A Review on Thermal Comfort Evaluation of Head-Worn Devices

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Abstract. Head-worn devices are widely used in both work and leisure. Previous studies have showed that thermal discomfort would arise with usage of head-worn devices. The present study conducted a literature review on thermal comfort/discomfort evaluation on head-worn devices to obtain a more complete understanding of the topic. The type of devices, research method, thermal comfort parameters and thermal effects of wearing headgear were examined and summarized. It is suggested that when evaluating thermal comfort of hear-worn devices, objective and subjective methods should be triangulated, and more controlled experiment is needed. The review provides a better methodological and empirical understanding of current research on thermal comfort of head-worn devices, which will facilitate product evaluation and product design improvement in industry.

Keywords: Thermal comfort · Literature review · Comfort evaluation
Head-worn devices

1 Introduction

Head-worn devices are widely used in both work and leisure, including protective helmet, masks, goggles, as well as head mounted displays. Previous studies have showed that thermal discomfort would arise with usage of head-worn devices, which is a major reason for not wearing those devices with protective capabilities. Head plays an important role in heat transfer and directivity determines the whole body thermal sensation and thermal comfort [1]. Improvement on thermal physiological comfort would greatly improve the willingness to use and user experience. Current evidence on reasons that lead to thermal discomfort are inconsistent. Some studies have showed that increase in temperature in the microclimate would lead to thermal discomfort, but other studies suggested that the thermal discomfort is due to skin wetness and increased relative humidity [2–4], or the speed of temperature change [5]. The inconsistency of the results might be due to those studies were focusing on different products, utilized different thermal comfort parameters, and adopted different assessment methods. In addition, the experiments were conducted under different environmental conditions, i.e., warm, cool or neutral ambient temperature with different levels of relative humidity.

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The present study is aiming at summarizing current evidence on thermal comfort/discomfort on head-worn devices to obtain a more complete understanding of the topic. The research design and the objective and subjective parameters used in evaluating the thermal comfort head-worn devices would be summarized. This paper could help provide a better theoretical and empirical understanding of current research on thermal comfort of head-worn devices, which will facilitate product evaluation and product design in industry.

2 Methods

Article search was conducted in five databases, including Elsevier, Scopus, Springer, GoogleScholar, and Web of Science. Three groups of key words were used for searching: (1) "comfort" or "discomfort"; (2) "thermal" or "heat" and (3) search for devices worn on head. Since headgears are studied in many fields, it was decided to broadly include search term such as "head-wearing", "helmet", "masks", "headset". Title, abstracts and full papers were screened by the author. Inclusion criteria of the articles are: original research published in English; experiments, quantitative, qualitative or multiple research methods; and research aimed at assessing or evaluate the thermal comfort/discomfort of head-worn devices. A total of 16 papers met the criteria and were reviewed.

3 Results and Discussion

3.1 Characteristics of the Reviewed Articles

The included 16 articles were aiming at assessing the comfort or discomfort of wearing head-worn devices. In respect of the devices or objects examined by the 16 studies, 11 of them were about helmets, four were on face masks and one investigated earmuff. All of the 16 studies employed experiment design with objective measures, whereas seven studies also combined with subjective measures. Nine out of 16 studies involved human subjects with sample size ranging from three to forty-four. Remaining seven studies used manikin headform without human participation. Most of the studies controlled the ambient temperature and relative humidity in experiment environment. The ambient temperature ranged from 7° C to 29.8° C and the relative humidity ranged from 28% to 70%. Eleven studies also controlled the wind speed. The results were summarized in Table 1.

It is found that many of the discussion about the thermal comfort of head-worn devices were on helmets. Although wearing facemasks and hearing protectors may also cause thermal discomfort, they are not of interest of researchers comparted with helmets. These might be due to helmet-wearing is mandatory in some sports and working places because of its protective abilities, and thermal discomfort is considered as a major reason for not wearing. Therefore, improving on helmets thermal comfort could increase the willingness to wear which could be lifesaving in some circumstance.

Table 1. Characteristics of the identified 16 articles

No.	Reference	Device type	Method	Subject	Independent variables	Dependent variables	Environment control
1	Abeysekera and Shahnavaz [6]	Cricket helmet	Experiment and survey	N = 6 (male)	Four helmets differed in color and ventilation holes	Heart rate; scalp skin temperature; subjective feeling of (dis)comfort and hotness	AT = 29.8 °C; RH = 28%
2	Alam et al. [7]	Bicycle helmet	Experiment	Mannequin	Five helmets under a range of wind speeds, yaw and pitch angles controlled by wind tunnel	Temperature distribution measured by thermocouple; aerodynamic drag coefficient	Different wind speed
3	Bogerd and Bruhwiler [8]	Full-face motorcycle helmets	Experiment	Manikin headform	Six helmets differed under head tilt angle; hair; wind speed controlled by wind tunnel	Convective heat loss	AT = 22 °C
4	Bogerd et al. [9]	Full-face motorcycle helmets	Experiment and survey	N = 8 male; headform	Four helmets under two different wind speeds (air speed = 39.2 ± 1.9 km h^{-1} or 59.3 ± 1.4 km h^{-1})	Convective heat loss (temperature and RH in microclimate measured by sensors); subjective perceptual effects of local temperature, airflow, and thermal (dis)comfort	AT = 23.7 ± 0.4 °C or 27.5 ± 0.3 °C; RH = 50 ± 2%; two wind speeds
5	Brühwiler [10]	Bicycle helmets	Experiment	Manikin headform	26 helmets with two head tilt angles, with and without visor	Convective heat loss	AT = 25 ± 0.05 °C; RH = 50 ± 0.1%; air speed = 3.1 ± 0.1 ms^{-1}
6	Dullah et al. [11]	Cricket helmet	Experiment and survey	N = 3	Two helmets differed in ventilation and material	Temperature and relative humidity in microclimate using micro wig sensor; subjective thermal and moisture perception	AT = 17.8 ± 0.8 °C and 53 ± 5% RH
7	Ghani et al. [12]	Safety helmets	Experiment	Dummy head	Incident wind speed, heat source (radiation and head), PCM material, human sweat	Air channel temperature and dummy head skin temperature measured by thermocouples	Microclimate AT = 45 ± 1 °C; RH = 65 ± 5%; air speed = 0–3 ms^{-1}

(*continued*)

Table 1. (*continued*)

No.	Reference	Device type	Method	Subject	Independent variables	Dependent variables	Environment control
8	Guo et al. [13]	Masks	Experiment and survey	N = 10 (5 male and 5 female)	Two masks with exhaust valves or exhaust hole	Ear canal temperature; heart rate; blood pressure; clothing microclimate (temperature and humidity) by thermistors and humidity sensors; and subjective perception of discomfort	AT = 25 °C; RH = 70%
9	Hsu et al. [4]	Safety helmet	Experiment	Manikin headform	Heat sources: radiant, body heat, and convection; color	Temperature beneath the helmet shell and the temperature contour beneath the helmet shell measuring by thermocouple, the speed of heat dissipation	AT = 23 ± 0.5 °C; RH = 40%–60%; air speed = 0.8 ms^{-1}
10	Hsu et al. [14]	Earmuff	Experiment and survey	N = 44	Headband forces, temperature, airtightness, and weight	Self-perceived discomfort on headband force, temperature, airtightness and weight	–
11	Li et al. [15]	Face surgical masks	Experiment	N = 10 (5 female; 5 male)	N95 (3M 8210) and two facemasks with and without nano-functional treatments	Heart rates; outer surface temperature; microclimate and skin temperatures; absolute humidity inside and outside of surface; perception of humidity, heat, breath resistance and overall discomfort	AT = 25 °C; RH = 70%
12	Nielsen et al. [16]	Face mask	Experiment	N = 6 (2 female and 4 male)	AT (7, 16, 25 °C); mask air temperature (22, 27, 33 °C); mask air RH (61, 86%)	Skin temperatures by thermocouples; heart rates by ECG; skin wettedness by dew point sensors; subjects' thermal sensations, sensations of sweating and skin wettedness and their thermal preferences	Air speed = 0.05 ms^{-1}
13	Pang et al. [1]	Cricket helmet	Experiment	Manikin headform	Five helmets	Surface temperature measured by ThermaCam; microclimate temperature measured by thermocouples; heat transfer	AT = 23 ± 0.5 °C; RH = 40%–60%; air speed = 0.8 ms^{-1}

(*continued*)

Table 1. (*continued*)

No.	Reference	Device type	Method	Subject	Independent variables	Dependent variables	Environment control
14	Pang et al. [17]	Cricket helmet	Experiment	Sweating manikin headform	Five helmets under 1) AT = 23 ± 0.5 °C; RH = 50 ± 5%; 2) AT = 35 ± 0.5 °C; RH = 40 ± 5%;	Thermal resistance; evaporative resistance; heat dissipation, permeability index	Air speed = 0.08 ± 0.01 ms^{-1}
15	Roberge et al. [18]	Filtering facepiece respirators	Experiment and survey	N = 10 (7 male; 3 female)	3 filtering facepiece respirators differed in filter resistance (3, 6, 9 mm H_2O pressure)	Physiological parameters (i.e., heart rate, respiratory rate, oxygen saturation, transcutaneous carbon dioxide levels, tympanic membrane temperature); pulmonary function variables (i.e., tidal volume, respiratory rate, volume of carbon dioxide production, oxygen consumption, or ventilation); subjective ratings (i.e., exertion, thermal perception, inspiratory effort, expiratory effort and overall breathing discomfort).	AT = 20.9 ± 1.3 °C; RH = 23.5%–5.6%
16	Ueta et al. [19]	Noninvasive ventilation with helmet	Experiment and survey	N = 28 (19 male and 9 female)	Helmet with and without humidification (31, 34, 37° C)	Subjective comfort score; breathing frequency; temperature, absolute and relative humidity inside helmet	8 cm H_2O CPAP ventilation with F_{IO2} of 0.21 and 0.5

N = the number of human subject; AT = ambient temperature; RH = relative humidity; H = humidity

Comfort or discomfort is a subjective sensation or state, therefore human subjects were always involved in product comfort evaluation. The advantage of human participation is that the results are more closely relevant to end-users, and relationships between objective parameters and subjective perceptions could be established. However, the results of subjective studies may subject to individual differences compared with objective methods, especially when sample size is small. In the reviewed studies, nine out 16 involving human participation, but seven studies had sample size less than 10 and had more male participants. The problem of small sample size and gender imbalance among subjective methods would impede result generalization.

Studies were published using different kind of headforms [9, 10, 17]. The anatomically formed thermal manikin headforms are equipped with heating elements and temperature sensors, so that the surface temperature of headforms can be controlled. With manikin headforms, researchers could be able to quantify the heat transfer or heat loss by convection, conduction and radiation using mathematical methods. Compared with subjective methods, experiments using headforms provide more objective data on product thermal properties and less time consuming. However, the manikin headforms might not exactly reflect human thermal physiological responses and most importantly without human participation, the human perception of objective parameters changes could not be evaluated.

Whole body thermal sensation was primarily determined by the ambient air temperature [16]. Therefore, in the reviewed researches, experiments were conducted in a climate chamber with controlled ambient temperature, humidity and wind speed. Many studied had set the ambient temperature greater than 25 °C because previous evidence shows that thermal discomfort is a problem only exist in warm environment [20].

4 Method for Thermal Comfort Evaluation

A range of objective indicators were used to assess thermal comfort or discomfort of head-worn devices. The most frequently used indicator is the temperature (skin temperature or microclimate temperature), which is measured by all reviewed articles. Five studies also measured microclimate relative humidity or skin wettedness. Other biological parameters of thermal comfort include heart rate, blood pressure, chest temperature, ear canal temperature, respiratory rate, pulmonary function variables. It is noted that more physiological parameters were measured in research on face masks compared with helmets. Helmet-related studies usually measures microclimate temperature beneath helmet with or without microclimate humidity. The skin or microclimate temperature were mainly measured using digital sensors or thermocouples, but one study used non-invasive ThermalCam.

In addition to physiological parameters, some study used numerical method to evaluation helmet thermal performance, including aerodynamic efficiency [7], primarily forced convective heat loss [1, 8–10, 21], computational fluid dynamics (CFD) model [12], thermal and evaporative resistance [17]. These studies used manikin headform as the research subject to calculate thermal properties of helmet.

Nine out of 16 studies involving human users asked for subjective perception of thermal discomfort or thermal perception (hot or cold) through a questionnaire survey.

The most frequently adopted response scale is rating from "no discomfort" to "strongly discomfort" [6, 14, 18].

There is a conceptual distinction between comfort and discomfort, where "comfort is a pleasant state or relaxed feeling of a human being in reaction to its environment" and "discomfort is seen as an unpleasant state of the human body in reaction to its physical environment" [22], although many researchers always used these two terms altogether. The review shows that current evidence on thermal comfort of head-worn devices have seen comfort as an absent of discomfort. In other words, all the reviewed studies focus on the objective or subjective parameters which would lead to discomfort sensation, such as increased temperature and humidity.

5 Factors that Impact on Thermal Comfort or Performance

The present review identified a number of studies in which the effects of independent factors on the thermal properties and/or comfort were investigated, including color of helmet, helmet tile angle [7, 8], wind speed [7–9], hair [8], helmet materials [12, 17], heat source [4], ventilation [6, 9], etc.

It is found that white helmet could reduce hotness compared to red and green color helmet [6]. Because radiation heat is the major source of heat for helmet [4], white surface is more reflective and have better insulation against radiation heat. Moreover, helmet visor can optimize thermal comfort by reducing radiation heat [10]. Ventilation properties could help to dissipate heat and reduce the temperature for both helmet and face masks [6, 7, 11, 13]. In particular, the wind channel, i.e., air channel under helmet or face masks, played an import role for intensify convective heat loss and improve thermal perception and comfort [4, 13].

Studies also investigated effects of head-worn devices on whole body physiological parameters [1, 6, 13, 15, 16, 18, 19]. These studies demonstrated difference among headgear devices: no helmet-mediated effect on heart rate and core temperature [1]; however, wearing face masks would significantly influence heart rate, ear canal temperature and chest microclimate temperature [13, 15]. Whole body thermal sensation was significantly influenced by the microclimate temperature [6, 9] and humidity [13]. Increased temperature together with humidity would lead to greatest discomfort [19].

Although a number of factors affecting thermal effects were examined, interpretation of the results need to be careful. Current thermal comfort evaluation research was conducted by using headgears which differed in brand, design characteristics and materials. Because these headgears are not comparable and controlled, the differences between their thermal performance or comfort preference could not be well explained. Without controlling confounding factors, the results would be contaminated.

6 Conclusion

The present study provides a review on the existing studies on thermal comfort of head-wearing devices. Local thermal stimulus in the head region would impact the whole-body thermal sensation, thus improving headgear thermal properties could improve user experience and increase the willingness to wear. We provide a concise overview of research design and method, thermal comfort parameters and measures, and thermal effects of different types of headgear. Helmets has been intensively studies, while other headgear products such as facemasks and hearing protector were of less interest of researchers. More and more recent studies used the manikin headform to quantify heat transfer between head and helmet, but results from these objective methods should be cross-validated with subjective perception from human participation. Skin or micro-climate temperature is considered as the major parameter influencing thermal comfort. Besides thermocouple, more advance technology has been used in measure temperature, such as temperature distribution in different regions of head could be shown by using micro sensors, or non-contacting infrared thermography. Radiation is the major source of heat, while convection is effective in reduce heat. Ventilation in the micro-climate is the most effective way for heat dissipation and improve thermal perception. Based on the review, it is suggested that when evaluating thermal comfort of hear-worn devices, objective and subjective methods should be triangulated. More controlled experiment is needed to establish stronger evidence on factors that would alter thermal performance.

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