



Comfort evaluation of hearing protection

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Abstract

Hearing protection is very important for workers in noisy work environments, although the willingness of workers to wear hearing protectors depends heavily on their comfort. This paper evaluates and recommends improvements for the comfort of hearing protection. Workers' experience and comfort needs for hearing protection were investigated through a questionnaire that established the "comfort indices" for hearing protection. An earmuff "comfort tester" was designed to measure the comfort indices, and an experiment was conducted to measure workers' perceived comfort into quantitative data. From the data, the range of these comfort indices in which workers will feel comfortable was determined. Finally, guidelines to improve the design of current hearing protection based on these "comfort indices" are proposed, which may help increase workers' willingness to wear hearing protection.

Relevance to industry

Using these proposed guidelines may help improve the comfort of hearing protection and increase workers' willingness to wear hearing protection in noisy work environments.

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1. Introduction

The influence of noise on humans can be divided into psychological and physiological aspects. Psychologically, sudden loud noise can easily cause shocks. Physiologically, when a person is exposed to noisy surroundings for a period of time, the hearing threshold may be permanently

affected. Ahmed et al. (2001) pointed out that gross occupational exposure to noise has been demonstrated to cause hearing loss.

Noise can be controlled by blocking the noise at the source, along its path from the source to the receiver, and at the end of the receiver. Lowering the noise at the source is the most effective way to noise control. An alternative would be blocking the path of noise. Finally, wearing personal hearing protection is the last passive means of self-protection. However, it is often the most cost-effective method of individual

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exposure control (Sanders and McCormick, 1987; Patton, 2000).

Noise-induced hearing loss can be prevented by avoiding excessive exposure to noise and using hearing protection such as earplugs and earmuffs (Phoon and Lee, 1993; Rabinowitz, 2000). Paakkonen et al. (2000) found that the attenuation (insertion loss) was 16–23 dB for earplugs, 10–20 dB for earmuffs, and 24–34 dB for the combined use of plugs and muffs.

However, due to the discomfort of wearing hearing protection, workers in noisy work environments often do not wear them. Sergio and Miguel's (1996) research project on the use of personal hearing protection concluded that education and motivation of the employees, as well as hearing protection comfort, encourage their correct use. Parmentier et al. (2000) used an artificial head made of hard polyurethane for the evaluation of hearing protection, and ISO 1999 has been revised and updated according to the results of this research.

This paper evaluates and provides guidelines to improve the comfort of hearing protection. Workers' experience and comfort needs for hearing protection were investigated through a questionnaire that established the "comfort indices" for hearing protection. A "comfort tester" for earmuffs also was designed and constructed to measure these indices. Workers' perceived comfort data was transformed into quantitative data. From this data, ranges for the comfort indices in which workers feel comfortable were developed. Finally, proposed guidelines to improve the design of current hearing protection on these comfort indices is presented. It is hoped that these guidelines will increase the willingness of workers to wear hearing protection.

2. Finding comfort indices for hearing protection

A questionnaire was designed to identify the critical factors for comfort of hearing protection. The main purpose of the survey was to understand workers' perceptions and actual comfort needs when wearing hearing protection. In particular,

the survey aimed at developing "comfort indices" for hearing protection.

There were four parts in the questionnaire. The first part asked for basic information, including gender, age, and whether the respondent had experience wearing earplugs or earmuffs at work. The second part investigated respondent's work environment, whether it was high decibel, hot and humid, and dusty and dirty. The authors also hoped to find out how long did the worker wear hearing protection at work everyday, and how often did the worker change from normal to high-decibel environment everyday. Some of these questions may not be directly related to the comfort of hearing protection. These items were put in the questionnaire by request of Institute of Occupational Safety and Health, Taiwan, to investigate the current situation of high decibel work environments in Taiwan.

The third part of the questionnaire surveyed workers' comfort needs of wearing hearing protection at work. To construct survey items for this purpose, 10 frequent users of hearing protections were interviewed to collect their descriptions of the uncomfortableness of wearing hearing protection at work. These were then summarized into 14 comfort attributes. The questionnaire asked the respondent to select uncomfortable perception when wearing hearing protection at work from these 14 attributes, plus "no discomfort" and "other". The questionnaire also asked that, after wearing earplugs or earmuffs for how long would the respondent start feeling uncomfortable.

The fourth part of the questionnaire asked the respondent to evaluate the importance of design factors of earplugs and earmuffs that might influence their comfort. To find out the possible factors, 4 hearing protector manufacturers were interviewed to collect their description of important factors for the design of earplugs and earmuffs. Patents of hearing protection were also searched to collect the keywords of hearing protection patents. The descriptions and keywords were summarized into 7 design factors for earplugs and 9 design factors for earmuff. The questionnaire asked the respondent to evaluate the importance of these factors on the comfort of hearing protection using a 5-point scale

(very important/important/regular/less important/not important).

This questionnaire was subsequently refined based on consultations with experts of Institute of Occupational Safety and Health, Taiwan, and a limited pretest by a convenience sample of 44 workers from a local factory.

A comprehensive survey was then conducted in 9 selected factories with various types of noisy work environments. The finalized questionnaire (see Appendix) was presented in a booklet style with a cover letter that explained the purpose of the study and provided instructions for its completion. Forty workers were selected by random sampling in each factory for the survey, and a total of 358 questionnaires were distributed (in one factory only 38 workers took the questionnaire). The total response rate of the survey was 77.9%. Among the respondents, 86.7% were male and 13.3% were female. The largest age group was from 35 to 44, and 94.6% of the respondents were between 25 and 44. Most of the respondents (87.5%) had experience wearing earplugs, and 45.2% of them had experience wearing earmuffs.

A large proportion of the respondents were required to wear hearing protection at work for a long time everyday. Among them, 44.8% had to wear hearing protection for more than 8 h, and 54.8% had to wear them for more than 6 h. In addition, the percentage of workers who had to frequently change between normal and high-decibel (over 85 dB) work environment (more than 10 times per day) was 41.6%. As for the work environment, 81.7% of the respondents worked in high-decibel (over 85 dB) environments, 53.8% worked in hot and humid work environments, and 35.1% worked in dusty and dirty surroundings.

The third part of the questionnaire asked the respondent to choose uncomfortable perceptions when wearing hearing protection at work from the 14 comfort attributes plus “no discomfort” and “other”. As shown in Table 1, 53.4% of the respondents chose “having difficulties in conversations”, followed by “sense of oppression” (39.4%), “feeling itchy” (33.7%), “feeling dirty” (29.7%), and “feeling stuffy” (25.8%). Only 5.0% of the respondents did not feel any discomfort while wearing hearing protection.

Table 1

Statistics of comfort attributes when wearing hearing protection at work

Rank	Comfort attributes	Headcount	Percentage
1	Having difficulties in conversations	149	53.4
2	Sense of oppression	110	39.4
3	Feeling itchy	94	33.7
4	Feeling dirty	83	29.7
5	Feeling stuffy	72	25.8
6	Easy to slide or fall off	66	23.7
7	Feeling of an object in the ear	63	22.6
8	Tinnitus	53	19.0
9	Poor soundproofing	53	19.0
10	Acoustics change	36	12.9
11	Interfere with work	35	12.5
12	Discomfort due to hard contacting parts	28	10.0
13	Protectors deform easily	22	7.9
14	Headache	19	6.8
15	No discomfort	14	5.0
16	Other	4	1.4

The survey also showed that 48.4% of the respondents felt discomfort after wearing earplugs for 1 h; and only 25.0% did not have any discomfort after wearing them for over 2 h. The endurable time of wearing earmuffs was much shorter. 67.0% of the respondents felt uncomfortable after wearing earmuffs for 1 h, and only 12.0% of them did not feel any discomfort after wearing earmuffs for over 2 h.

The last part of the questionnaire asked the respondent to evaluate the importance of the design factors on the comfort of hearing protection using a 5-point scale (very important/important/regular/less important/not important). The 5-point scale was converted into (2, 1, 0, -1, -2) to calculate the average score and standard deviation of each factor. As shown in Table 2, the most important factor for earplugs was the soundproofing (with the lowest standard deviation), followed by texture and inflation pressure. As for earmuffs, soundproofing was still considered the most important factor, followed by airtightness, weight, heat-sinking ability, texture,

Table 2
Importance of design factors of earplugs and earmuffs that might influence their comfort

Rank	Earplugs			Earmuffs		
	Factors	Average	Std.	Factors	Average	Std.
1	Soundproofing	1.70	0.54	Soundproofing	1.65	0.56
2	Texture	1.36	0.74	Airtightness	1.48	0.65
3	Inflation pressure	1.18	0.81	Heat-sinking ability	1.36	0.71
4	Wearing convenience	1.16	0.72	Texture	1.31	0.77
5	Heat-sinking ability	1.08	0.82	Weight	1.30	0.72
6	Sweat absorbing ability	0.93	0.91	Headband force	1.21	0.72
7	Weight	0.85	1.22	Adjustability	1.12	0.69
8				Wearing convenience	1.12	0.75
9				Sweat absorbing ability	1.11	0.85

and headband force. Although many patents for earplugs or earmuffs emphasize adjustability or wearing convenience, these two factors were rated less important in the responses to the questionnaire. The respondents also considered sweat-absorbing capacity to be less important for both earplugs and earmuffs.

Using hearing protection is the most important means of individual hearing protection. However, the results of this questionnaire showed that most of the workers found it uncomfortable to wear hearing protectors, which obviously would affect their willingness to wear them. The questionnaire results also showed that airtightness, heat-sinking capacity, weight, and headband force are the primary “comfort indices” for earmuffs.

3. Design of earmuff “comfort tester”

After determining the related comfort indices, a “comfort tester” for earmuffs was designed and constructed to measure these comfort indices. As shown in Fig. 1, this earmuff “comfort tester” can simultaneously measure the airtightness, heat-sinking ability, and headband force of an earmuff.

The headband force is measured conforming to EN352-1 (1993), using a standard head frame with an s-shape load cell in the center of the tester. When an earmuff is mounted on the two side plates, the load cell can measure the pressure applied by the earmuff. The height of the head frame and the distance between the two side plates

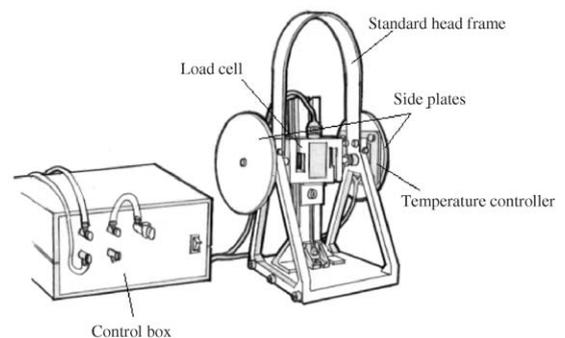


Fig. 1. The earmuff “comfort tester”.

can be adjusted for measuring the headband forces for different head sizes. The evaluation of the heat-sinking ability of an earmuff imitates the condition when a worker wears an earmuff. A temperature controller is mounted at the back of one of the side plates to maintain the temperature of the side plate at human body temperature. A thermal couple protruding from the same side plate measures the temperature inside the earmuff when the earmuff is in contact with the side plate at human body temperature. A control box supplies power to the electronic devices, and a single chip microprocessor controls the sequence of the test and collects signals from sensors, which are sent to a computer for display and further analysis.

The evaluation of airtightness is similar to the method of evaluating airtightness of breathing protectors. As shown in Fig. 2, the control box also contains two airflow sensors and an air pump.

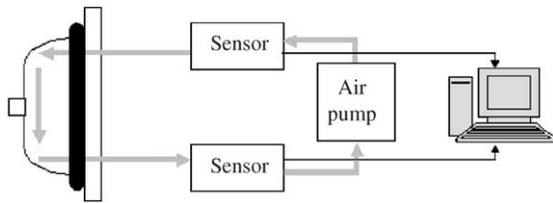


Fig. 2. The evaluation of airtightness.

Table 3
Test results of headband forces of earmuffs

Headband force	Small head size	Medium head size	Large head size
Maximum (N)	14.4	14.5	16.9
Minimum (N)	3.3	3.9	4.5
Average (N)	8.9	9.5	10.6
Standard deviation (N)	2.8	2.9	3.3

When an earmuff is mounted on the tester, the air pump sends air through one of the side plate into the earmuff. The air circulates back through another hole on the side plates. The amount of airflow is controlled at 11/min in our tester. Air tightness of the earmuff can be evaluated by the ratio between exhale and inhale airflow measured by the two airflow sensors.

A total of 28 commercial earmuffs were tested using this comfort tester. Table 3 shows the test results of headband force. Headband forces for small head size (the distance between side plates is 130 mm), medium head size (150 mm), and large head size (170 mm) were measured. The headband forces of 6 earmuffs were above the EN standard for maximum headband force 14 N. As expected, the headband forces of the earmuffs tend to be larger for the large head size, and the headband adjustability of some earmuffs was limited, which resulted in high headband forces for the large head size.

In the heat-sinking ability test, temperatures inside the earmuffs varied from 30°C to 35°C. It was observed that an earmuff with larger interior space tends to have lower inner temperature. In the airtightness test, 18 out of the 28 earmuff

Table 4
Test results of earmuff inside temperature, airtightness and weight

	Temperature (°C)	Airtightness (%)	Weight (g)
Maximum	35.3	99.7	323.3
Minimum	30.0	49.7	113.8
Average	32.2	89.2	203.6
Standard deviation	1.6	12.6	58.4

Table 5
Correlation between airtightness and headband force for the same earmuff

Headband force (N)	Earmuff A	Earmuff B
	Airtightness (%)	
6	91.8	91.0
8	92.6	92.2
10	92.8	94.2
12	93.3	95.5
14	96.4	98.0
Pearson coefficient	0.88	0.99

tested had airtightness of over 90%, and 6 earmuffs were over 99%. However, the airtightness of 5 earmuffs was lower than 75%, and for 1 earmuff it was lower than 50%.

The weight of the 28 earmuffs ranged from 114 to 323 g. The average weight was 203.6 g and standard deviation was 58.4 g. Weight of the muffs accounts for 68–77% of the total weight, which should be the major target if a lightweight design is desired. Table 4 summarizes the test results of earmuff inside temperature, airtightness and weight.

The test results of the 28 commercial earmuffs did not show any correlation between headband force, temperature, and airtightness of different earmuffs. For further study, two earmuffs were modified to adjust their headband forces at 6, 8, 10, 12, and 14 N, and then were tested for airtightness. Table 5 shows that for the same earmuff, airtightness has strong correlation with headband force. Airtightness, and therefore soundproofing effect, may be affected when trying to reduce headband force.

4. Finding the acceptable ranges for the comfort indices

After measuring commercial earmuffs for their comfort indices, an experiment was conducted to determine the acceptable ranges of headband force, earmuff inside temperature, and weight. For this experiment, an earmuff with good comfort indices was used as the base, and it was modified into 3 groups of sample earmuffs. There were 5 identical earmuffs in the first group, although the headband forces were adjusted to 6, 8, 10, 12, and 14 N when measured on the comfort tester on the medium head size. Similarly for the second group of sample earmuffs, small temperature controllers were installed inside the earmuffs of the 4 identical earmuffs in the second group to control the temperature at 30°C, 32°C, 34°C, and 36°C. Finally, weights were added to the 6 identical earmuffs in the third group to adjust their weights to 130, 170, 210, 250, 290, and 330 g.

The purpose of the experiment was first explained to the test subject. Then the subject randomly picked an earmuff from the group of earmuffs, wore it for 240 ± 10 s, and then expressed his/her perceived feeling on the comfort index being examined using a 5-point scale. The subject rested for about 5 min, then randomly picked another earmuff from the same group again. This process was repeated for 4–6 times in each group depending on the number of sample earmuffs in the group, and it is possible that a subject picked the same earmuff repeatedly. The experiment was

conducted in a comfortable lab environment without noise, so that the subjects could concentrate on the comfort index being examined.

A total of 44 subjects finished the experiment for all 3 comfort indices. Their ages were between 18 and 54, and 86.3% of the testers were male. Tables 6–8 show the results. Numbers in a column represent the times subjects choose a certain answer after wearing the sample earmuff. Note that since the subjects picked the sample earmuffs randomly, the sum of the numbers in each column may not be the same. Finally, the average score (total score/total times) is computed for each sample earmuff.

The results in headband force and weight showed that tighter and heavier earmuffs were more uncomfortable, as expected. The results of subjects' reaction to temperature did not show any trend, perhaps because the subjects did not feel significant differences while temperature change was within 30–36°C.

Using the data in Tables 6 and 8, Fig. 3 shows continuous contours of the relation of subjects' perceived feelings and magnitudes of earmuff headband force and weight. Further interpolating the data, it was found that a headband force under 10.5 N would be described by 80% of the wearers as "no particular feeling" or "a little tight", while an earmuff weight under 245 g would be described by 80% of the wearers as "no particular feeling" or "a little heavy". Twelve out of the 28 commercial earmuffs tested in this project (43%) had average headband forces higher than 10.5 N, and 7 (25%) were heavier than 245 g.

Table 6
Subjects' perceptions for earmuff headband force

	Subjects' qualitative feeling	Score	Earmuff headband force				
			6 N	8 N	10 N	12 N	14 N
1	No particular feeling	0	37	19	13	3	1
2	A little tight	-1	5	22	21	19	8
3	Tight	-2	0	0	4	14	13
4	Very tight	-3	0	0	1	3	20
5	Unbearable	-4	0	0	0	0	6
Total score			-5	-22	-32	-56	-118
Average score (total score/total times)			-0.12	-0.54	-0.82	-1.44	-2.46

Table 7
Subjects' perceptions for earmuff temperature

	Subjects' qualitative feeling	Score	Earmuff temperature			
			30°C	32°C	34°C	36°C
1	No particular feeling	0	22	7	26	7
2	A little hot	-1	18	26	23	15
3	Hot	-2	7	9	1	7
4	Very hot	-3	1	1	2	0
5	Unbearable	-4	0	0	0	0
Total score			-35	-47	-31	-29
Average score (total score/total times)			-0.73	-1.09	-0.60	-1.00

Table 8
Subjects' perceptions for earmuff weight

	Subjects' qualitative feeling	Score	Earmuff weight					
			130 g	170 g	210 g	250 g	290 g	330 g
1	No particular feeling	0	29	36	27	10	4	3
2	A little heavy	-1	2	1	21	27	17	12
3	Heavy	-2	0	0	4	6	12	20
4	Very heavy	-3	0	0	0	1	7	7
5	Unbearable	-4	0	0	0	0	0	4
Total score			-2	-1	-29	-42	-62	-89
Average score (total score/total times)			-0.06	-0.03	-0.56	-0.95	-1.55	-1.93

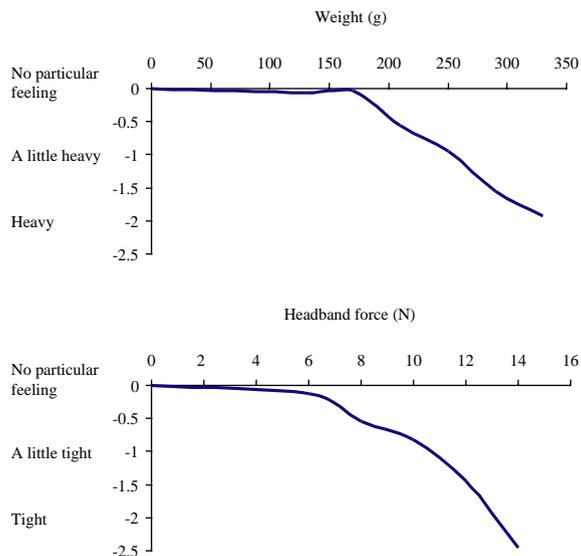


Fig. 3. Relation of subjects' perceptions and magnitudes of earmuff headband force and weight.

5. Conclusions

From this study, guidelines to improve the design of current hearing protection can be summarized as follows:

- (1) The important design factors that influence the comfort of earmuffs are airtightness, weight, heat-sinking ability, texture, and headband force. Adjustability and wearing convenience, which are emphasized in many hearing protection patents, were rated less important.
- (2) An earmuff weight under 245 g would be described by 80% of the wearers as “no particular feeling” or “a little heavy”. Weight of the muffs accounts for 68–77% of the total weight, which should be the major target if a lightweight design is desired.

- (3) An earmuff with larger interior space tends to have lower inner temperature.
- (4) A headband force under 10.5 N would be described by 80% of the wearers as “no particular feeling” or “a little tight”. “Sense of oppression” is the number 2 reason of discomfort of wearing hearing protection, but 43% of the commercial earmuffs tested in this project had average headband forces higher than 10.5 N. More attention should be paid to reduce the headband force, while keeping airtightness at an acceptable level.
- (5) “Having difficulties in conversations” is the number one reason why workers perceive that hearing protection are uncomfortable, so future research could emphasize the development of electronic earmuffs that enables conversation but filters out the noise.

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Appendix

1. Basic information:
 - Gender: (Male /Female).
 - Age: (15–24/25–34/35–44/45–54/over 55).
 - Do you have experience wearing earmuffs at work? (Yes/No)
 - Do you have experience wearing earplugs at work? (Yes/No)
2. Work environment:
 - Do you work in a high decibel (over 85 dBA) environment? (Yes/No)
 - How many hours do you have to wear hearing protection at work everyday? (Less than 1 h/1–2 h/2–3 h/3–4 h/4–6 h/6–8 h/over 8 h)
 - How many times do you have to change between normal and high-decibel environment at work everyday? (1–3 times/4–6 times/7–10 times/over 10 times)
 - Do you work in a hot and humid environment? (Yes/No)
3. Uncomfortable feelings of wearing hearing protection at work:
 - Do you work in a dusty and dirty environment? (Yes/No)
 - Select uncomfortable feelings when you wear hearing protection at work. (No discomfort/Feeling dirty/Feeling itchy/Feeling of an object in the ear/Sense of oppression/Feeling stuffy/Easy to slide or fall off/Headache/Protectors deform easily/Having difficulties in conversations/Poor soundproofing/Interfere with work/Tinnitus/Acoustics change /Discomfort due to hard contacting parts /Other -----).
 - (Skip this question if you do not have experience wearing earplugs at work.) When you wear earplugs at work, you start to feel uncomfortable after wearing them for (within 15 min/15–30 min/30 min–1 h/1–1.5 h/1.5–2 h/over 2 h).
 - (Skip this question if you do not have experience wearing earmuffs at work.) When you wear an earmuff at work, you start to feel uncomfortable after wearing it for (within 15 min/15–30 min/30 min–1 h/1–1.5 h/1.5–2 h/over 2 h).
4. Evaluate the importance of design factors of earplugs and earmuffs that might influence their comfort:
 - (Skip this question if you do not have experience wearing earplugs at work.) Please evaluate the importance of following factors to the comfort of earplugs on a 5-point scale (very important/important/average/less important/not important): weight, texture, inflation pressure, heat-sinking ability, sweat absorbing ability, wearing convenience, soundproofing.
 - (Skip this question if you do not have experience wearing earmuffs at work.) Please evaluate the importance of the following factors to the comfort of earmuffs on a 5-point scale (very important/important/average/less important/not important): weight, texture, headband force, adjustability, heat-sinking ability, sweat absorbing ability, wearing convenience, soundproofing, airtightness.

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