



Towards a “global” definition of the comfort of earplugs

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ABSTRACT

Many workers are regularly exposed to potentially dangerous noise levels. The risk of hearing loss then depends on both the level and the duration of exposure. Hearing protection devices (HPD) and more specifically earplugs are the most commonly used noise control solution. Nevertheless discontinuous use, misuse or refusal are frequently observed. Thus, while the "comfort" dimension may a priori seem secondary compared to the stated attenuation, it impacts the effective protection by influencing the HPD consistent and correct use. Despite the fact that this last point (and consequently the protection one) cannot be dissociated from the comfort one, earplugs still remain exclusively characterized by the acoustic attenuation they provide. It raises the question of identifying and understanding the comfort attributes and therefore the question of the definition of the comfort itself. This turns out to be major because this will finally impact the protocol of any research dedicated to comfort. Consequently, in order to progress on this crucial point, this paper presents different comfort attributes identified in a recent literature review (which includes the following four typologies: physiological, auditory, functional and psychological) and that will constitute the first step towards a "global" definition of comfort.

Keywords: HPD, Earplugs, Comfort

Classification of Subjects Number(s): 36

1. INTRODUCTION

Comfort impacts the effective daily protection by influencing the user habits (correct fitting, consistent use, etc.). In order to protect and improve the auditory health of workers, the INRS (France) and the IRSST (Canada) have started working in close collaboration on the comfort of earplugs, in terms of both its understanding and its modeling. One major achievement of this project would be to progress toward a method enabling to easily rank the comfort of a given earplug using dedicated indices. Such a project first requires establishing an inventory of the parameters that could be involved in the perception of the comfort in all its diversity and with as few a priori as possible. This paper summarizes this first key step. After contextualizing the problem of comfort of earplugs in the workplace, results and observations from the literature are presented by encompassing (without any prioritization) attributes that could potentially impact the earplug comfort and be included in its future “global” definition.

2. BACKGROUND

2.1 Hearing protection devices at work

Numerous workers are exposed on a daily basis to noise levels that can cause hearing impairment. The risk of hearing loss is then a function of both the noise level at the eardrum position and the exposure duration. In order to comply with the regulatory limits imposed by the various international

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directives (set without taking into account a possible protection) (1), several options are available: (a) to reduce the emission levels of the noise sources and/or act on the room acoustics; (b) to reduce the exposure duration of the workers; (c) to use individual hearing protection devices (HPD). While the best solution undoubtedly remains the action at the source, it requires either taking into account the noise constraints during the design of the machines or, in the case of existing machines, modifications which can be expensive and time consuming to set up. Another option is to act on the sound propagation by using acoustic treatments, screens or enclosures. The organization of the work may also help to reduce the noise exposure duration. However many workplaces are not suitable for this type of measures (e.g. steel plants, sawmills, foundries, airports, etc.). Finally, for all these reasons, the most commonly encountered solution is the action at the individual scale through the use of HPD. Thus although their use is recommended as a temporary solution, it eventually becomes permanent for practical reasons (2).

2.2 Why do we care about comfort?

HPDs are often considered by their users more as a drawback than as a protection. Their use then appears embarrassing, problematic (3) or simply uncomfortable (4). These negative thoughts may partly be explained by the absence of "instantaneous benefit" on health: damages of the auditory system are generally appearing gradually. For example the profit resulting from the use of HPD is less obvious than the one for helmets or protective glasses (3, 5, 6, 7). Thus the misuse of HPD seems to be partly related to the poor perception of the hearing loss risk. Nevertheless, this only partially explains their lack of "success" (as pointed out by Morata in her 2001 state-of-the-art review (8)) and the need to improve their utilization rate.

Historically, the notion of comfort for HPD appears first in 1958 in a paper by Zwislocki dealing with the necessary tradeoff between attenuation and comfort (9). Bhattacharya et al. (10) point out that workers generally consider earplugs as uncomfortable because of the irritation of the ear canal, difficult fitting, etc. Physiological and ergonomic aspects thus seem to impact the "unpleasantness". Similarly, an on-site study by Royster & Holder⁴ reveals in 1981 that 50% of HPD users complain of general discomfort, irritation, headaches, etc. As a result, workers are often reluctant to use HPDs: a retrospective 80s study conducted on various industrial sites reveals a "non-use rate" ranging from 20% to 80%. Concerning intermittent use it is necessary to keep in mind that the theoretical effectiveness of the protection falls quickly: for example for a 5 minutes unprotected exposure over an 8 hours period, the equivalent attenuation drops from 30 dB(A) to 20 dB(A) (5). Thus a HPD which is worn sporadically or badly fitted will not optimally fulfill its protective role (11, 12). The question of the correct and continuous use is therefore essential: the most useful and effective protection remains the one which is used (13) in a correct and consistent way (14). Thus while the comfort (the components of which remain to be determined) may be a priori considered as secondary compared to the theoretical attenuation, it will in fact condition the user protection through the HPD use duration and its correct fitting: comfort will impact the exposure and thus the hearing loss risks (2). In fact as early as 1980, Nilsson & Lingrend (15) argue that attenuation values are of secondary importance and that comfort should be the first parameter to consider when choosing a HPD. This conclusion is supported by Canetto (5) when he claims in 2009 that despite habits focusing on attenuation indicators, the selection of a HPD should also equally consider communication and comfort (one can note here that the communication dimension is not considered as part of the comfort). More recently similar recommendations can be found in the 2014 Canadian CSA-794.2-14 standards (16).

Numerous studies have been carried out to quantify the comfort of earplugs. These studies evaluated comfort on site (3, 17, 18, 19, 20, 21) or in laboratory (11, 22, 23, 24) in order (a) to identify the main attributes related to HPD (dis)comfort; (b) to rank different types of earplugs; (c) to evaluate the main design attributes related to (dis)comfort. These various studies (a) find that the comfort evaluation of a given earplug can be based on tradeoff (for example when it is simultaneously judged to be very painful and very practical); (b) show that the main identified attributes of comfort are: attenuation, intelligibility, occlusion effect, static mechanical pressure, skin irritation, ease of application and need for replacement. These two points suggest the difficulty to understand the complex strategies people use when rating comfort. These are going to depend on which attributes each user considers as components of the comfort and their respective prioritization. From the research

⁴ Cited in (11).

and understanding side, if some attributes are not initially envisaged as possible components of comfort, their impact can hardly be evaluated. Thus another problem can be stated here: the concept of "comfort" can vary from one researcher to another. This raises two problems: (a) it makes difficult to compare results from different studies; (b) results will depend on the initial assumptions concerning the attributes that will be included in the concept of comfort. This confirms that there is a real need to head for a definitive and comprehensive definition of the comfort in the field of hearing protection.

2.3 HPD of interest

There are two main families of hearing protection devices: earplugs (which fit into the ear canal) and earmuffs (which cover the external ear). Each family has advantages and disadvantages and in many contexts they are not substitutable. This paper focuses on earplugs for several reasons: (a) earplugs represent the most used HPD family⁵; (b) the protection provided by earplugs is known to be less reliable than the one provided by earmuffs because of their more difficult fitting; (c) earmuff comfort has already been approached more consistently in the past (see for example (2) and (25)). From a practical point of view, there are three main types of earplugs: "moldable", "premolded" and "custom molded" whose properties (attenuation, ergonomics, etc.) depend on the model and family and will necessarily influence the comfort. But there still remains to define the earplug comfort...

3. COMFORT TYPOLOGIES

Any study related to the comfort is structured and conditioned by how comfort is initially defined. Due to its subjective nature and to the large number of (subjective and objective) factors that can be taken into account, the definition of comfort is a complex task. However, despite the vagueness of its definition, it turns out that any individual has already experienced it (14).

Comfort can then be related to physical and/or psychological attributes. In a rougher way, as Williams says (26), the absence of comfort is more specific than just disliking a HPD. But at the same time it still remains difficult to define it with objective measures. Indeed comfort may result from multiple factors and these related sensations may be difficult to name by people. As an example of this complexity, Branson & Sweeney have proposed an interesting definition related to clothes comfort: a state of satisfaction indicating a balance between the physiological, psychological and physical factors of the person, his/her clothes and his/her environment (14). This sums up quite well the interactions that may exist between the user, his/her equipment and his/her environment in a more general way. In other words, comfort is (a) a subjectively defined personal construction; (b) affected by factors of several nature (physical, functional, psychological); (c) a reaction to the environment (27).

Papers related to earplugs (dis)comfort usually focus on the acoustic and physiological aspects. However it seems necessary to envisage and understand the comfort from a more general perspective. The first step is then to try to inventory any parameter that may impact comfort, in order to ensure that no relevant component could a priori be arbitrarily excluded. Thus because of this will of considering comfort in its most general perspective, this study includes the psychological and functional typologies in addition to the physiological and acoustic ones cited above.

3.1 Acoustic comfort

The first (and more documented) typology is related to the acoustics itself. There is a consensus in the literature about the relation between the comfort and the **sound attenuation** induced by the protection. Indeed, the sound pressure at the eardrum must be adapted, even when the ear is occluded: the earplug must protect from ambient noise without overprotecting in order to prevent the person from taking it off to communicate or from being unable to hear the useful sound signals. In fact it is unnecessary or even inappropriate to overprotect workers (i.e. the attenuation is too high), since the feeling of isolation is then disproportionate (4). However the relationship between attenuation and comfort is unclear and still under investigation (20). Damongéot (28) finds no relation between the two attributes. Nevertheless the fact that the attenuation can accentuate an effect of isolation seems ignored here, as well as the impact of the outside noise level and therefore the satisfaction provided by the earplug use⁶ (cf. section 3.3). Some recent results by Davis and Shaw (20) illustrate the complex

⁵ Source: 3M Europe.

⁶ Casali et al. (11) suggest that since comfort affects the utilization duration, the actual attenuation could be

relationship that can exist between attenuation and comfort when they find on the one side that as the variables *loose-tight* and *hard-soft* become more uncomfortable, the Personal Attenuation Rating (PAR) increases and on the other side that the variable *rough-smooth* becomes more comfortable as the PAR increases. Finally, the experienced discomfort is also related to the exposure levels: the higher the exposure level, the more aware of the danger and the more tolerant will be the user. Prevention can then also reinforce this tolerance (26). On the opposite, an attenuation felt too low can be considered as unsuitable by its user (18).

A large number of works relate the problem of the **intelligibility** reduction (8, 11, 13, 17, 29, 30, 31, 32). For their part, Ivarsson et al. (33) only find a minor impact of the intelligibility on the reported comfort. Giguère et al. (34) observe an improvement of the intelligibility for normal-hearing individuals wearing earplugs in many cases while Sweetland (35) does not observe a significant correlation between the attenuation and the level of interference of the communication. In fact the effect of the earplug on the **perception of the voice** will depend on the properties of the speech signal, the background noise and the attenuation characteristics of the HPD. This remark also applies to the **perception of useful signals**, the importance of which can be found in numerous publications (8, 11, 17, 35, 31, 36). In the workplace, this bad audibility accentuates the feeling of risks (operators can then be unable to hear or localize a suspicious noise (17)) and consequently impacts the reported comfort. In a similar vein, Tufts et al. (37) mention the importance of environmental awareness (which may also be related to the feeling of isolation).

The **occlusion effect**⁷ (11, 32, 36) is also a recurrent attribute of comfort. From a practical side, occlusion is associated with a low-frequency amplification of the sounds generated inside the body and radiated into the ear canal. It generates an unpleasant sensation: a deformation of one's own voice and an increased perception of the physiological noise. This effect should be limited as much as possible even if it will have more or less impact on comfort depending on the profession. For example for a person working in a very noisy environment, the perception of physiological noise is limited by the masking effect due to the ambient noise. On the contrary for a musician's panel, Laitinen & Poulsen (36) report that the occlusion effect justifies the fact that 43% of respondents stopped wearing earplugs. However, without questioning this result, this very high rate also raises the question of the correct understanding of the "occlusion" term, which may, for example, have been mixed up with the alteration of high frequencies (which rather depends on attenuation). This underlines the importance of a questionnaire adapted to the profile of the respondents and the possible existing interaction between the numerous components of the comfort.

3.2 Physiological comfort

The second typology commonly found in the literature is linked to the physiological attributes, such as the **pain** or the **physical bother/trouble** due to the use of earplugs. As indicated by Ivarsson et al. (33), people with ear canal pain problems logically tend to wear less their protections. Studies by Casali et al. (11) and Park & Casali (22) conclude that the generic attribute "pain" is strongly correlated with the concept of comfort (at least as probed in their questionnaires). But of course the absence of pain is not synonymous with comfort.

Physiological (dis)comfort can first be associated with the **pressure** exerted by the earplug on the auditory canal (skin, soft tissues and bones) (11, 17, 31, 32, 36). The static mechanical pressure is in fact a feature of the tribological system "ear canal / earplug". It will therefore be as much related to the properties of the earplug as to those of the auditory canal. In fact from 1958, Zwislocki (9) considers (without relying on subjective tests) that this static pressure is the main source of discomfort, while it also determines the effective attenuation of the earplug. Zwislocki contrasts comfort and attenuation from the exclusive prism of this pressure (and suggests a necessary tradeoff between attenuation and

positively related to comfort.

⁷ Most studies dealing with the relation between occlusion and comfort are related to hearing aid devices (38).

pressure). This vision remains rather basic but already points out 60 years ago the importance of this attribute.

The second physiological attribute which can be found in the literature is the **irritation** of the auditory canal (11, 14, 17, 35). The irritation may then be related to the texture of the earplugs (17) and accentuated by working conditions (e.g. heat or moisture).

3.3 Functional comfort

The third typology is related to the functional and ergonomic components of the comfort. In order to support the potential relevance of this typology, the concept of usability is particularly important (39). Usability can be considered from the perspective of four components: **effectiveness** (whether or not the earplug reaches its goals), **efficiency** (duration for the earplug fitting, necessary number of gestures, etc.), **satisfaction** (satisfaction felt because the earplug correctly fulfills its objectives), **learning and memorizing** (is the implementation still as difficult after several days of use? Etc.). Thus, the better the usability of the earplug, the more comfortable it will be considered.

Several attributes related to the functional comfort can be found in the literature. These are mainly related to the *need for readjustment* (which is related to the effectiveness) and the *ease of application* (which is related to the efficiency) (22, 29, 30, 35, 36). In a study by Coles & Rice (30), the earplug considered to be the least comfortable is described as the more difficult to put on and having a tendency to fall (despite the fact that in this case this earplug offered a better intelligibility than the other tested ones: again the comfort assessment seems based on tradeoffs and prioritization). The difficulty of insertion is linked to the ergonomic, geometric or material aspects. Concerning the need for readjustment, Sweetland (35) insisted that it can be an important factor in the estimation of comfort (confirming (32)), especially for difficult occupational conditions (e.g. dirt, heat, moisture, etc.). In the same way, this will be equally linked to the geometry and to the material of the earplug.

By looking more deeply into the definition of the satisfaction concept, its connection with the notion of comfort clearly appears. Indeed as noted in (39), satisfaction refers to the level of comfort felt by the user when using a product. It is the acceptance of the fact that the object is a way of satisfying the goals of the user. Satisfaction is therefore a subjective evaluation resulting from the comparison between what the act of use brings to the individual and what he expects to receive. Its assessment is one of the criteria used to evaluate the acceptance of a product.

Some studies tend to relativize the importance of the functional components on perceived comfort. For example, contrary to the observations of Coles & Rice (30) mentioned above, Casali et al. (11) conclude that the ease of application and the perceived comfort are not always correlated (this is in accordance with some other works by Azares et al. (3) and Sviech et al. (19)). In fact Casali et al. differentiate three criteria in their questionnaire: "comfort", "ease of insertion" and "general preference". This indirectly suggests to the participant that the ease of insertion (and in a more global way the usability) is not part of the comfort components. This does not challenge Casali et al. observation but it again puts into perspective the ability to shift researchers' perceptions of the concept of comfort through the chosen questions and the relations between them. This shows how the definition of the comfort will eventually structure the research and the investigation itself and hence the gathered data. For information purposes, the hygienic aspect is sometimes cited, the formable earplugs being particularly easily contaminated and perceived as such (13, 35).

3.4 Psychological comfort

The psychological typology of earplug comfort has been rarely considered. However, this cannot be a priori ignored, since it is an integral part of the concept of comfort and how it is perceived / evaluated.

Similarly to the functional typology, attributes of the psychological one can rarely be found in the literature related to HPD comfort. From ergonomics and psychological literature it is nevertheless possible to report several ones related to psychological comfort such as **habituation**, **protection feeling**, **isolation feeling** or **unease**. These parameters should be considered as having a possible impact on the comfort evaluation. For example, Park & Casali (22) reported that ear canal cap did not become part of their laboratory study because of the complaints received about the discomfort

generated by this type of protection for an extended use. This is a typical situation during which there has been a lack of habituation (or acceptance).

4. CONCLUSIONS

In the light of the above observations obtained from a literature review, this paper identified four typologies of comfort: acoustic, physiological, functional and psychological. More precisely the following attributes have been found possibly relevant in the comfort evaluation: intelligibility and environment perception (both related to the attenuation and the occlusion effect), pain and irritation (both related to the pressure and friction attributes and consequently to the earplug texture), effectiveness (need for readjustment for example), efficiency (ease of application for example), satisfaction, learning as well as the protection and isolation feelings, habituation and unease. All of these components can influence people feelings in a more or less important and independent way. In the light of this literature review it is obviously yet impossible to prioritize the importance of attributes or to identify the relevant ones, since all parameters have never been considered in a comprehensive manner in any study so far. Moreover it is obvious that some are correlated. But this was a necessary first step to ensure that no relevant component will be arbitrary excluded from the future comfort ratings.

Hence the next step of this project will be to develop a questionnaire based on the conclusions of this preliminary work. This will integrate every identified parameter and then use it during field studies. This will help to identify (scientifically and without any a priori) which parameters have a significant influence on the comfort and then which ones should be considered in the future definitive “global” definition of the earplug comfort. Eventually a consensual definition will also make it possible to compare results from different future studies.

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