ELSEVIER

International Journal of Industrial Ergonomics 27 (2001) 321–329

International Journal of
Industrial Ergonomics

www.elsevier.nl/locate/ergon

Effects of ventilated safety helmets in a hot environment

G.A. Davis[a,*], E.D. Edmisten[a], R.E. Thomas[a], R.B. Rummer[b], D.D. Pascoe[c]

[a] *Department of Industrial and Systems Engineering, Auburn University, Auburn, AL 36849, USA*
[b] *Andrews Forestry Science Laboratory, USDA Forest Service, DeVall Drive, Auburn, AL 36830, USA*
[c] *Department of Health and Human Performance, Auburn University, Auburn, AL 36849, USA*

Received 11 May 2000; accepted 28 November 2000

Abstract

Forest workers are likely to remove head protection in hot and humid conditions because of thermal discomfort. However, a recent Occupational Safety and Health Administration (OSHA) regulation revision requires all workers in logging operations to wear safety helmets, thus creating a compliance problem. To determine which factors contribute to forest workers' thermal discomfort, this study evaluated subjects' physiological and psychophysical responses during tasks approximating the workload of forest workers in a high-temperature environment similar to that found in the southeastern United States during the summer. Environmental conditions in the helmet dome space were also evaluated. Three helmets were used in this study: a standard helmet, a passively ventilated helmet, and an actively ventilated helmet. It was found that none of the tested helmets burdened the body significantly for the physiological variables that were examined. Evaluation of the dome space environmental conditions showed that both the dry-bulb temperature (DBT) and wet-bulb temperature (WBT) varied significantly among the helmets tested. Psychophysical results showed that ventilation contributes to greater helmet comfort, and that weight and fit are important factors in helmet design.

Relevance to industry

Protective helmets for use in hot and humid environments should be modified to make them more comfortable, encouraging forest workers to wear them and thus comply with OSHA regulations.

Keywords: Head protection; Heat stress; Personal protective equipment; Protective headwear; Safety helmet; Ventilation

1. Introduction

On February 9, 1995, a revision to OSHA standard 29 CFR 1910.266 went into effect that addressed the safety requirements for logging operations. This standard, which formerly applied only to pulpwood logging, now covers employees involved in all logging operations. One of its major provisions specifies that head protection must be worn by all employees working where "there is potential for head injury from falling or flying objects" (Department of Labor, 1994).

Although wearing head protection, i.e. a safety helmet, is now mandatory and can be enforced to a degree through supervision, forest workers are likely to remove the helmets during uncomfortably hot weather if they experience discomfort such as

*Corresponding author. Tel.: +1-334-844-1411.
E-mail address: davisga@mail.auburn.edu (G.A. Davis).

PII: S 0 1 6 9 - 8 1 4 1 (0 0) 0 0 0 5 9 - 7

heat stress while wearing them (Abeysekera and Shahnavaz, 1988; Thomas et al., 1995). Therefore, forest and other workers should have thermally comfortable safety helmets available to encourage them to comply with this standard.

The reasons for the thermal discomfort experienced by wearers of safety helmets must first be determined in order to fully understand the problem. Several possibilities exist. The discomfort could be: (1) physiological, where the body experiences excessive stress when the helmet is worn; (2) psychophysical, where the discomfort is more of a mental perception than a physical burden; or (3) related to uncomfortable environmental conditions, such as high temperature and humidity, in the helmet dome space. This combined thermal effect might not significantly affect the body physiologically, but could cause enough discomfort that the worker would remove the helmet.

1.1. Previous helmet studies

Abeysekera and Shahnavaz (1988) investigated the potential benefits of helmets with ventilation holes in both laboratory and field settings. In laboratory tests, they found no significant differences in the subjects' heart rates and skin temperatures based on whether they wore the ventilated or unventilated helmets. In the much larger field study, the ventilated helmet was judged less hot and caused less sweating than the other helmet styles tested. However, the unmodified helmet was judged more acceptable by the users, presumably because it offered more protection. They also found that only 5–10% of the 1245 workers who participated in the field study actually wore their helmets. The workers said the helmets were "too hot and sometimes caused headaches and loss of hair".

Jung and Schenk (1984) compared the climatic conditions (air temperature and relative humidity) inside and outside the safety helmet shell for a wide variety of helmet types. In a laboratory analysis, five employees of the Professional Association for Safety at Work wore 30 types of helmets for extended periods of time in order to model typical working conditions, and found temperature and humidity inside the helmets to be greater than outside by as much as 5°C and 39% relative humidity, respectively. This finding was confirmed by field studies. The authors suggested that vents and internal padding influence air circulation under the helmet shell, and that vented unpadded helmets appear to maintain thermal comfort more effectively.

Fonseca (1976) investigated the effect of ventilating slots in helmets on evaporative heat transfer, using ventilating slots at the top and around the helmet which removed about 8% of the helmet surface. He determined that the total head coverage area had to be reduced from 67% to 47% to significantly increase the evaporative heat transfer. He also found that when a large air space existed between the helmet and the head, the benefit from the ventilating holes was lost. Reischl (1986) carried out a similar investigation of helmet ventilation designs for firefighter helmets, and found that a helmet with side ventilation holes was cooler than an otherwise identical unventilated helmet and that increasing the separation between the helmet shell and the user's head also enhanced the cooling action due to the improved air circulation.

Gisolfi et al. (1988) investigated helmet effects on the thermal balance of cyclists, measuring their heart rates, core and skin temperatures, and rating of perceived exertion (RPE) both with and without helmets. They found that wearing a helmet did not appear to significantly affect any of the measured parameters.

As this survey of the literature shows, investigators have reached different, often contradictory, conclusions on the effect of wearing protective headgear in hot conditions and on the possible benefits of ventilating holes. In the experiment reported here, we will attempt to resolve this anomaly.

2. Methods and procedures

2.1. Objectives

This study evaluated the physiological effects and environmental conditions – dry-bulb temperature (DBT) and wet-bulb temperature (WBT) – in the dome space of safety helmets. The study was set up to approximate the workload of forest workers in the hot environment typical of the southeastern United States. Subjects walked on treadmills in an environmental chamber at a temperature of 35°C and a relative humidity of 40%. Responses were measured for a standard helmet, a passively ventilated helmet, and an actively ventilated helmet.

All trials were in Auburn University's thermal laboratory environmental chamber. Subjects were assigned randomly to a helmet-wearing sequence, counter-balancing the treatment application, and to one of two treadmills for each trial. After each trial, psychophysical responses to the helmet used were evaluated with an oral survey (given in Appendix A) during which subjects assessed and compared helmets for comfort, hotness, and heaviness.

2.2. Independent variables

The independent variables were helmets and subjects. Three helmet styles, shown in Fig. 1, were used:

(1) An orange plastic standard helmet that meets ANSI Z89.1–1986, weighing 368.5 g.

(2) A passively ventilated orange plastic standard helmet with 37 (9.5) mm holes (approximately 9% of the surface) drilled in a symmetrical circular pattern in the shell, around the centerline. The holes were added to allow heat to escape from the dome space, although they may have compromised the helmet's impact protection so that it no longer conformed to the ANSI specification. This helmet weighed 361.1 g.

(3) An actively ventilated white plastic RACAL airstream anti-dust helmet type AH.1 with a battery-powered, dust-filtering fan. Although not specifically designed to promote cooling, this was included in the study because of its potential cooling effects. This helmet weighed 956.5 g and required a belt-attached battery pack that weighed an additional 532.8 g.

2.3. Dependent variables

The dependent variables measured were: core temperature, mean skin temperature, and heart rate; dome space DBT and WBT; and the subject's opinion of the helmets.

A rectal probe measured core temperature, a Polar heart rate monitor recorded heart rate, and four thermistors – one each on the chest, upper arm, thigh, and calf – measured skin temperatures. Core temperature was chosen over tympanic due to the possible confounding effects of the radiant lamp and air flow across the helmets.

A thermistor in each helmet measured dome space DBT. A second thermistor in each helmet measured dome space WBT. The WBT thermistor was covered with a clean cotton wick and fastened next to the DBT thermistor. To prevent the actively ventilated helmet's WBT thermistor from drying out due to the higher air velocity, a sponge was fastened to the wick base allowing more water storage. Both thermistor bulbs were positioned to

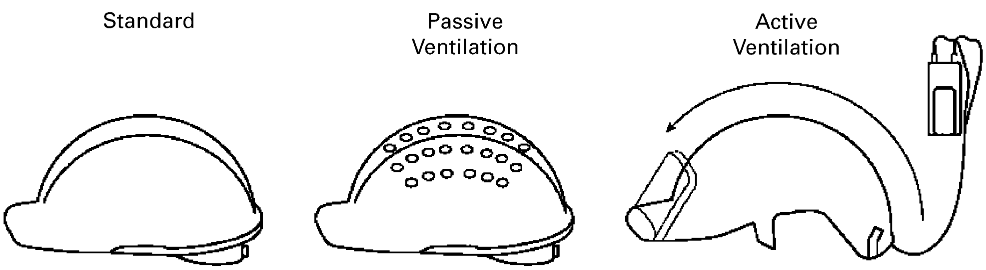

Fig. 1. The three helmets tested.

ensure no contact was present with the helmet shell or subject's head. The remainder of the lead wire was securely taped to the helmet shell and exited above the rear headband.

Subjective opinions and comparisons of helmet comfort, hotness, and heaviness were elicited with a questionnaire based on that used by Abeysekera and Shahnavaz (1988). The questionnaire (Appendix A) used opposite adjectives, rank-scale data, and paired comparisons. Subjects provided RPE at 10 min intervals throughout the trials.

2.4. Subjects

Eight male university students of above-average fitness were subjects in this study. They were paid $125 each for participating. Table 1 summarizes the subject data.

2.5. Experiment location and setup

Subjects had to pass a forestry step test (Sharkey, 1990), which required them to step on and off a bench at 90 steps/min for 5 min. After completing the step test, each subject's pulse was taken to determine aerobic capacity. Only subjects whose aerobic capacity was 45 ml O_2/kg min or greater were allowed to participate.

The two treadmills in the environmental chamber were calibrated to 5.6 km/h $\pm$0.08 km/h. After 50% of the trials (16) were completed, the treadmills were rechecked and found to still be within $\pm$0.08 km/h.

Table 1
Subject data

	Range	Mean	Standard deviation
Age (yr)	24–28	25.8	1.49
Height (cm)	170–196	181.1	9.28
Weight (kg)	61.8–90.9	74.2	9.74
Aerobic capacity (ml O_2/kg min)	45–67	59.4	7.54

To create a radiant load that simulated sunlight (globe temperature 39.0°C), six 250 W Sylvania infrared heat lamps were hung on a polyvinyl chloride (PVC) pipe frame behind the treadmills. A baseboard heater controlled the ambient DBT, and a humidifier and dehumidifier regulated the humidity.

2.6. Data recording equipment

Core and skin temperatures and DBT and WBT in the helmet were recorded at 1 min intervals using two Grant Remote Squirrel Meter/Loggers (one 1200 series, one 1250 series). Environmental conditions were monitored with a Reuter Stokes RSS-211D Heat Stress Monitor (the WIBGET®) on a tripod in the center of the chamber. Before each trial, thermistors measuring core, skin, and dome space temperatures were calibrated against the heat stress monitor. Temperature readings were accurate to 0.1°C.

2.7. Experimental design and procedure

Before data collection began, each subject read and signed a University approved informed consent form, filled out a medical history questionnaire, and completed a pilot trial to become familiar with equipment and procedures.

Each subject completed four trials in a random sequence: one with the standard helmet, one with the passively ventilated helmet, one with the actively ventilated helmet, and one with no safety helmet. Before each subject arrived, the environmental chamber was heated to a DBT of 35.0°C, the helmet for that trial was put inside for its temperature to stabilize, and the wick for the WBT thermistor was soaked with distilled water.

Each subject wore denim jeans, a cotton T-shirt, and tennis shoes. Before each trial, the subject was fitted with four skin thermistors to determine mean skin temperature, a rectal probe to determine core temperature, and a heart rate monitor.

After entering the chamber, the subject stepped onto his assigned treadmill, put on a helmet (if any), and adjusted it for a comfortable fit. Leads for skin and core temperatures and helmet dome space conditions were plugged into channels on the Grant logger. When the subject began walking, the data logger was immediately activated. The treadmill pace of 5.6 km/h approximates a work-load of 360 kcal/h (Sharkey, 1990) and corresponds to self-paced manual tasks in forest harvesting as defined by Smith and Rummer (1987).

In addition to the data recorded by the loggers, data were also recorded manually at start-up and at 5-min intervals throughout the 45 min trial, in order to confirm the equipment was operating correctly and subjects were offered water to replenish lost fluids.

After finishing the trial, removing the leads and cooling down, the subject was verbally asked survey questions about the helmet he had worn for that trial, if any. Comparison questions were only asked after the subject had completed trials with at least two helmets.

3. Results and discussion

3.1. Physiological evaluation

Mean heart rate data for the control (no helmet) ranged from 92.6 to 113.9 beats/min (BPM) for the duration of the trial. Recorded heart rates for the treatment conditions had a range of 88.6–116.7 BPM. The data suggest that the subjects' heart rates did not increase as rapidly when they wore passively ventilated helmets as they did with the other helmet treatments.

Fig. 2 shows mean core temperature data. When subjects wore either of the ventilated helmets, they generally had lower core temperatures than when they wore a standard helmet, by approximately 0.05°C.

Thermocouples were taped to the subject's chest, arm, thigh, and calf. A four-site formula was used for the calculation of mean skin

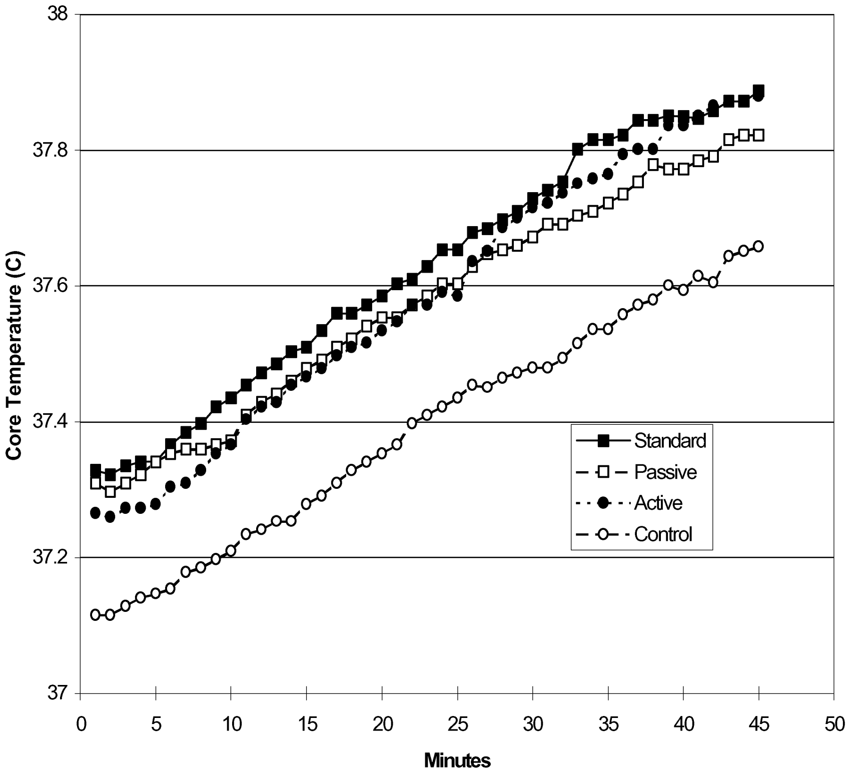

Fig. 2. Core temperature results.

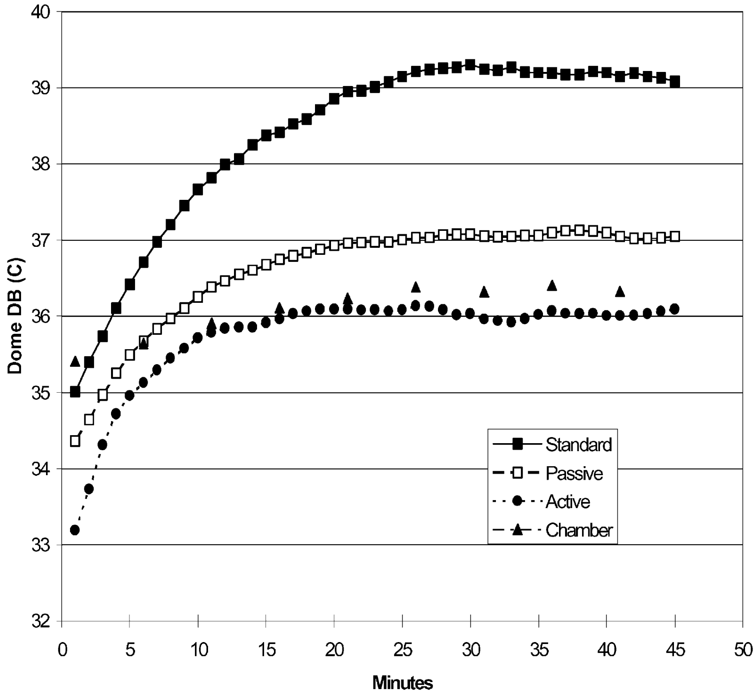

Fig. 3. Dome space dry-bulb temperature results.

temperature. When subjects wore passively ventilated helmets, their mean skin temperatures were consistently lower (by approximately 0.1°C) than when they wore other helmets. However, none of the differences in the physiological variables were statistically significant when tested by ANOVA ($p<0.05$).

3.2. Environmental evaluation

Fig. 3 shows the mean DBT for each helmet design compared with the average DBT in the environmental chamber for all trials. DBTs for the standard helmet were consistently higher than those for the passively and actively ventilated helmets. The rise in each curve indicates that the temperature increased in the space between the subject's head and the helmet shell until a steady state was reached, about 20 min into the trial. The average steady-state difference between the standard and actively ventilated helmets was 3.16°C.

Fig. 4 shows the mean WBT for each helmet design compared with the average WBT in the environmental chamber for all trials. Again, the standard helmet resulted in statistically higher temperatures than the other two helmet designs. Although the transition to a steady state is not as pronounced for WBT, temperatures did tend to stabilize after 20 min. The small initial dip occurred because air velocity increased when a helmet was lifted and adjusted before the trial. The damp wick then cooled for a short time before heat from the subject's head made the temperature rise. The average difference in steady-state WBT between the standard helmet and the actively ventilated helmet was 4.07°C.

ANOVA tests showed that the dome space DBT was significantly lower in the passively ventilated helmet than in the standard helmet. Also, the DBT in the actively ventilated helmet was significantly lower than that in the passively ventilated helmet. The WBT was significantly lower in the ventilated helmets than in the standard helmet. Both tests indicate that a helmet's effect is significant, with p-values of less than 0.0001. ANOVAs were run on data from mins 25 to 45 of all trials.

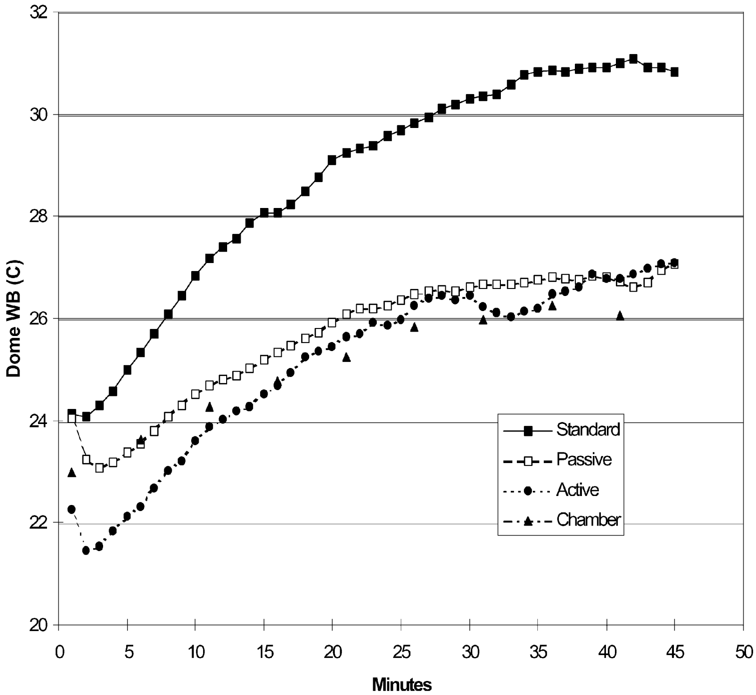

Fig. 4. Dome space wet-bulb temperature results.

Table 2
Environmental chamber data (C)

	Mean	Maximum	Minimum
Dry bulb temperature	36.1	38.4	34.1
Wet bulb temperature	25.2	28.7	24.7
Globe temperature	29.1	40.8	36.6
WBGT (all min)	29.1	31.6	26.3
WBGT (min 25–45)	29.8	31.6	28.0

Table 2 summarizes the ambient environmental conditions. Although DBT and WBT varied during and between trials, mean WBT during the steady-state phase (mins 25–45) never varied more than 3.6°C. Natural WBT readings were converted to aspirated WBT with a formula developed by Nishi and Gagge (1971). These aspirated WBTs were combined with the DBT to find relative humidity on a psychometric chart. Steady-state humidity in the environmental chamber ranged from 33% to 54%, and the differences between dome space and chamber humidity ranged from 0.9 (passively ventilated helmet) to 11.5% (standard helmet).

3.3. Psychophysical evaluation

The first part of the three-part survey contained opposite adjectives. All eight subjects judged the passively ventilated helmet comfortable, acceptable, not hot, not itchy, and not heavy. However, seven subjects judged the actively ventilated helmet heavy, and six judged it not acceptable. Responses to the standard helmet were generally favorable but were not as favorable as responses to the passively ventilated helmet.

In the second part of the survey, subjects ranked the helmets on a scale of 1–5 for comfort, hotness, and heaviness. The results were analyzed using the Kruskal–Wallis test (Sprinthall, 1994) and showed a significant difference for each of the three criteria: comfort, hotness, and heaviness. Also, the helmets were ranked in the same order in all three criteria, with the passively ventilated helmet ranked the least uncomfortable, the least hot, and the least heavy. The standard helmet ranked second in all three criteria, and the actively ventilated helmet was a distant third.

The third part of the survey consisted of paired comparisons. No one preferred the actively ventilated helmet to either of the other two helmets and no one preferred the standard helmet to the passively ventilated helmet. More subjects preferred the passively ventilated helmet than preferred the other two helmets in all respects, judging it to be more comfortable, less hot, and less heavy than the other helmets.

The data collected on RPE showed that subjects perceived more exertion when wearing helmets than when not wearing a helmet, as would be expected. The passively ventilated helmet RPEs were significantly lower than the RPEs of the other two helmets when a Friedman ANOVA by ranks was done on the mean values.

Subjects made additional comments to the survey questionnaire that shed light on the survey results. More than half the subjects said they disliked the actively ventilated helmet because it not only fit poorly but also was too heavy — weighing more than twice as much as the standard and passively ventilated helmets and in addition requiring a heavy battery. The actively ventilated helmet was actually designed as a dust helmet, and most subjects found its tight fit at the temple uncomfortable.

4. Conclusions

The following conclusions could be drawn from this study:

(1) The physiological variables that were tested had no statistical significance.
(2) The dome space DBT and WBT of the ventilated helmets were cooler.
(3) The actively ventilated helmet maintained a significantly lower dome space DBT than either the standard helmet or the passively ventilated helmet, but despite having the lowest dome space DBT and WBT, was not preferred due to its excessive weight and uncomfortable fit.
(4) Psychophysical results showed that ventilation contributes to greater helmet comfort, and that weight and fit are important factors in helmet design.
(5) Further research is needed on improving the comfort and effectiveness of ventilating safety helmets without compromising the safety of the wearer. A helmet needs to be developed with acceptable weight, comfortable fit, and adequate ventilation while still meeting ANSI requirements for impact protection.

Acknowledgements

This study was funded by the USDA Forest Service USFS–19–95–065/USDA/The Effects of Personal Protective Equipment on Heat Comfort and Stress in Woodsworkers.

Appendix A. Subject questionnaire

Section 1: Opposite adjectives

For the helmet tested, select one of each pair of adjectives that best describes how it felt to you.

Comfortable/uncomfortable	Hot/not hot
Not itchy/itchy	Acceptable/not acceptable
Sweating/not sweating	Not heavy/heavy

Section 2: Rank scale

For the helmet tested, rate how it felt to you, on a scale from 1 to 5.

Comfort						
Very uncomfortable	1	2	3	4	5	Not at all uncomfortable
Hotness						
Very hot	1	2	3	4	5	Not at all hot
Heaviness						
Very heavy	1	2	3	4	5	Not at all heavy

Section 3: Paired comparisons (*After at least two helmets have been tested.*)

Of the pair given, select the helmet you preferred for each of the criteria given.

	Comfort	Less hot	Less weight
Standard/ passive			
Standard/ active			
Passive/ active			

Adapted from Abeysekera and Shahnavaz (1988).

References

Abeysekera, J.D.A., Shahnavaz, H., 1988. Ergonomics evaluation of modified industrial helmets for use in tropical environments. Ergonomics 31, 1317–1329.

Department of Labor, Occupational Safety and Health Administration, 1994. Federal Register, Part II. 59:196 (12 October).

Fonseca, G.F., 1976. Physiological factors in protective helmet design. (M1/77/14/USARIEM) U.S. Army Research Institute of Environmental Medicine Natick, MA.

Gisolfi, C.V., Rohlf, D.P., Navarude, S.N., Hayes, C.L., Sayeed, S.A., 1988. Effects of wearing a helmet on thermal balance while cycling in the heat. The Physician and Sportsmedicine 16, 139–146.

Jung, K., Schenk, H., 1984. Zur erfassung des mikroklimas im schutzhelminnenraum [Determination of the micro-climate inside a safety helmet]. Health and Safety Executive Translation Services, HSE Translation No. 11013, 1984. Arbeitsmedizin Sozialmedizin Praeventivmedizin, 19 (9), 209–213. (Swedish).

Nishi, Y., Gagge, A.P., 1971. Humid operative temperature. A biophysical index of thermal sensation and discomfort. Journal of Physics (Paris) 63 (3), 365–368.

Reischl, U., 1986. Fire fighter helmet ventilation analysis. American Industrial Hygiene Association Journal 47 (8), 546–551.

Sharkey, B.J., 1990. Physiology of fitness: prescribing exercise for fitness, weight control, and health. Human Kinetics Books, 3rd Edition. Champaign, IL, pp. 293–300.

Smith, L.A., Rummer, R.B., 1987. Development of a heat stress prevention activity guide for use by the southern forest harvesting managers. USDA Forest Service Research Agreement No. 19–87–065.

Sprinthall, R.C., 1994. Basic Statistical Analysis,, 4th Edition. Allyn and Bacon, Boston, MA.

Thomas, R.E., Smith, L.A., Rummer, R.B., 1995. The effects of personal protective equipment on heat comfort and stress in woodsworkers. Co-operative Study Proposal. USDA Forest Service, DeVall Drive, Auburn, AL 36830.