

What do we know about hearing protector comfort?

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ABSTRACT

The purpose of the present article is to review comfort studies on hearing protector devices. Comfort is probably the most important dimension for long-term worker acceptance and effective wear of hearing protectors in noise. A short digression has been made to introduce comfort work from the textile and clothing industries where models of comfort have been attempted and comfort research is much more sophisticated. Finally, presented are some recent efforts by NIOSH to examine issues of hearing protector comfort in greater detail. These efforts include a field study of a semi-custom earplug hearing protector.

Keywords: Comfort, hearing protectors, personal protective equipment

“The investigation shows that in this case the attenuation values are of secondary importance, so that the wearing comfort of the HP determines the degree of usage. Thus, in order to increase the motivation in this and similar situations the comfort of the protector should be the first consideration in the choice of HP.”

Nilsson and Lingrend, 1980^[1]

The most effective hearing protector is the one that is worn consistently and correctly. When workers are asked why they are not wearing their hearing protector in noise, two reasons are the most common: the inability to communicate and discomfort.^[19] Communication is a serious problem involving understanding safety signals and oral instructions. However, this paper will not deal with communication issues. The purpose of this paper is to review much of the hearing protector comfort literature, to describe an early experiment in our laboratory, and to provide some direction to future comfort research.

When asked about comfort, the average hearing protector researcher gives a response similar to what a Supreme Court Justice said about pornography:

“I shall not today attempt further to define the kinds of material I understand to be embraced within that shorthand description [pornography]; and perhaps I could never succeed in intelligibly doing so. But I know it when I see it, and the motion picture involved in this case is not that.” (Supreme Court Justice Potter Stewart, *Jacobellis vs Ohio*.)

No one may be able to adequately define “comfort,” but like

Justice Stewart, we all know it when we experience it. The lack of pain or irritation is not comfort, although that is a factor. Classic pain research describes two dimensions: a physical sensation dimension, associated with tissue damage or irritation, and a psychological dimension which is moderated by social, visual, emotional, historical, and personality factors. Pain research shows that the psychological dimension is very important at low levels of pain sensation.^[3] Thus, tolerance levels for pain differ from person to person and from time to time in the same person. The female executive will wear uncomfortable, expensive, designer, high-heeled shoes because such wear is socially motivated and time-limited. The same executive would not wear an equally uncomfortable hearing protector at work for ten minutes. The opposite end of the spectrum from pain—painless—does not, however, imply comfort.

Textile and clothing researchers have long been exploring comfort. Clothing and textile researchers have expended much effort to define the dimensions of comfort, to model comfort, and to develop objective measurements of comfort. One goal of textile researchers is to be able to predict subjective comfort based on a series of objective laboratory tests. A reading of the literature indicates that they are on the right path but have not yet reached this goal. Markee and Pedersen^[4] developed a vocabulary for clothing comfort including an appendix of 20 comfort terms, 22 subconcepts of thermal comfort, and nine discomfort-related cases. On the way to developing their own comfort metatheory and measurement system, Branson and Sweeney^[5] reviewed past efforts for systematizing and quantifying comfort. A reasonable definition of comfort is a “state of satisfaction indicating physiological, psychological

and physical balance among the person, his/her clothing, and his/her environment.”^[5] Yoo and Barker^[6] recognized two main factors of comfort: thermophysiological and sensorial. Thermophysiological comfort refers to the ability of the cloth or clothing to buffer and dissipate metabolic heat and humidity. Sensorial comfort refers to the way the cloth or clothing interacts with the senses of the wearer—specifically the tactile response of the skin.^[7] Sensorial comfort is “associated with skin contact sensations and is often expressed as feelings of softness, smoothness, clamminess, clinginess, prickliness, and the like. These descriptors can be related to specific, measurable fabric mechanical properties, including the number of surface fibers and contact points, wet cling to a surface, absorptivity, bending stiffness, resistance to shear and tensile forces, and coolness to the touch.”^[6] To develop ISO standards, textile researchers have developed an instrumented mannequin that perspires similar to a human.^[8]

Previous Research on Hearing Protector Comfort

The universe of hearing protectors is traditionally divided into three types: earplugs, earmuffs, and canal caps. Earplugs insert into the ear canal and may be custom molded to fit the wearer’s ear canal, semi-custom fitted (*i.e.*, the general shape of the wearer’s ear canal but flexible enough to adjust slightly with each wearing), or universal fit. Earmuffs are solid cups which surround the ear with cushions which protect the head and seal the cups. Canal caps are earplugs which are attached to a metal or plastic band and either insert into the ear canal or block the entrance to the canal.

Comfort research is not widely represented in hearing protector literature. Perhaps because many researchers (and manufacturers) look on comfort as a secondary concern, most comfort papers include multiple reports of multiple protectors. Thus, to summarize these papers often requires careful reading and adept reporting. Studies are reviewed in chronological order in this report.

Ivergård and Nicholl^[9] tested ten of the most common earmuffs used in Swedish industry with the aims of developing reliable and valid methods for accident risk, ease and simplicity of use, and comfort. They were also interested in determining if short-term wear-testing correlated with long-term wear-testing. Finally, they wanted to find any differences between cold- and warm-environment testing. A meat-product factory was chosen as the cold environment and a motor foundry and testing shop was chosen as the warm environment. Twelve people from each factory were chosen at random to take part in the long-term (half-shift) wear tests. Two earmuffs were worn per day and changed at the half-shift break for two days (four muffs total). A 15-item questionnaire was administered at the end of each wear period. Questions 1 and 2 had to do with instruction comprehensibility and usability; question 3 was about the ease of adjusting the muff and headband;

question 4 about pressure against the head; question 5 with the hardness of the cushions (rings); question 6 with whether the pinna was in contact with the edge or outside of the muff; question 7 asked about the perceived weight of the muffs; question 8 dealt with the stability of the muffs; question 9 asked about the subjective protection against noise; question 10 asked about general comfort and allowed for a ranking of the muffs; questions 11 through 14 dealt with ease of removing and replacing the cushions for cleaning and changing, and question 15 dealt with the subjective feeling of warmth after a longer period of wear. After all four muffs had been worn, the subjects were asked to rank them in order of preference.

For the short-term tests, 51 people were randomly chosen from the two industries. Each person tested all ten muffs. They wore each muff while they filled out the 15-item questionnaire (3–5 minutes each) in the presence of 83 dB(A) noise. At the end, the subjects rank-ordered the ten muffs.

Ivergård and Nicholl found, first of all, that the short-term wear tests were highly predictive of the long-term tests, except for muff weight and softness of the cushions. They indicated that first impressions of the muff are good for predicting the long-term feelings about the muff. They concluded that an ideal muff is light and comfortable, but also must be easy to clean and maintain. The size of the muff should be large enough in width and depth to cover 95% of the workers without applying pressure to the pinna. Muffs should contain sound-absorbent material to prevent resonances and reduce sound within the cup. There should be thick, soft cushions which can be taken on and off for cleaning. The headband should be wide and give enough pressure against the head to provide good fit without discomfort. It should be noted that 85% of the subjects in the study were experienced earmuff wearers prior to the study.

Schulz *et al.*^[10] examined five hearing protection devices used in East Germany. These were the Lauscha hearing protective cotton, Pneumant hearing protection (plug), E-A-R[®] protector (foam plug), Optac earmuff and Hermetos III (canal cap). Worker Group A consisted of 17 workers in a screw production factory with a relatively constant noise level of 94 dB(A). Worker Group B consisted of 11 workers in the forging industry exposed to impulse-like noise. Group B had a long-term L_{eq} of 95–109 dB(A). Of the 17 workers in Group A, only two subjects had previously worn hearing protection while nine of eleven workers in Group B had worn cotton or plugs for a long time. The researchers used the lack of temporary threshold shift at 4 kHz at the shift end as a measure of hearing protector effectiveness. For comfort, they administered a seven-question questionnaire with four levels. Each device was worn for four days by each subject. In Group A, temporary threshold shifts (TTS) could not be detected on the days that hearing protection was worn (previously measured TTS was 10–17 dB). Reports of comfort differed

significantly with consistent preference for the plug variants. In ease of application, ease of effectively fitting it to the ear, and noise attenuation, the canal caps (Hermentos) received the most favorable evaluation. The earmuffs were ranked first only for noise attenuation. The plugs were ranked best for lack of burden and easiest to wear. Cotton was ranked first for least hampering communication. Twenty-four percent of the subjects complained of canal cap pressure, whereas 20% complained of burdensome pressure pain due to the earmuffs, and 9% complained of ear canal irritation due to protective cotton. Schulz *et al.*^[10] report in their conclusions that the canal caps were not worn for the full eight-hour shift (except in rare instances) due to comfort issues. The investigators did not demonstrate adverse communication effects for any of the hearing protectors as measured by their questionnaire.

A reasonable hypothesis would be that a lower headband force for an earmuff hearing protector would produce greater comfort. Berger and Mitchell^[11] discussed the correct measurement of headband force and reviewed five earmuff comfort studies. They concluded that objective headband pressure is not a good predictor of subjective comfort. In a number of studies, the most comfortable earmuff was the one with the highest headband pressure. Berger and Mitchell also indicated that no research to date has investigated the role of physical appearance on comfort.

Casali, Lam, and Epps^[12] conducted an exploratory study of earplugs and earmuffs / canal caps with the aim of developing a multidimensional bipolar rating scale and ranking methodology for assessing HPD comfort, ease of use, and user preference issues. They then applied these scales and ranking methods to a variety of HPDs to determine their feasibility. They were interested in developing methods that were able to statistically analyze comfort. Five earplugs were tested by 50 subjects, all of whom wore each earplug once. Four earmuffs and two canal caps were tested by another group of 50 subjects who wore each earmuff and canal cap once. Subjects responded to a seven-step rating scale anchored with opposite adjectives on the scale ends. The earplug study used a ten-item questionnaire; the earmuff study utilized a 23-item questionnaire. In addition, at the end of the session, the subject was asked to rank each earplug or rank each earmuff in order of comfort, ease of donning, and personal preference. For earplugs, the scales which significantly correlated ($P < 0.05$) with the “comfortable-uncomfortable” scale were “soft-hard,” “smooth-rough,” “tight-loose,” “shallow-deep,” and “painful-painless.” For the earmuff and canal cap rating scales, 21 of the 23 scales were significantly correlated with “comfortable-uncomfortable” (the only uncorrelated scales were “heavy-light” and “thick-thin”). For earplugs, devices perceived as softer, rounded, smoother, looser, shallower, and less painful were considered more comfortable. For the earmuff data, devices perceived as softer, smoother, looser, less cumbersome, less restrictive, and less painful were more comfortable. “Uncomfortable pressure” was highly correlated

with “uncomfortable,” yet “heavy” was not. They found that clamping force of the earmuffs (but not canal caps) did not seem to be associated with comfort. Earmuff weight was not associated with comfort. They noted that manipulating these parameters within commercially available HPDs is difficult.

Earplug postwear rankings generally supported the comfort ratings. Generally, formable earplugs rated higher than preformed earplugs in comfort. There were significant differences in ease-of-insertion rankings. Clearly, comfort and ease-of-insertion do not equate. Wax plugs, rated the most comfortable, were rated difficult to insert by subjects, whereas the foam plug and the ear down plug were rated comfortable and easy to insert. The earplugs with the greatest general preference were the foam earplug and the down earplug, although there was no statistical difference between the formable earplugs.

Comfort rankings for the earmuff / canal caps were statistically significant; the rankings agreed with the comfort ratings: canal caps were ranked lower than earmuffs. Ease-of-application rankings resulted in both canal caps being ranked lower than the earmuffs. One earmuff with a smaller auricle opening and higher clamping force was ranked significantly lower in ease-of-application than the other earmuffs.

In an extended abstract, Ivarsson *et al.*^[13] reported the administration of a questionnaire to 263 Swedish auto workers. Thirty percent of workers wearing hearing protection reported discomfort issues due to heat and humidity. It appears that “earplugs” consisted of mineral down wool. Of the consistent earmuff wearers (31% of the total), 28% reported discomfort which is about the same as the 29% reported by the consistent earplug wearers (36% of the total). Forty-three per cent of a group which alternated between plugs and muffs (33% of the total) reported discomfort. The researchers hypothesized that affected workers may deal with their discomfort by alternating between different types of hearing protectors. They also reported that 13% of the workers indicated suffering from eczema or itching of the ear canal at some time, with 7% having objective signs of ear canal eczema. They also note that one half of those workers with objective signs also have eczema on other parts of the body, which may indicate a susceptible person or a cause other than hearing protectors. Ivarsson *et al.*^[13] also reported heat and humidity build-up captured by “absorbent material” inside the earmuff while riding on a stationary bicycle; subject number was not reported. The results are presented only in graphic form and they reported a skin temperature build-up of about 2°C in the first ten minutes. The temperature under the muffs then leveled off over 40 minutes with relative humidity building up quickly in the first ten minutes, then growing more slowly over the entire 60 minutes of the test.

Park and Casali^[14] conducted two studies of comfort: a laboratory study and a field study. The studies differed in that the laboratory study used naïve hearing protector users while

the field study used workers who, if not currently wearing hearing protection, should have been wearing hearing protection based on measured noise levels. The studies also differed in the hearing protectors used. The laboratory study utilized three hearing protectors (earmuff, foam cylinder earplug, and triple flanged earplug) and a combination of earmuff-over-foam earplugs. Each protector was worn exclusively by ten subjects for a total of 40 subjects. In addition, the laboratory study utilized a subject fit condition and an experimenter fit condition for each protector. Subjects were involved in various tasks for one hour to simulate moderate to active work conditions. Comfort information was collected at 15 minutes and at two hours after beginning wear. Comfort information was collected using a 14-scale, seven-points-per-scale questionnaire [Table 1]. Adding the values together gave a score or a “comfort index” for each condition. Hearing protector device (HPD) convenience was collected on a seven-step bipolar scale [Table 2].

The field study utilized some of the same design. The hearing protectors used included the same foam plug, the same triple flanged plug, and the same earmuff, but instead of the double protection condition, they utilized a set of canal cap hearing protectors. Each protector was worn exclusively by a group of ten subjects for a total of 40 subjects. For the first week, each field subject was asked to wear the hearing protector as presented on the packaging for each full workday. In the second week, the experimenters instructed the workers in the proper fit and they were asked to wear them as presented by the experimenters for each full day. In the third week, no additional instruction was presented other than to wear the protector. Once per week, at an unannounced time, the worker was brought into the laboratory, tested for the attenuation of the hearing protector, and tested for comfort using the same comfort index as the laboratory study.

Surprisingly, there were no differences between the laboratory subjects who wore the HPDs once for two hours and the field subjects who wore the HPDs daily during work

Table 1: Bipolar comfort rating scales; between each extreme were 7 levels, one of which the subject would check. (from Park and Casali^[14])

How does your hearing protector feel now?	
Painless	Painful
Uncomfortable	Comfortable
No uncomfortable pressure	Uncomfortable pressure
Intolerable	Tolerable
Tight	Loose
Not bothersome	Bothersome
Heavy	Light
Cumbersome	Not cumbersome
Soft	Hard
Cold	Hot
Smooth	Rough
Feeling of complete isolation	No feeling of complete isolation
Ear open	Ear blocked
Ear empty	Ear full

hours for three weeks. There was a statistically significant difference in comfort between fitting types in the laboratory study: the subject-fit was judged more comfortable than the experimenter fit. Also statistically significant: the comfort of the earmuff degraded over time. In the convenience index for the laboratory study, the foam plug was rated the most acceptable and attractive, but also the most difficult to apply. The earmuff was rated the easiest to apply but the least attractive and the least stable in the laboratory. The combination of ear muff-and-foam earplug was rated the most difficult to apply. The experimenters detected a fitting effect for the foam earplug: the foam earplug was rated as easy to apply under the experimenter fitting, but more likely to loosen and less stable under the subject-fitting condition.

There was good agreement in the comfort indices between the laboratory and the field studies. For comfort, there was a significant interaction between the fitter (subject vs experimenter) and the length of use and the HPD. The foam plug appears to be the important variable: it was more comfortable when placed under subject fit, whereas it was less comfortable when placed under experimenter fit. There was also a significant interaction between the fitter and the HPD. There was a significant main effect for the HPDs; the uncomfortable HPDs of note were the canal caps. These are designed to be worn for short periods of time while in noise and are designed to be easy to don and remove.

The field convenience index found that the canal caps were also the least attractive, the least acceptable, and the poorest fit, but also the simplest to use. The earmuffs and the triple flanged earplugs were judged acceptable. The earmuff was judged as stable under field conditions. The foam plug was judged easy to apply with a tendency to loosen under subject fit field conditions.

Park and Casali concluded that fitting of the foam earplug has a significant effect on comfort which is not measured with earmuffs, triple flanged earplugs, or canal caps. They also concluded that wear time was only significant for earmuff comfort. Movement did not appear to have any effect on HPD comfort. Finally, the least comfortable HPDs were the canal caps.

They did note some differences between the laboratory and

Table 2: The bipolar convenience rating scales; these scales were arranged as with those in Table 1, with 7 intermediate steps between opposing words (from Park and Casali^[14])

Easy to apply	Difficult to apply
Unacceptable	Acceptable
Good fit	Poor fit
Stable	Unstable
Unattractive	Attractive
Simple	Complicated
Easily loosens	Doesn't loosen
Inhibits head movement	Doesn't inhibit head movement

field conditions. There was a difference in comfort between the fitting conditions of the earmuff in the two conditions. There was also a comfort difference after training for the triple flanged earplug. Overall, however, there was little difference in comfort levels among the two earplugs and the earmuff. They concluded that HPD selection should be left up to personal choice.

Bhattacharya *et al.*^[15] tested three earplugs and five earmuffs in two groups: college students and weavers. The subjects were given eight trials on each device and asked to give a binary comfortable / uncomfortable response. Ninety-seven to ninety-eight per cent of the people rated the earplugs as being comfortable. On the other hand, the five earmuffs were rated comfortable by 50–90% of the subjects. Comfort scores were similar between the students and the weavers. The researchers identified some factors that seemed to correlate with comfort. As reviewed earlier in this article, they did not find any correlation with headband force and comfort. In fact, the two earmuffs with the highest headband force were rated the most comfortable. They concluded that the following factors were important for comfort: oval-shaped cups which conform to fit around the pinna, more noise attenuation, larger space inside the cups to accommodate the pinna, foam cushions that conform to the head, and circumaural cushions which conform to the head to distribute the headband force. They concluded that the cushions are very important for comfort.

NIOSH Hearing Protector Comfort Work

Laboratory studies

In 2003, the National Institute for Occupational Safety and

Health (NIOSH) funded a small, internal project looking at physical factors in HPD comfort.^[16] This project has had three efforts which will be presented in greater detail below. The first effort was to develop tools which could be used to make analytical measurements of hearing protector factors which might relate to comfort. The second effort was a field study in partnership with a major automobile manufacturer. Two articles are in preparation. Finally, a study of temperature and humidity build-up under an earmuff-type hearing protective device (HPD) is currently being conducted.

In 2004, NIOSH contracted with Jay Kim, Ph.D. of the Department of Mechanical Engineering of the University of Cincinnati, to develop a technique for characterizing pressure of insert-type hearing protectors against the ear canal wall. A goal of the contract was to develop a system which could be utilized outside the laboratory. A test jig was created by drilling ten artificial ear canals into a block of Delron®. These artificial ear canals varied in diameter from 7.0 to 11.5 mm in half millimeter steps. These sizes correspond to the diameters of the measurement balls on the AO Otogauge used to size the V-51R hearing protector. (We know from previously collected but unpublished NIOSH data, that the average male ear canal diameter is 9.3 mm and the average female ear canal is 8.8 mm in diameter.) Each artificial ear canal is vented. An initial effort to quantify extraction force (and thereby the canal pressure) utilized precision weights. While successful in the artificial ear canal, it was decided that weights would not be adaptable for field use. Using weights would require the head to be held in an awkward position for a number of minutes. A technique using a precision spring scale (Pesola, model 40600, Switzerland) was developed. Figure 1 presents

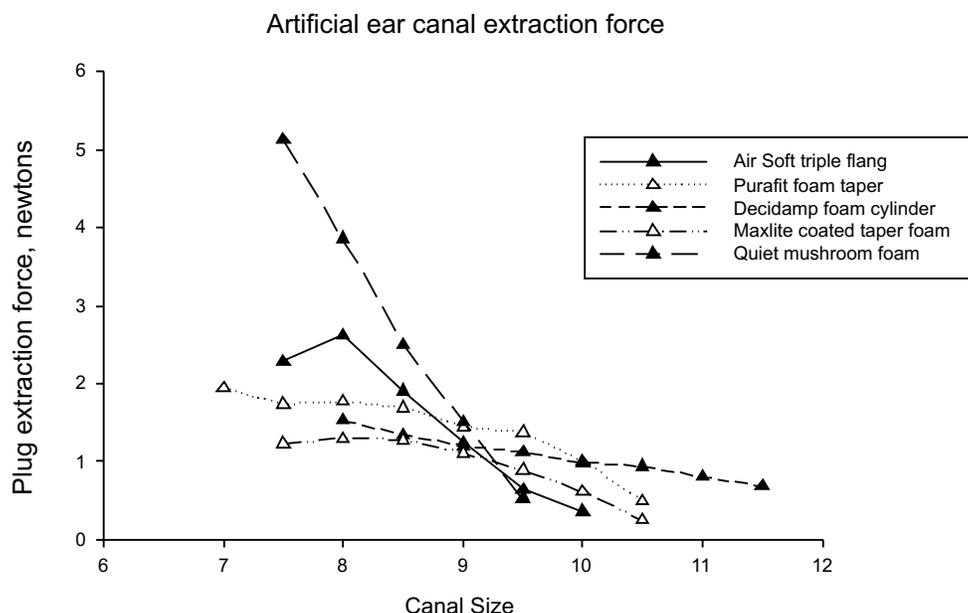


Figure 1: Extraction force of 5 different earplugs from artificial ear canals. There is a general trend for the extraction force to decrease with increasing canal size. However, some plugs (the Quiet mushroom) seemed to be only acceptable for the median ear canal. The Decidamp foam cylinder produces about the same force for all canal sizes. Missing points indicate that the canal was either too large or too small for the earplug to be able to fit.

the results of extracting five different hearing protectors from the ten artificial canals. These protectors were representative of those utilized in an operating factory hearing conservation program.^[17] All protectors seem well suited for the average size ear canal. Some hearing protectors such as the Max-Lite Quiet exert increasing canal pressure with smaller diameter canals. On the other hand, the North Deci-Damp II foam hearing protector, produces about the same amount of canal pressure for all diameters of ear canals. The Deci-Damp plug seems especially suited for use with larger sized ear canals. None of the HPDs tested seem to be well suited for smaller canals such as those of women and children.

Field study

A longitudinal study of hearing protector comfort was conducted in partnership with a major American auto manufacturer from February 2004 to February 2005. The goals of this effort were to examine the acceptance of a semi-custom earplug in a factory setting, to observe the changes in attitude and beliefs about HPDs and noise with training, and to measure the changes in comfort over one year. There are currently two journal articles under preparation at this time,^[2,17] so this article will not go into detail. The subjects were experienced HPD users with an average of 20.0 years of use ranging from 2 to 37 years. The study utilized the Parks and Casali^[14] comfort scale to have the workers rate their HPD comfort four times. We found that neither comfort nor attitudes and beliefs had changed significantly over the course of one year. Also, workers rated the comfort of their protectors as less comfortable than neutral. Counseling the workers did not modify comfort or the attitudes and beliefs scores. A vast majority of workers received adequate insertion loss with their hearing protectors to provide protection from noise.^[18] Generally, experienced HPD users preferred to be overprotected (*i.e.*, hearing protection which reduced the noise exposure level to < 70 dBA) in spite of sacrificing verbal communication. The policy in this particular factory was that instructions were not to be modified unless written down on paper—perhaps a response to overprotection.

New directions in HPD comfort

The passive hearing protector has changed little since World War II. The dimensions of durability, comfort, cost, communication, and aesthetics have been balanced to produce the variety of earplugs and earmuffs we can purchase today. Lately, the area of greatest hearing protector research is acoustics, with electronics playing an important role. Thus, level-limiting hearing protectors, which pass normal levels of sound through the muff or earplug, but produce maximum attenuation at a preset acoustic threshold, are now commonly sold in sporting goods stores. Active noise-cancelling headsets are moving out of the high-end aviation field to the factory floor. Active noise cancellation is one of the few ways of attenuating low frequency noises. To reduce boredom, level-limited AM/FM broadcast radio receivers are being built into earmuffs. Radio

communication systems are also available in earmuffs.

However, comfort may be sacrificed in the rush to outfit the worker with ever more sophisticated electronics. Earmuffs may contain electronics with multiple batteries, weighting the head. If the worker also wears a hardhat / helmet, a headlamp (as in mining), a face shield / respirator or any other head-worn contrivance, the sophisticated hearing protector may contribute to neck and shoulder discomfort or even injury.

Studies reviewed here show that hearing protector comfort can be reliably and validly quantified on psychophysical scales. Workers can consistently rate HPD comfort on multiple psychological scales. In addition, the HPD user can effectively rank order hearing protectors on comfort, ease of use, and desirability. The tools for sophisticated HPD comfort research exist.

Future directions in hearing protection should focus on comfort. Manufacturers should expand from adult males and utilize women and children for wear-testing of their products. Hearing protection devices should be cool, light-weight, and conduct perspiration away from the skin. Advanced materials should be investigated for the possibility of producing HPDs which block hazardous sound with minimal skin pressure. Attempts should be made to make HPDs more visually attractive. The best hearing protector is the one worn consistently and effectively in noise.

In the future, it will be possible to produce a qualitative measurement on which hearing protectors are rated on comfort, so purchasers can judge them on things other than the greatest noise-reduction rating.

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