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EARPLUGS COMFORT: DEVELOPMENT OF A LABORATORY EVALUATION PROTOCOL

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ABSTRACT

Today, personal noise protectors, especially earplugs, remain the most common option for reducing noise exposure. Despite this, they are frequently discontinued, misused or rejected by exposed employees. Thus, the "comfort" dimension appears to be paramount in terms of the use of earplugs and, consequently, in terms of the effective protection provided. Based on this observation, a French-Canadian study (INRS/IRSST) was initiated in order to better understand the parameters involved in the feeling of comfort. Firstly, field tests (not presented here) were carried out in order to collect, via daily and weekly questionnaires, data under working conditions. But this approach, despite its advantages (realism of working conditions, noise environment, activities, needs and uses of earplugs), presents various constraints linked to the very nature of field tests (time-consuming protocol, complicated follow-up, numerous uncontrollable parameters, etc.). The second part of this project therefore aims to evaluate the comfort of earplugs under controlled laboratory conditions in order to eventually better understand comfort and to compare field and laboratory data. This presentation will focus on presenting this protocol and the way it sometimes echoes field tests (plug models, questionnaires, etc.) while taking into account the possibilities and constraints of the laboratory.

1. INTRODUCTION

In France, many workers are exposed on a daily basis to noise levels that are potentially hazardous for their hearing. In addition to collective protection solutions, the use of individual hearing protection devices (HPD), and more specifically earplugs, remains widespread. While the "comfort" dimension may at first seem secondary, it conditions the acceptance and duration of wear and, consequently, the effectiveness of the protection. Therefore, the question of the use of HPDs cannot be dissociated from the comfort one. Based on this observation, a French-Canadian study (INRS/IRSST) has been initiated in order to address the issue of earplug comfort [1]. This has been done through a global approach which does include different dimensions identified during a preliminary work [2][3][4]. The next step was to develop questionnaires based on this work. It was then deploy in

the field in different companies. The goal was to assess and rank several earplugs (self-reported comfort) and to establish relationships between the overall comfort and the different properties of comfort [5].

While field studies make it possible to assess comfort under real conditions of use, noise environment and people's activities, this approach also proves to be time-consuming, subject to many uncontrollable parameters (sound environment, activities, use assiduity, duration of use of the earplugs, etc.) and monitoring people can be difficult. In order to overcome these constraints, the next part of this project focuses on the development of a protocol dedicated to the evaluation of the comfort under controlled laboratory conditions. This paper presents this protocol and how it sometimes echoes field tests (earplug models, questionnaires, etc.), while taking in account the possibilities (control of the sound environment, repeatability of tasks, verification of the earplugs positioning, etc.) and constraints (unrealistic working conditions, shorter test duration, etc.) of the laboratory.

2. COMFORT DEFINITION

Approaching a concept such as comfort requires first to define it. However, the comfort definition varies a lot in the literature (and consequently the parameters related to its evaluation). Therefore the first step of this study consisted in a literature review [3][4] in order to identify the parameters that can influence the feeling of comfort and to apprehend it as comprehensively as possible. Four dimensions of comfort were then proposed [3][4]. « Physical comfort » is inversely related to pain and physical annoyance. It may be due to sensations of irritation in the ear canal (during insertion, wearing or removal) or to the earplug mechanical pressure against the ear canal. « Acoustic comfort » is related on the one hand to good perception of useful sounds (ease of communication, sounds from machines, alarms, messages, vehicles) as well as sound localization, and on the other hand to discomfort related to the occlusion effect (distortion of user's own voice, exacerbated perception of body noises). « Functional comfort » has been defined through several notions: efficiency, related to the feelings of protection and over-protection; ease of use, related to intuitiveness, ease and speed of insertion and removal, to requiring few gestures or actions, to staying in position and to ease of cleaning; utility with regard to the working environment and working activities; the perceived impact on concentration, quality of work and productivity. Finally, « psychological comfort » (which reflects the well-being associated with the earplug use) is related to : trust, habituation, absence of discomfort due to the feelings of isolation, perceived satisfaction, the extent to which needs are met and, finally, considering readiness to reuse of the earplug model in the future.

3. PARTICIPANTS

As in the field tests [5], laboratory participants should be normal hearing (BIAP criteria, i.e. mean value of the losses at the frequencies 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz less than 20 dB for both ears) and non-naïve regarding the use of earplugs. In addition, as some tasks involve color detection (see section 7.1), a non-color blind condition has also been included.

4. TESTED EARPLUGS

Earplug types tested in the laboratory will be identical to those tested in the field [5]. Thus, nine types belonging to three different families will be tested: roll-down foam (A_1 , A_2 , A_3), premolded (B_1 , B_2 , B_3) and custom molded (C_1 , C_2 , C_3). In order to establish a general ranking and to conduct inter-family and intra-family analyses, an experimental design involving nine different configurations was chosen for both field and laboratory tests (this design is detailed in [5]), each participant testing a single configuration. Over 6 sessions, each participant will test 3 models (1 per family) according to the following sequence $X_i, Y_j, Z_k, X_i, Y_j, Z_k$ (with $[X; Y; Z] \in [A; B; C]$ and $[i; j; k] \in [1; 2; 3]$). This sequence is in accordance with the field tests. Advantage has been taken of this point by introducing two sound environments in the protocol (cf. section 6). The distribution of the configurations among the participants as well as the order in which the earplugs are tested will be random.

5. QUESTIONNAIRES

All the attributes identified during the preliminary literature review (cf. section 2) were included into the field questionnaires [5]. In order to be able to compare laboratory and field results, and to keep a global approach to comfort, the majority of the items from the field questionnaires were included into the laboratory protocol (without rewording, except where necessary due to the context). Only items too specific to field or off-topic conditions were excluded: earplugs cleaning (unsolicited action in the laboratory); impact on productivity (too much linked to knowledge of productivity associated to a usual task); perception of the sounds of the machines useful for your work (laboratory tests do not involve the use of machines); perception of company communication messages (this aspect is included in the intelligibility task - cf. paragraph 7.2); perception of vehicles (the laboratory sound environment - cf. paragraph 6 - includes vehicles noises, so there would be a risk of confusion).

6. SOUND ENVIRONMENT

A great variability of sound levels and sources (inter or intra-company) was observed in the field. Moreover, the current state of knowledge does not allow to know (1) which sound level(s) would allow to get closer to the field results (the literature is rather poor concerning

comparisons between field and laboratory); (2) if the sound environment has an impact on earplug comfort (in the field as well as in the laboratory). In order to place the participants in realistic conditions without trying to reproduce a specific environment (due to the variability mentioned above), a "fictive" soundtrack was constructed from industrial recordings. Level fluctuations were limited ($L_{10} - L_{90} = 1.4$ dB(A)) in order to avoid uncontrolled masking effects for the intelligibility and perception of sound signals tasks (see sections 7.2 and 7.3). The spectrum was also adjusted according to the pink noise described in International Standard 62168-1 [6]. Concerning the sound levels, two L_{Aeq} modalities were selected according to three conditions: (1) they are based on the levels observed in three different field test sites (in the areas concerned by HPD mandatory use, measurements range from 70 dB(A) to 99 dB(A)); (2) from a regulatory point of view [7], they require the use of plugs. In accordance with the first action threshold that can be found in the regulation [7], the first L_{Aeq} value is 80 dB (A) (despite the fact that measurements sometimes indicate lower minimum levels in the field. The second value was set at 95 dB(A) because (1) levels measured in the field may be high and (2) a large difference between the two conditions is preferable to observe a possible impact of the L_{Aeq} on perceived comfort. Under protection, the exposure of participants will therefore not exceed the regulatory limits [7]. Concerning the broadcasting conditions, a stereo system in a quiet room was chosen.

7. TASKS

7.1 Tasks involving varying levels of mental load

In this study, mental load was defined as the set of mental operations performed by the worker during the performance of his work tasks generating efforts of concentration, comprehension, attention, precision, speed and required quality. Mental load was first assessed in the field in order to estimate its variability. The employees participating in the field tests were asked to list all the tasks performed in the course of their work and to evaluate each of them on a Borg scale ranging from 1 to 10 (CR10). Then this score represents the result of a compromise between all the above-mentioned aspects.

As for the noise environment, there is great variability in the inter-company or intra-company tasks and therefore in the mental load levels to which people are subjected. Thus, despite the desire to maximize the similarities between field and laboratory tests, it remains impossible to reproduce field tasks in the laboratory in a realistic and generalizable way. Moreover, the impact of mental load on the feeling of comfort is still unknown, as well as the similarity of this impact in the field or in the laboratory. Therefore, at this stage of knowledge, these different points suggest to define laboratory tasks requiring several levels of mental load. In order to accentuate the possible effect of this parameter while limiting the number of modalities, two levels were chosen: "low" and "high"

mental load. The need to use the earplugs for at least 2 hours [8] and the fear of participant weariness or fatigue made it necessary to select several tasks per modality. In the end, 12 tasks were selected. All of them were sized to last about 5 minutes (this duration results from the compromise between the number of tasks, possible fatigue for some of them and the wearing time of the earplugs). A first pre-test made it possible to quantify the mental load. Seven participants assessed (CR10 Borg scale) the mental load for each task. This step was carried out in the sound environment described above (see paragraph 6) at 60 dB(A). This level was selected in order to avoid participants having to use earplugs, as the choice of an arbitrary model could introduce a bias related to its properties. Furthermore, this level corresponds approximately to the level under the protector for a 80 dB(A) broadcast. Based on the pre-test results, six tasks associated with a low mental load were selected (clicking on boxes, comparison of successive patterns, easy level Sudoku, additions, reading a comic strip, word categories game). They had average Borg scores ranging from two to 3.2 (mean: 2.4). Six tasks were similarly associated with a high mental load (memorization of a list of numbers, memorization of the position of figures, puzzle, Stroop test, memorization of a path, counting of figures). They had average Borg scores ranging from 7.4 to 8.7 (mean: 8). These levels are consistent with those observed in the field (mean Borg scores equal to 1.9 for tasks requiring a low mental load and to 7.8 for tasks requiring a high mental load).

Laboratory questionnaires items related to the relationship that may exist between activity and comfort address the perceived impact of earplug use on concentration and on the quality of work (functional comfort - see paragraph 2).

7.2 Intelligibility task

Acoustic comfort (see paragraph 2) is partly related to speech intelligibility. One should note that the aim here is to evaluate the participants' feelings and not to measure perceptual thresholds. The selected task is based on the identification of words (2 to 5 syllables) in the sound environment described above (cf. paragraph 6). After each broadcast, the participant is asked to write in the dedicated graphic window the word he/she heard. Concerning the sound level of the word, studies dedicated to the relation between HPDs and intelligibility have proposed protocols with background noise levels ranging from 60 to 95 dB(A) with SNRs (Signal to Noise Ratio) ranging from +10 to -10 with 5 dB steps [9][10]. Background noises were unrealistic synthetic noises (white or pink) and words were monosyllabic. On this basis, five SNRs were selected. Results show a decreasing distribution of the number of correct answers with SNR reduction: rates of 81%, 71%, 40%, 17% and 0% for respective SNRs of +10, +5, 0, -5 and -10 dB. Pre-tests showed that these levels were appropriate, despite the fact that success rates were lower than the ones usually found in the literature. Random pauses were included before each broadcast (between 0

and 5 seconds) in order to reduce the bias related to a possible anticipation effect.

7.3 Perception of useful signals task

Acoustic comfort is also related to the perception of useful signals and to their localization (see paragraph 2). The nature of these signals (alarms, machine noises, etc.) will then depend on the working environment. For the laboratory tests, three five-second signals were selected (AFNOR fire alarm, bi-tonal back-up alarm, French railway society alarm) and level normalized. Five SNR levels were selected (-20, -15, -10, -5, 0 dB), as well as two localizations (left or right). Pre-tests showed that the SNR levels were appropriate. A decreasing distribution of the signal perception rate was observed with the reduction of the SNR (ranging from 95% signal perception for the upper modality (0 dB) to less than 20% for the lower modality (-20 dB)). Random pauses were included before each broadcast (between 0 and 5 seconds) in order to reduce the bias due to a possible anticipation effect. After each broadcast, the participant is asked to indicate the signal localization, the localization failure, or the lack of perception. In an unknown laboratory context, the list of multiple choices enables him/her to evaluate the perceived quality of his/her signal perception with the tested earplugs.

7.4 Occlusion effect tasks

The occlusion effect is the third aspect related to acoustic comfort (see section 2): discomfort related to the perception of the user's own voice, internal body sounds and discomfort related to jaw movements. There are few subjective assessments of the occlusion effect in the literature and they are mainly performed in the context of hearing aid studies. There are two types of tests: (1) assessment of the participant's own voice [11][12] and (2) assessment of an external voice [13]. In the present study, the perception of external voices is approached with the intelligibility task (see section 7.2). In order to solicit the perception of one's own voice, a task of reading aloud in noise was selected. This will also be addressed in a quiet environment during a median break (see detailed protocol in section 8). Concerning the discomfort related to the perception of jaw movements or body noises, participants will be invited to chew gum, eat a cake and drink during this same break.

7.5 Movements

Preliminary literature work (cf. paragraph 2) has identified some specific movements as a possible source of physical discomfort and pain. Consequently, a task requiring simple movements (turning the head, inclining the head, standing up and inclining to the right, left or back and forth) has been included into the laboratory protocol in order to solicit this aspect.

8. PROTOCOL

The laboratory protocol addresses, as in the field, all the items that were identified during the preliminary work and included in the field questionnaires, with the exception of items that could not be transposed to the laboratory (cf. section 2). It integrates all the tasks described in section 7. For each one, scores (number of correct answers, response time, progress, etc.) are recorded so that, if necessary, analyses can be carried out based on objective data. The process is sequential (no overlapping of tasks). If field tests participants had to answer the questionnaire all at once, it was decided to segment the laboratory questionnaire in order to collect participants' feelings as they go along. It also enables to multiply the collections for the repeated tasks.

The sound environment is launched from the time the earplugs are inserted until they are removed. A first block of tasks is presented to the participant. It does include (in random order): 3 tasks associated with a low mental load, 3 tasks associated with a high mental load, as well as intelligibility, perception of useful signals, reading aloud and movement tasks. After each one, the dedicated items are presented to the person. This first group of 10 tasks is followed by a median break of about 15 minutes during which the participant is extracted from the sound environment and is invited to talk, eat and drink while keeping the earplugs. The items associated with these points are then presented. A second group of 10 tasks follows the break. The tasks related to mental load are not the same as in the first block, the order is still random and the tasks of intelligibility, perception of alarm signals, reading aloud and movement are repeated a second time. This second block is followed by the earplug removal (the items dedicated to the feeling of comfort during removal are then presented). At the end of the session, all the items that are included the field questionnaires and that could not be evaluated yet are presented.

At the beginning of the test, earplug insertion is explained with the help of a video support and supervised by a technician. As leaks are detectable at 250 Hz and 1000 Hz, the quality of the insertion is checked by calculating (for these two frequencies) the difference between the auditory thresholds with and without protectors. In order to validate the set-up, this must be at least a 20 dB difference for each frequency.

The protocol detailed above corresponds to the sequence of a single session. Each participant will take part in six sessions: three models of earplugs (see section 4) will be tested for two sound levels (see section 6). The order of the tests will be random (for both earplugs models and sound levels). The total duration of each session will be approximately 2.5 hours, including two hours of effective use of the earplugs, according to the literature [8]. Complementary data (socio-demographic information, usual working environment, use habits of earplugs, etc.) will be collected at the beginning of the first session. The complete protocol has been pre-tested with five people and validated.

9. CONCLUSIONS / PERSPECTIVES

In order to be able to evaluate the comfort of earplugs under controlled conditions, a laboratory protocol was constructed. The objective being to be able to compare field and laboratory data, a special effort was made to encourage mimicry between field and laboratory protocols: (1) the tested models of earplugs (roll-down foam (A₁, A₂, A₃), premolded (B₁, B₂, B₃) and custom molded (C₁, C₂, C₁)) are identical to both tests[5]; (2) earplugs are tested according to an Xi, Yj, Zk, Xi, Yj, Zk sequence (with $[X ; Y ; Z] \in [A ; B ; C]$ and $[i ; j ; k] \in [1 ; 2 ; 3]$); (3) as far as possible, the comfort items included in the questionnaire(s) are similar; (4) the sound environment is realistic and reproduces a (fictive) industrial environment; (5) the diffusion levels are consistent with the levels measured on site (80 and 95 dB(A)). Conversely, (1) the duration of the laboratory tests is shorter than the duration of the field ones (2 hours vs. one week); (2) the laboratory questionnaire was segmented in order to collect participants' feeling immediately after each step (the answers are therefore not potentially altered by an overall feeling).

The analysis of the laboratory data will enable (1) to identify the effect of mental load on responses; (2) to identify the effect of noise level on responses; (3) to assess the impact of time on responses to repeated items; (4) to compare field and laboratory data in order to identify similarities or differences (earplugs ranking, relevant comfort parameters) and to validate or modify the laboratory protocol.

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