25

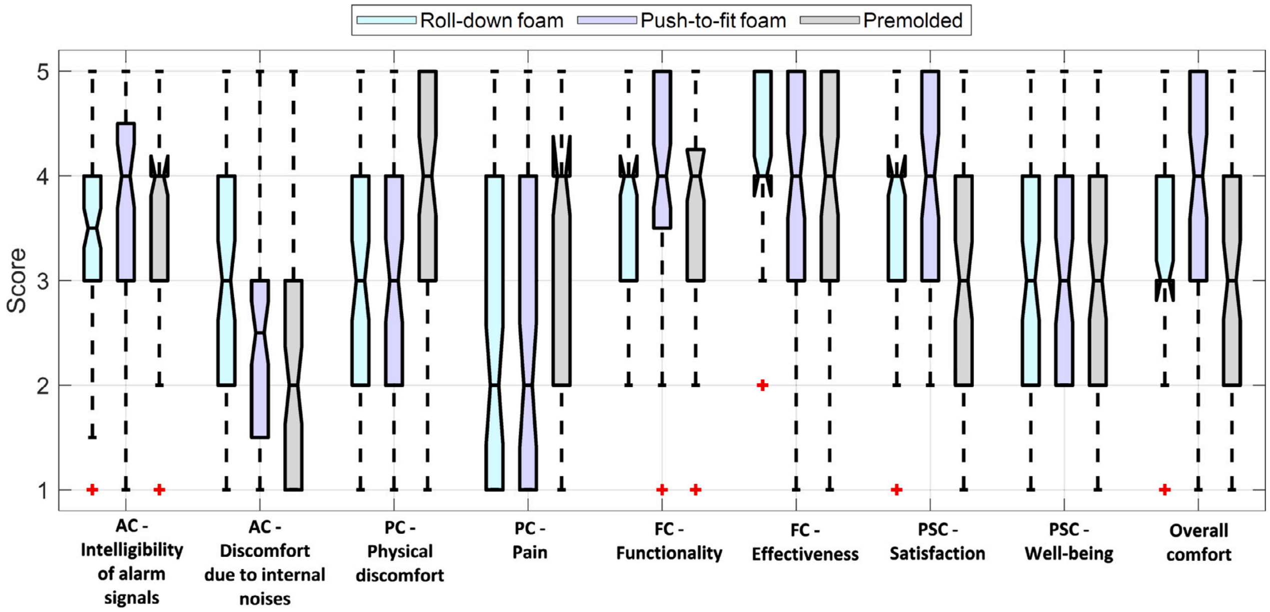


Fig. 9. Box plot of the perceived comfort of the main attributes of each dimension of comfort when only considering the earplug family as a factor. The central mark of the box indicates the median, the notch indicates the 95% confidence interval of the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. Outlier values are indicated using red crosses. AC, PC, FC, and PSC in the horizontal labels refer to acoustical, physical, functional, and psychological comfort, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

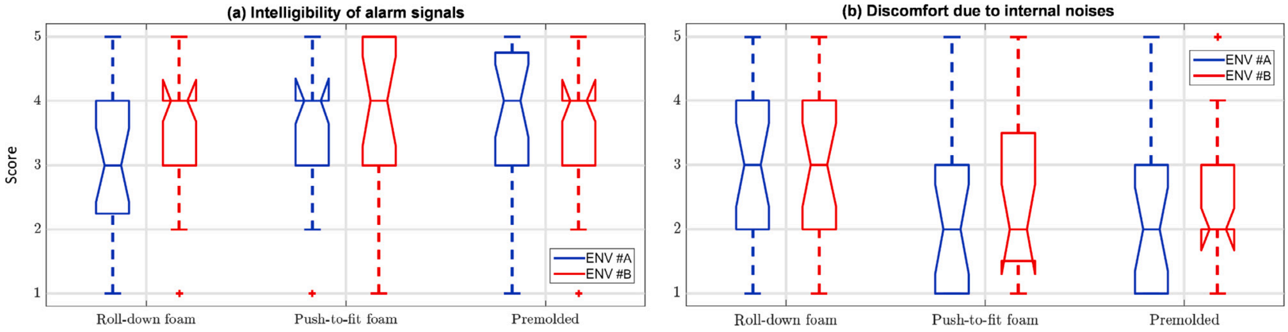


Fig. 10. Box plot of the perceived comfort of the main attributes of acoustical comfort when only considering the sound environment as a factor. The central mark of the box indicates the median, the notch indicates the 95% confidence interval of the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. Outlier values are indicated using red crosses. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 5
Average preference rank for each comfort dimension. The italicized text corresponds to the dimension description stated in the questionnaire titled "Your Ideal Earplugs".

	Average rank
Acoustical dimension *The earplugs allow good hearing (to be able to communicate, to perceive useful signals and not to be disturbed by internal body noises)*	2.95
Physical dimension *The earplugs do not cause pain or physical discomfort*	1.85
Functional dimension *The earplugs are functional (effective, good fit, easy to use)*	1.95
Psychological dimension *The earplugs allow you to feel good (to be confident, to get used to having them in your ears quickly, not to be afraid to wear them and to feel isolated)*	2.7

These results are consistent with the overall comfort scores in Fig. 7, even though the difference in the overall comfort scores was not found to be statistically significant. Participants estimate the physical dimension as the most important factor they take into account when evaluating HPDs. The functional dimension was considered the second most important factor by the participants, followed by the psychological dimension, and the acoustical dimension.

3.5. Earplugs mechanical characteristics

Questionnaire results show that pre-molded earplugs are perceived as causing more physical discomfort and pain than foam earplugs. We used linear mixed-effects modeling to investigate how physical discomfort and pain were influenced by the presence of a stem on the earplug (Stem), the radial force at 9 mm diameter compression (RF9), the extraction force (EF), and the friction coefficient (μ) (Ezzaf, 2023). These variables were selected from those reported in Poissenot-Arrigoni et al. (2023), based on their significance on the perceived physical discomfort/pain of earplugs. Given the relatively limited sample size of 24 participants, this analysis was conducted using three Linear Mixed Models (LMM) with two independent variables:

- LMM #1 with the two independent variables “Stem” and “RF9”.
- LMM #2 with the two independent variables “Stem” and “EF”.
- LMM #3 with the two independent variables “EF” and “μ”.

The results of the linear mixed-effects model analysis on perceived physical discomfort/pain are presented in Table 6. Results from the mixed linear models demonstrate that both physical discomfort and pain increase when: (1) there is the presence of a stem (which is the case for pre-molded earplugs), (2) the coefficient of friction increases (which is the case for pre-molded earplugs as they have a higher coefficient than foam ones), (3) the radial force increases (however, in this case, the radial force of foam earplugs is higher than that of pre-molded ones), and (4) the extraction force decreases.

These results are consistent with the results found by Poissenot-Arrigoni et al. (2023), namely that the presence or absence of the stem in the plug, radial force, coefficient of friction, and extraction force are parameters that potentially influence the perception of physical comfort attributes, namely physical discomfort and pain. Moreover, the direction of effect of these variables found in the present study is similar to that found by Poissenot-Arrigoni et al. (2023).

4. Discussion

4.1. Influence of the virtual sound environment

The objective alarm detection tests revealed that when the task is not difficult, the alarm is always detected by the participants, as expected. However, when the detection task is difficult (SNR = −15 dB), a masking effect occurs, rendering the detection of alarm signals more difficult. In such context, the acoustical features of the background noise modulate the masking effect imposed by the acoustical environment on the alarm signals. As can be seen on Fig. 4, environment #B has less energy than environment #A in the frequency range between the 630 Hz to 6300 Hz 1/3 octave bands. Within this frequency range, the alarm signal has its maximum of energy (cf. Fig. 6). These differences in this frequency range contribute to increase the masking effect induced by the sound environment #A on the alarm signals. Since the participants were instructed to never remove their hearing protectors throughout the entire experiment, the attenuation provided by the earplugs remains relatively constant. Consequently, the earplugs’ contribution to the masking effect remains unchanged, and it cannot explain the observed difference in results between environment #A and #B.

Similarly, in the objective speech perception in noise tests, the task difficulty varied with stimulation level. When the speech comprehension task is difficult (“raised voice” and “normal voice” conditions), the masking effect created by the background noise is so intense that it prevents participants from understanding the speech, regardless of the environment. However, when the speech comprehension task is not difficult (“shouted voice” and “loud voice” conditions), participants are able to discriminate the speech from the noise with more or less success depending on the background noise played as the environment. In fact, in such situations, participants are facing challenges similar to those encountered by hearing-impaired individuals when trying to discriminate speech from background noise. When individuals suffering from high frequency sensorineural hearing loss try to understand people speaking in noisy situation, they struggle to hear certain consonants (such as [s] or [f]), which are spoken at a higher pitch (typically in the 1.5–4 kHz frequency range) (Phatak et al., 2009). According to Fig. 4, environment #B has less energy than environment #A in the frequency range between the 630 Hz to 6300 Hz 1/3 octave bands, despite having a louder global sound pressure level (93.0 dB SPL versus 90.9 dB SPL). Consequently, the masking effect induced by environment #B on the speech stimuli is less pronounced than the one induced by environment #A, which explains the largest recognition scores for environment #B.

The subjective comfort questionnaires revealed that the sound environment had no significant effect on all the comfort dimensions as well as overall comfort attributes, indicating that individuals’ comfort levels while wearing hearing protectors were not influenced by the chosen sound environments.

While the questionnaire assessments yielded minimal differences in participants’ subjective evaluations of comfort, the objective measurements revealed significant differences in performances outcomes, specifically in terms of alarm detection and speech comprehension in the presence of high-level background noise environment. This suggests that individuals’ subjective perceptions may not fully capture the actual challenges and effects of the sound environment, emphasizing the importance of incorporating objective measures to gain a comprehensive understanding of the influence of the sound environment while evaluating the performance and effectiveness of HPDs. This result is in accordance with what has been reported by Doutres et al. (2022): objective perceptual tests and questionnaire-based evaluations may not necessarily align, as they capture different aspects. The perception of an effect, measured through objective perceptual tests, and the comfort judgment, assessed using questionnaires, represent two distinct concepts. Moreover, participants filled out the questionnaire only once, following 20 min of the “Speech in Noise Test” and 15 min of the “Alarm Detection Test”, despite undergoing five different conditions for the “Alarm Detection Test” and four for the “Speech in Noise Test”. This single questionnaire administration may have potentially averaged their experiences, resulting in a diminished perception of differences between environments. To mitigate this, conducting more frequent comfort assessments would help accentuate variations in subjective evaluations.

4.2. Influence of earplug family on comfort

The objective tests revealed that the earplug family had no significant effect on alarm detection results. However, speech perception in

Table 6
Summary of linear mixed-effects model analysis on earplug variables.

Model	Variable	p-value (physical discomfort)	p-value (physical pain)
LMM #1	Stem	0.005	0.001
	RF9	0.011	0.001
LMM #2	Stem	0.037	0.004
	EF	0.011	0.001
LMM #3	EF	0.008	0.001
	μ	0.037	0.004

noise scores in the "loud voice" condition were significantly lower for the roll-down foam earplugs as compared to both the push-to-fit and the pre-molded earplugs, when the environment #A served as background noise. This finding might explain the superior ranking in Table 4 of the push-to-fit earplugs compared to the roll-down foam and the pre-molded earplugs, especially considering that speech perception in noise results revealed that this task was more difficult when performed with the environment #A as background noise.

Regarding the responses to "comfort assessment" questionnaires and specifically the acoustical comfort dimension, push-to-fit and pre-molded are considered more comfortable with respect to the attribute related to discomfort due to internal noises. Park and Casali (1991) report that the comfort rating for the roll-down foam earplugs is principally affected by the fitting procedure, but it is not the case for the pre-molded earplugs. The differences in the perception of discomfort caused by internal noises may be due to the fact that roll-down foam earplugs are difficult to insert (Park and Casali, 1991; Casali et al., 1987; Samelli et al., 2018; Doutres et al., 2019). In our experiments, they may have not been inserted deeply enough and therefore generated more occlusion effects, as reported by Berger (2003) who argues that the less the earplug is inserted, the greater the occlusion effect. However, there is no significant effect of the family of earplugs on the attribute associated with the intelligibility of alarm signals. This observation is consistent with the objective results of alarm detection tests.

For the physical dimension, the subjective assessment of the comfort show that the perceived physical discomfort and pain are higher for pre-molded earplugs compared to roll-down foam and push-to-fit. Gonçalves et al. (2015) also find the same results in their study which reports an important physical discomfort for earplugs with silicone flanges (pre-molded earplugs in this case) compared to other earplug models, especially for the mechanical pressure (Epps and Casali, 1985; Casali et al., 1987). The higher perception of physical discomfort and pain associated with the pre-molded earplugs may be attributed to the mechanical pressure exerted by this particular earplug model, as suggested by Gerges and Casali (2007) who argue that the primary source of perceived discomfort in the physical dimension is likely due to the mechanical pressure.

The functionality of earplugs is measured by ease of insertion, stability (positioning), and good fit in the subjective comfort questionnaire. The results show that push-to-fit foam earplugs are considered more functional compared to roll-down foam and pre-molded earplugs. Push-to-fit foam earplugs are an alternative between the roll-down foam and pre-molded families tested in this work. They offer a compromise between the adaptability of compression of roll-down foam and the insertion quality of pre-molded earplugs. Push-to-fit foam earplugs are therefore more likely to be perceived more functional than the other earplugs, which is what our subjective results demonstrate. Contrary to the results of our questionnaire, Gonçalves et al. (2015) report that pre-molded earplugs are found easy to fit. This type of earplug is made of flexible materials (silicone type) and is less deformable than foam earplugs. These earplugs may fit well, but the lower perception of their functionality in our study is probably due to the fact that there is only one size of these earplugs and they do not adapt in the same way to different ear canal geometries. It was found in previous work that roll-down foams present a good maintaining in position, but they are difficult to insert (Park and Casali, 1991; Casali et al., 1987; Doutres et al., 2019). The lower perception of the functionality of roll-down foam earplugs in this study may be due to the difficulty of inserting these earplugs for naive participants.

The psychological dimension is less cited in the literature related to the comfort of hearing protectors. From a psychological point of view, the results of the subjective comfort questionnaire show that the participants satisfaction level is higher for push-to-fit foam earplugs compared to pre-molded earplugs, while roll-down foam earplugs do not stand out significantly. However, the earplugs family has no significant effect on the participants' perception of well-being.

4.3. Influence of earplugs mechanical characteristics

Despite the limited sample size, the results of this analysis are consistent with the findings reported by Poissenot-Arrigoni et al. (2023). Specifically, earplugs with stems (i.e., push-to-fit and premolded earplugs) were found to be less comfortable in the physical dimension than those without stems. Additionally, earplugs with higher coefficients of friction and radial force were associated with increased physical discomfort and pain, while earplugs with a high extraction force were correlated with decreased physical discomfort and pain. This is consistent with what was reported by Gerges and Casali: the primary source of perceived physical discomfort and pain is likely due to mechanical pressure (Gerges and Casali, 2007). These findings, along with those from Poissenot-Arrigoni et al. (2023), seem to confirm that:

- Earplugs with stems (pre-molded foam earplugs with stems and pre-molded earplugs) generate more physical discomfort and pain than compressible foam earplugs.
- The greater the radial force, the greater the physical discomfort and pain.
- The greater the extraction force, the less the physical discomfort and pain.
- The greater the coefficient of friction, the greater the physical discomfort and pain.

The consistency of these results lies in the fact that soft tissue undergoes greater compression in the presence of a high radial force, leading to increased physical discomfort and pain. In addition, irritation of the skin of the ear canal could also be exacerbated by a high coefficient of friction, accentuating the level of discomfort experienced. Similarly, increased motion of the earplug in the ear canal may be caused by low extraction force, leading to irritation and, consequently, physical discomfort and pain.

5. Conclusion

This paper introduces a novel laboratory method for comprehensive assessments of the multidimensional comfort aspects of earplugs, combining objective perceptual tests (alarm detection and speech perception in noise) within virtual industrial sound environments replicating *in-situ* noise exposure, and questionnaire-based evaluations. The specific goals of this study were: (1) to evaluate how the acoustic environment and the earplugs family affect the acoustical dimension of comfort using objective perceptual tests (alarm detection tests and speech perception in noise tests) and questionnaire-based evaluations (through "comfort assessment" questionnaires), and (2) to investigate how the acoustic environment and the earplugs family impact the physical, functional and psychological dimensions of earplugs comfort using questionnaire-based evaluations.

In terms of the impact of sound environments, objective alarm detection and speech perception results underscore the significance of considering real-world sound environments when evaluating earplugs comfort and effectiveness. Objective alarm detection tests revealed that in challenging detection scenarios, specific acoustic characteristics, such as sound energy distribution in certain frequency ranges, significantly affect alarm signal detection by influencing how background noise masks alarm signals. These findings highlight the need to tailor earplugs recommendations to specific workplace noise environments to ensure effective alarm signal detection. Similarly, speech perception in noise tests when wearing earplugs confirmed that the difficulty of understanding speech in noisy settings depends on both the speech level and the characteristics of the background noise. This emphasizes the importance of not only considering the overall noise level but also the spectral content when selecting earplugs for improved speech comprehension in noisy environments. While subjective questionnaire-based comfort assessments did not reveal substantial differences related to the sound environment, objective measurements showed significant performance variations, underscoring the importance of including objective measurements when evaluating sound environments' impact on HPD performance and effectiveness. These results substantiate that the perception of an effect, measured through objective perceptual tests, and the comfort judgment, assessed using questionnaires, represent two distinct concepts.

Regarding the impact of the earplug family, objective alarm detection results indicated no significant impact. However, for objective speech perception tests in noisy environments, roll-down foam earplugs were less effective compared to push-to-fit and pre-molded earplugs, especially in challenging conditions. This suggests a preference for push-to-fit earplugs, particularly in high-noise environments, for speech-related tasks. Subjective comfort assessments revealed that push-to-fit and pre-molded earplugs were considered more comfortable in terms of acoustical comfort, particularly regarding discomfort related to the occlusion effect. In contrast, pre-molded earplugs were associated with higher perceived physical discomfort and pain, which may arise from the pressure applied by the earplugs. Push-to-fit foam earplugs were perceived as more functional than roll-down foam and pre-molded earplugs, possibly due to their adaptability and insertion quality. From a psychological perspective, participants expressed higher satisfaction levels with push-to-fit foam earplugs compared to pre-molded earplugs. However, the choice of earplug type did not significantly affect participants' overall sense of well-being.

The analysis of earplug mechanical characteristics revealed that earplugs with a stem (i.e., push-to-fit and premolded earplugs), higher radial force, and higher friction coefficient significantly increased perceived physical discomfort and pain, while those with higher extraction force were associated with decreased discomfort and pain, which is consistent with previous work (Poissenot-Arrigoni et al., 2023).

CRediT authorship contribution statement

Olivier Valentin: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Said Ezzaf:** Formal analysis, Data curation, Software, Writing – original draft, Writing – review & editing. **Philippe-Aubert Gauthier:** Investigation, Methodology, Project administration, Supervision, Writing – review & editing, Conceptualization, Data curation, Formal analysis, Resources, Software, Validation, Visualization. **Djamal Berbiche:** Data curation, Formal analysis, Supervision, Validation, Conceptualization, Investigation, Methodology, Project administration, Resources, Software, Visualization, Writing – review & editing. **Alessia Negrini:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – review & editing. **Olivier Doutres:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing – review & editing. **Franck Sgard:** Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Supervision, Writing – review & editing, Methodology, Validation. **Alain Berry:** Conceptualization, Funding acquisition, Project administration, Supervision, Validation, Writing – review & editing, Investigation, Methodology, Resources.

Declaration of competing interest

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

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