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A review on ergonomics of headgear: Thermal effects

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A R T I C L E I N F O

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A B S T R A C T

The thermal effects related to wearing headgear are complex and different studies have investigated single parts of this topic. This review aims at summarizing the different findings to give a complete overview on this topic as well as to suggest new perspectives. Headgear increases head insulation and therefore is mainly problematic under warm conditions, which is the focus of this review. Helmets do not affect physiological parameters other than the local skin temperature and sweat rate. However, the head is among the most sensitive body parts related to thermal comfort, thereby directly affecting the willingness to wear headgear. Several methods have been used to study thermal aspects of headgear, which could be categorized as (i) numerical, (ii) biophysical, (iii) combined numerical and biophysical, and (iv) user trials. The application of these methods established that heat transfer mainly takes place through radiation and convection. Headgear parameters relevant to these heat transfer pathways, are reviewed and suggestions are provided for improving existing headgear concepts and developing new concepts, ultimately leading to more accepted headgear.

Relevance to industry: This review provides a sound basis for improving existing headgear concepts. Firstly, a concise overview of headgear research related to thermal effects is given, leading to empirically based improvement suggestions and identification of research fields with a high potential. Finally, relevant research methods are described facilitating evaluation in R&D processes.

1. Introduction

Headgear is widely used in both occupation and leisure; it is used as a fashionable accessory or as an optional/mandatory means of protection. Substantial research attention went to optimizing its protective abilities (Aare et al., 2004; Cui et al., 2009; Deck and Willinger, 2006; Mills and Gilchrist, 2008). However, there is evidence that thermal comfort of headgear is suboptimal in neutral and warm environments. In fact, thermal discomfort is considered as a reason not to wear protective headgear (Li et al., 2008; Patel and Mohan, 1993; Skalkidou et al., 1999). For instance, Servadei et al. (2003) reported motorcycle helmet usage rates in the Northern and Southern Italy of 93% and 60%, respectively. This could at least partly be due to higher levels of warmth perception and/or thermal discomfort in warmer climates (Orsi et al., 2012; Papadakaki et al., 2013). Improving thermal comfort of headgear is likely to improve the willingness to wear (protective) headgear, and motivated an increasing number of studies, of which most were published in the last decade (Fig. 1). The available body of literature allows for a valuable first review of this literature. The recent rise of these publications indicates the need for a review for an increasing number of scientists active in this field. Moreover,

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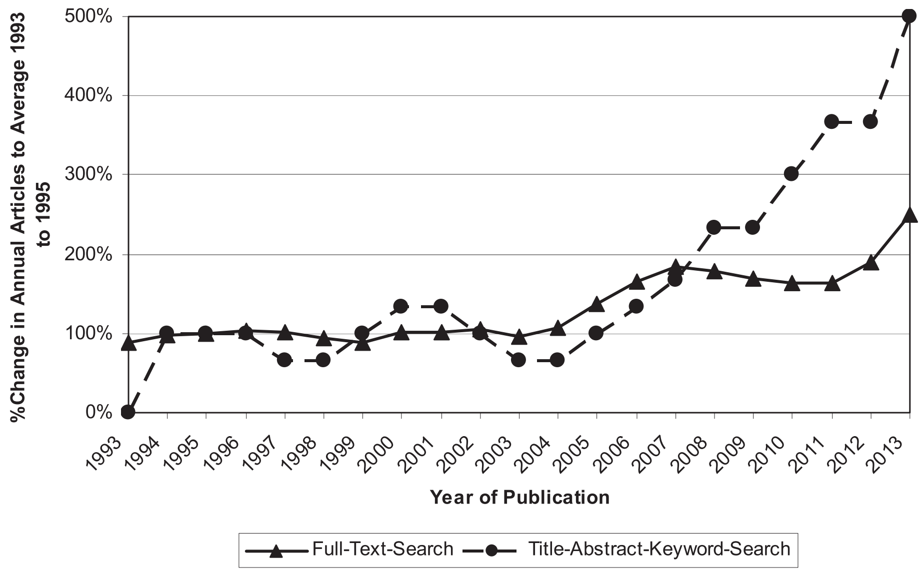

Fig. 1. Percentage change in annual publications concerned with headgear thermal ergonomics during the past two decades compared to the values averaged over 1993–1995. Article searches were performed in SciVerse and ScienceDirect® on 15.05.2013 for: pub-date > 1992 AND (headgear OR helmet) AND (ergonomics OR thermal OR physiology OR "mass transfer" OR "heat transfer") to occur in the full text or in the title-abstract-keywords, respectively. Series were smoothed by 3-years backward moving averages.

warm environments are of special interest for comfort impairment, given that headgear increases the thermal insulation and will thus provide a benefit in cold environments.

The aim of this manuscript is to provide an overview and synthesizes of the available evidence pertaining to the thermal aspects of headgear and to suggest improvements for existing and novel headgear concepts. Publications are reviewed extends beyond headgear used in an industrial setting it rather reviews relevant literature from all types of headgear, distilling patterns applicable to all types of headgear, including those used in the industry. While headgear generally refers to everything one can wear on the head, most studies focused on headgear designed to have specific impact protective properties. Such headgear is often referred to as helmet, a definition we also used in this review. First, the known effects of wearing headgear on humans are described in detail, with focus on thermal physiology and cognition (Section 2). Then, the biophysical heat and mass transfer of a headgear-head system is presented (Section 3). Section 4 reviews relevant methods utilized in studies of headgear properties related to heat and mass transfer including manikins and thermal physiological user trials. The last section (6) gives selected empirical data on results that could lead to improvement of the current headgear design.

2. User and the environment

This section introduces the basics of the human interaction with the thermal environment, which is determined by the environmental physical characteristics (i.e., air and radiant temperatures, humidity and wind) and by the individual factors (e.g., activity level and clothing worn). First the heat balance is explained, followed by the consideration of the local heat balance and related physiological responses at the head. Finally, user-related thermal effects of headgear on comfort, performance and health are discussed.

2.1. Body heat balance

The maintenance of a core body temperature at around 37 °C dictates the existence of a heat balance between the body and its environment. This heat balance represents a dynamic relationship between the heat generation within the body and the heat transfer between the body and the environment. The basic heat balance equation is (Blatteis et al., 2001):

$$S = M - W - (E_{res} + C_{res} + E_{sk} + C_{sk} + K + R) \qquad (1)$$

where M is the metabolic rate and W work rate. In most cases $M - W$ results in the rate of heat production. E, C, K, and R are heat transfer through evaporation, convection, conduction, and radiation. E and C occur through respiration (res) as well as at the skin (sk). The quantity of these heat transfer pathways depend on the environmental conditions and on thermal properties of materials covering the body (e.g., clothing and headgear) as well as hair on the head which provide substantial thermal insulation (Section 3.3). The sum of all these quantities provides the rate of heat storage (S). The units of these parameters are typically given as kJ h^{-1}, W, or expressed in relation to unit body surface area as W m^{-2}. A positive S leads to an increase in body temperature.

When exercising in the heat under circumstances of forced convection, heat loss from the head was estimated at 200–250 W (Rasch et al., 1991). Given a gross efficiency of cycling of the order of 20% (Ettema and Loras, 2009; Hettinga et al., 2007), which is lower than Rasch et al. (1991) used in their manuscript, this results in heat loss from the head of one-quarter to one-third of the total metabolic body heat. This is substantially higher than the head's proportion (7–10%) of the total body surface area. Another study (Nunneley et al., 1971) reported that cooling the head by a cap with water perfused tubes could remove 30% of metabolic heat produced at rest and 19% when exercising at 50% of maximal oxygen uptake, indicating the importance of the head as a heat sink. Thus, the head has a considerable heat loss capacity, which will be described in more detail in the sections below.

2.2. Heat transfer at the head

2.2.1. Cooling

Unique to the head is the lack of vasoconstriction responses in the skin of the head (Cheung, 2007; Froese and Burton, 1957). Since the head is often not fully covered with clothing or headgear, it keeps a high heat loss capacity, especially when exposed to cold. Under forced convective heat loss this may lead to a substantial temperature decrease of the head compared to the body core. When cycling outdoors at 6 m s^{-1} with 14 °C ambient temperature, tympanic temperature is on average 1.3 °C lower than oesophageal temperature, whereas in the laboratory at corresponding ambient temperatures, but at 0.1 m s^{-1} wind speed, no difference is observed (Nielsen, 1988). Similarly, in a clinical setting cooling the head surface with 14.5 °C air at a flow rate of 42.5 l s^{-1} reduced brain temperature by 0.5 °C as measured by magnetic resonance imaging compared to a net reduction of oesophageal temperature of 0.16 °C (Harris et al., 2008). As expected, these responses are reduced with headgear (Rasch and Cabanac, 1993) due to its thermal insulation. A few studies applied cooling to the head and showed a significant reduction in body core temperature at rest at 28 °C ambient temperature (Pretorius et al., 2010) or an attenuation of body core temperature during exercise at an ambient temperature of 29 °C (Ansley et al., 2008).

During both still air and windy conditions in the cold, the local head skin cooling rate is much higher at the nose compared to forehead and cheek (Gavhed et al., 2000). This is presumably due to its large surface to mass ratio resembling that of the fingers, which show similarly increased cooling rates (Shitzer and Tikuisis, 2012). Also the earlobes are at an increased risk for freezing (Lehmuskallio et al., 1995), which starts becoming a risk at ambient temperatures below −10 °C and is substantial at about −25 °C, especially in windy environments, i.e., under so-called wind-chill conditions (Danielsson, 1996; Shitzer and Tikuisis, 2012). As skin temperatures, especially at the nose, tend to increase with higher core temperature due to cold induced vasodilation (Brajkovic and Ducharme, 2006; Gavhed et al., 2000; Shitzer and Tikuisis, 2012), a high activity level might be beneficial in this respect, as would headgear covering the ears (Lehmuskallio et al., 1995). Thus, headgear may provide a thermal benefit in cold conditions.

2.2.2. Warm environments

Several studies have monitored the effects of headgear on multiple physiological parameters, for bicycle helmets (De Bruyne et al., 2008; Gisolfi et al., 1988; John and Dawson, 1989; Lee et al., 2013; Sheffield-Moore et al., 1997), equestrian helmets (Taylor et al., 2008), cricket helmets (Neave et al., 2004; Pang et al., 2013), football helmets (Coleman and Mortagy, 1973), and industrial protective headgear (Davis et al., 2001; Holland et al., 2002). These studies demonstrated no helmet-mediated effect on core body temperature or heart rate, while local effects pertain to increased local skin temperature on head areas covered by headgear, as one could expect from the increased local thermal insulation. The reported minimum microclimate temperatures underneath headgear range from 26 to 36 °C, with maximum temperatures ranging from 30.5 to 36.5 °C. The variation within these lower and upper limits seems mainly due to differences in the environmental conditions and the airflow over the skin under the headgear, possibly in combination with sweating.

In warm environments evaporation of sweat is the main heat loss pathway. Two main methods have been used to quantify sweat rates, by means of ventilated capsules (Cotter et al., 1995; De Bruyne et al., 2010; Machado-Moreira and Taylor, 2012; Machado-Moreira et al., 2008), and absorbent pad techniques (Bain et al., 2011; Cramer et al., 2012; Havenith et al., 2008; Smith and Havenith, 2011, 2012). The two methods have recently been shown to provide similar results (Morris et al., 2013). Local sweat rates at the head correlated significantly with whole body sweat rate (Bain et al., 2011) and varied spatially with most studies reporting higher sweat rates at the forehead compared to the temple, vertex or rear regions (Cabanac and Brinnel, 1988; Machado-Moreira et al., 2008; Smith and Havenith, 2011), whereas lower sweat rates at the forehead compared to the temple were observed in a study on bicycle helmets (De Bruyne et al., 2010).

A relative association of local head sweat rate to whole body sweat rate was reported by Smith and Havenith (2011) with values ranging from 64% to 126% depending on head region and exercise intensity. Using a ventilated helmet-like measuring device, O'Brien and Cadarette (2013) reported local head sweating rates amounting to approximately 80% of whole body sweat rate in a hot-dry environment, whereas under warm-humid conditions head sweating increased by 25% with unchanged whole body sweat rate. Relating local head sweat rate to the change in body core temperature, so-called sudomotor sensitivities ranging from 1.03 mg cm^{-2} min^{-1} $°C^{-1}$ at the top to 2.10 mg cm^{-2} min^{-1} $°C^{-1}$ at the temple region were derived (Machado-Moreira et al., 2008). Supplemental data were collected and calculated utilizing information form several studies using varying methodologies and experimental conditions (Smith and Havenith, 2011; Taylor and Machado-Moreira, 2013) and are summarized in Fig. 2. It shows considerable variation in head sudomotor sensitivity, although a consistent pattern of higher sweating sensitivity at the forehead compared to the lateral and medial head regions emerged. Integrating recent research on the intra-regional distribution of sweat gland density and sweating activity (Taylor and Machado-Moreira, 2013), first-level predictive equations for the head sweat rate under resting or exercising conditions could be developed. Those relations would allow adopting models predicting whole-body responses in core temperature or sweating to the prediction of local effects and thus complement models predicting local sweat rates under steady-state (Nadel et al., 1971) or transient specific conditions (De Bruyne et al., 2010).

2.3. User-related effects

2.3.1. Thermal sensation and thermal comfort

Unfavorable thermal sensation or thermal discomfort are frequently returning arguments for not wearing headgear (Abeysekera and Shahnavaz, 1988; Finnoff et al., 2001; Li et al., 2008; Orsi et al., 2012; Papadakaki et al., 2013; Patel and Mohan, 1993; Skalkidou et al., 1999), although adaptation may occur once the initial resistance has been overcome (Abeysekera and Shahnavaz, 1990). Thermal comfort largely depends on skin temperature and thermal sensation in moderate and cold conditions (Fanger, 1970; Flouris, 2011), but is more closely related to sweating and skin wettedness in the heat for both whole body and local effects (Fukazawa and Havenith, 2009; Gagge et al., 1969, 1967).

Locally perceived discomfort at a part of the body is sufficient to cause whole body discomfort related to thermal sensation (Zhang et al., 2010). In warm environments, face cooling has been demonstrated to enhance thermal comfort (Nakamura et al., 2008) and the local thermal sensation at the head dominates whole body thermal sensation (Arens et al., 2006). Moreover, Mehrabyan et al. (2011) observed local differences in thermal sensitivities on the head's surface after applying thermal stimuli with a thermode. Site-wise variations have been detected for warming and cooling thresholds. Whereby the forehead was typically more sensitive than sites at the scalp. In contrast, local skin wettedness may cause local discomfort, but whole body comfort can be maintained as long as the overall skin wettedness remains below a comfort threshold (Fukazawa and Havenith, 2009).

The impaired heat loss through headgear in warm environments or when exercising induces sweat accumulation at the skin-headgear interface associated with a feeling of moisture, which is mediated by thermal and haptic signals and causes discomfort

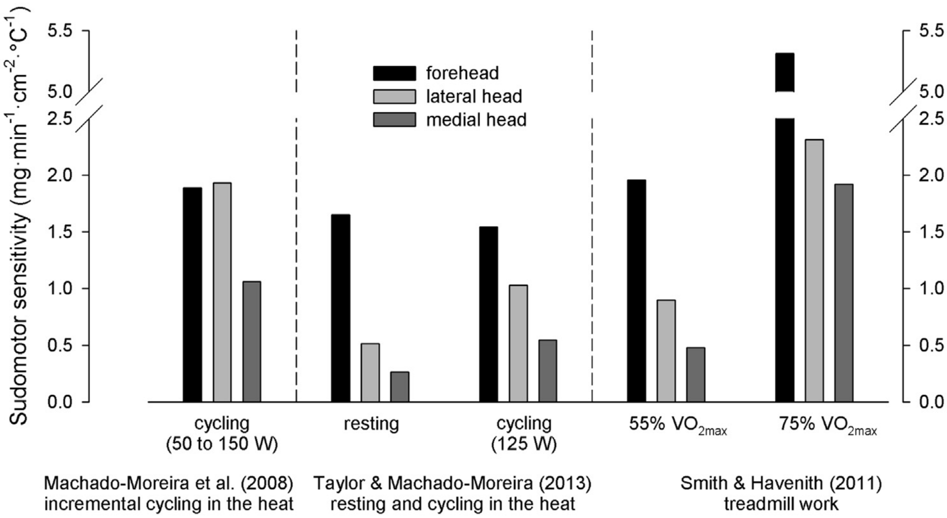

Fig. 2. Sudomotor sensitivities for different head regions related to type and intensity of physical workload derived from several studies.

(Berglund, 1998; Niedermann and Rossi, 2012). The relation of moisture sensation to thermal sensation provides the option to increase wearing comfort by using special textiles, e.g., phase change materials (Bergmann Tiest et al., 2012). However, our analysis suggests that the most often applied approach to optimize thermal comfort is to increase ventilation, which enhances both convective cooling and sweat evaporation and has been shown to improve the comfort of clothing, seats (Bartels, 2003; Bröde and Griefahn, 2005; Lund Madsen, 1994) and helmets (Abeysekera and Shahnavaz, 1988; Alam et al., 2010; Bogerd et al., 2011; De Bruyne et al., 2012; Holland et al., 2002; Liu and Holmér, 1995; Pang et al., 2013; Van Brecht et al., 2008), as discussed in Section 5.

2.3.2. Health and exercise performance

Working or exercising in the heat may raise body core temperature to levels possibly leading to fatal exertional heat stroke (Epstein and Roberts, 2011). This review shows no relationship between helmet-wearing and core temperature (Section 2.2.2), therefore a causal influence of non-encapsulating headgear on the risk for heat stroke seems unlikely. It is expected that American football headgear is no exception, even though it remains controversially discussed (Armstrong et al., 2010; Eichner, 2010). On the other hand, a helmet may protect the head from (ultraviolet) solar radiation especially at the vertex and forehead. Ultraviolet protection will be marginal at best at the cheeks and nose, as this would require larger brims (Diffey and Cheeseman, 1992).

It is well accepted that heat storage during activity leading to hyperthermia reduces physical performance (Nybo and Nielsen, 2001; Nybo, 2008). This heat-induced performance decline during exercise is probably due to impaired voluntary neuromuscular activation (Thomas et al., 2006). However, heat-induced altered brain neurochemistry (Meeusen et al., 2006) and reduced mental arousal (Nielsen et al., 2001) may be also involved. The effect of wearing a helmet on exercise performance has been reported in one study (Lee et al., 2013). This study compared 12 km self-paced cycling time-trial time between a well-ventilated and a poorly ventilated (aerodynamic) bicycle helmet. Though head skin temperature was higher with the non-ventilated helmet, that study did not find any significant differences in heart rate, core temperature, power output, and cycling performance. This result is in line with the lack of effects of helmet-wearing on relevant physiological parameters (Section 2.2.2). However, since helmet-wearing limits the capacity of the head to dissipate heat, it can increase the perceived thermal discomfort (Section 2.3.1) which can affect the perception of effort, especially when exercising in a hot environment (Armada-da-Silva et al., 2004; Flouris, 2011). The present analysis, therefore, suggests that helmets should be designed to impact the head's heat loss capacity as little as possible.

2.3.3. Cognitive performance

A potential negative effect of a helmet on cognitive performance is undesirable, especially as helmets are likely worn in situations with a substantial risk for an accident. Helmets are known to cause discomfort (Section 2.3.1). Thermal discomfort, caused by clothing or a warm environment, has been linked to degraded cognitive performance (Bell et al., 2005, 2003; Flouris et al., 2007; Gaoua et al., 2012). This motivated several groups to investigate the relationship between helmet-wearing and cognitive performance.

Our analyses revealed that four studies have evaluated the effect of passive headgear on cognitive performance, in the absence of physical exercise with adult participants. Three of these studies used the same helmet which covered the scalp and ears, but left the face uncovered (Hancock and Dirkin, 1982; Hancock, 1983; Holt and Brainard, 1976). One of these studies found increased reaction times on a dual task while wearing a helmet (Hancock and Dirkin, 1982). The other three studies did not find an effect. More recently a study revisited this topic by submitting participants to extreme but realistic conditions as to provide a maximum cognitive load so that fluctuations in cognitive performance could not be buffered by available resources (Bogerd et al., 2013). This study reported one out of nine cognitive parameters to show a significant effect of helmet-wearing, disappearing in a statistical post-hoc comparison. One other study investigated the effect of a cricket helmet on cognitive faculty combined with exercise among adolescents (Neave et al., 2004). They found a negative effect on some cognitive parameters of wearing the helmet during cricket practice, but only after grouping the measured parameters into global parameters using factor analysis. In light of the studies analyzed in the current review, wearing a helmet does not seem to generate a significant detrimental effect on cognitive functioning.

3. Heat and mass transfer and headgear

A head equipped with headgear exchanges heat with the surrounding environment through different mechanisms whose relative importance depends on several factors, e.g., (i) the environmental conditions prevailing inside the helmet, (ii) its properties and geometrical characteristics, (iii) the availability of convective currents resulting from the motion of the user, and (iv) the degree of exposure to radiant heat gain. These factors may differ considerably depending on the type of activity developed by the user (e.g., professional activity, sports activity, leisure). Studies on heat and mass transfer of headgear have focused on forced convection or ventilation, radiant heat gain and the effect of hair. These three topics will be discussed in this section.

3.1. Ventilation

In activities involving motion, forced convection is an important mode for heat loss: its magnitude depends on the temperature difference between the skin and the air flowing over it. For air temperatures approaching that of the skin, forced convective heat loss becomes less relevant, thus, the heat loss occurs mainly through the evaporation of sweat. The driving force for evaporation is the difference between the water vapor pressure at the skin and at the surrounding environment (which influences the gradient of water vapor pressure at the skin). As sweat evaporates, the humidity in the air increases, therefore, a continuous refreshment of the air is important to sustain evaporative heat loss.

The apparent porosity of headgear has increased over the years, with the inclusion of an escalating number of air vents in their structure. This is particularly evident in bicycle helmets, despite a potentially detrimental effect on impact protection. Several researchers have studied the ventilation across e.g. bicycle and motorcycle helmets designs (Bogerd and Brühwiler, 2009, 2008; Brühwiler, 2009; Brühwiler et al., 2006; De Bruyne et al., 2012). These studies indicated that parameters such as vents positions/shape/number, existence and characteristics of in-helmet channels, visor characteristics and head tilt, play relevant roles in the local cooling of the different head regions. The cooling promoted by helmet vents varies considerably between different head regions, with those closer to the front of the head showing higher ventilation efficiency (De Bruyne et al., 2012). Furthermore, some of the ventilation structures may have a detrimental effect in terms of cooling, by actually functioning as outlets for air currents flowing from the front of the head (Brühwiler et al., 2006; De Bruyne et al., 2012). The head tilt and the existence and characteristics of helmet visors are reported to influence the ventilation inside the helmet and, thus, affect the cooling rates (Bogerd and Brühwiler, 2008; Brühwiler, 2009, 2008; Brühwiler et al., 2004). Additional details on helmet design options are given in Section 5.2. From the above mentioned publications allow the conclusion that the ventilation performance of helmets is influenced by several different parameters, which should be taken into consideration when designing helmets for performance (e.g. using numerical approaches like CFD; Section 4.1.1).

3.2. Radiation shielding

When designing helmets for increased heat loss, there may be a conflict between increasing convective heat loss and improving radiant shielding, since increasing the head uncovered area, as a way to improve convective heat loss, often implies higher heat gains through radiation (Brühwiler, 2008). The overall trade-off between these mechanisms depends on parameters such as (i) vent design and position, which determine head exposure, (ii) helmet features such as visor dimension and optical properties, which influence convection through the helmet and the degree of radiation rejection, respectively, (iii) the existence and characteristics of hair (Section 3.3), and (iv) the actual environmental conditions surrounding the participant (which determine the extent of convection and radiant load). Section 5.1 provides further information on radiative heat transfer and extends the available literature to product implications.

3.3. Hair

Most measurements of local heat transfer performed with thermal manikin headforms and human participants have been carried out without hair (i.e., on nude or shaved heads). Such constraints may be prescribed by the applied methods, e.g. for measuring local sweat rates. In addition, the absence of hair reduces the "noise" caused by hair and therefore increases the reproducibility of the data. However, it raises the question as to what extent the results can be extrapolated to a typical human hairy scalp. Hair adds an additional insulation layer and the effect of such an additional layer on heat transfer is not well understood and difficult to investigate.

Most studies on this topic involved a thermal head manikin. Brühwiler et al. (2004) investigated the convective cooling power of various bicycling helmets using a thermal head manikin without hair. The measurements of the nude manikin agreed with subjective ratings by human participants with hair, indicating that hair might have a quantitative rather than a qualitative effect on helmet ventilation (Brühwiler et al., 2006).

Several studies have investigated the effect of a wig, employing a thermal manikin headform in combination with headgear (Abeysekera et al., 1991; Bogerd and Brühwiler, 2008; Bogerd et al., 2008; Brühwiler et al., 2006; Ellis, 2003). In all these studies a wig reduced the convective heat loss by 75%–50% of the value measured for the entire nude headform. A wig, however, is constructed from a base to which the hairs are attached. 40%–50% of the reduction in convective heat transfer due to a wig is ascribed to its base (Bogerd and Brühwiler, 2008). Headform measurements of convective heat exchange may be corrected for the absence of hair by taking roughly 70% of the reported values (Bogerd and Brühwiler, 2008). However, these estimations are based on manikin measurements on a single wig and therefore might not be easily extrapolated to results with humans. Furthermore, the effect of hair on heat transfer will likely vary as a function of hair-style (e.g., length, volume, and density). Headform measurements with a wig have not been carried out in combination with radiant heat load and/or simulated sweating. The presence of hair is reported to reduce heat gain (Bogerd et al., 2008), however, predicting the effect of sweating on the heat transfer through hair remains challenging since its thermal properties will likely change with different levels of wetness. Based on the above, the current analysis suggests that further research should focus on the relationship between such manikin and participant trails as a function of hair.

4. Methods for helmet evaluation

Several different methods have been developed and used which allow studying of the headgear. These methods can be divided into (i) numerical, (ii) biophysical, (iii) combined numerical and biophysical, and (iv) user trials. However, product optimization often includes a combination of these methods, and the results are seldom generalizable.

4.1. Numerical methods

4.1.1. Computational fluid dynamics

Besides experimental techniques, the performance of helmets can also be studied using numerical tools, such as numerical simulation by computational fluid dynamics (CFD). Several publications report the use of such techniques to analyze different features of helmet performance, from aerodynamic performance of the helmet or the rider (Blocken et al., 2013; Defraeye et al., 2011; Sims and Jenkins, 2011) to its ventilation or thermal performance (Desta et al., 2008; Pinnoji et al., 2008).

Some product developments used CFD for reducing the influence of head angle on the aerodynamic performance of a bicycle helmet through design modifications of its trailing edge (Sims and Jenkins, 2011). A specific truncation length was found which resulted in an improved aerodynamic performance when the helmet is used looking downward, while ensuring similar performance when the helmet is used looking forward. Others studies identified in the current review investigated the drag and convective heat transfer of individual body regions for different cyclist positions (Defraeye et al., 2011). They found a strong dependency of the drag area on the flow Reynolds number, and convective heat transfer coefficients that did not vary much between different body segments. CFD has also been used for simulating forced convective heat loss (Desta et al., 2008; Pinnoji et al., 2008). Based on the above-mentioned studies, it is clear that the use of CFD-based approaches to investigate helmet performance is promising. The decreasing costs of computational power and CFD packages provide researchers and helmet developers with the means to study, with increasing detail, the effect of helmet features/design on its performance. This will promote innovation and accelerate developments (of new concepts, ideas, approaches).

4.1.2. Numerical models of human thermal physiology

Prediction models of thermal physiological responses of the human body are highly repeatable but need validation and often poorly account for individual variances. This approach therefore mainly provides a general consideration. Several mathematical models of the human thermal physiology have been developed, with different levels of complexity and accuracy. The simulation of the body geometry has evolved from a single homogenous cylinder into multi-layered cylinders of various sizes, together with thermal physiological properties for individual body parts with applied blood circulation. Both the single-homogenous-cylinder approach as well as the advanced-multilayer-structure approach was refined independently as so-called one or two-node models (Fanger, 1970; Gagge, 1971; Lotens, 1993; Osczevski, 1995) and multi-node models (Fiala et al., 1999; Huizenga et al., 2001; Shin-ichi et al., 2002; Stolwijk et al., 1973; Wissler, 1985). Multi-node models typically provided more accurate predictions than the two-node models particularly for exercise conditions (Haslam and Parsons, 1994). The fundamentals for the multi-segment models were given by Stolwijk (1971).

One of the most advanced models is the multi-node thermal physiological model of Fiala (Fiala et al., 2010, 2001, 1999; Lomas et al., 2003). It is based on the approach chosen by Stolwijk (1971), according to which the thermoregulatory system is divided into two interacting sub-systems: (i) the controlled passive system and (ii) the controlling active system. The operation of these systems is based on the deviation from the thermo neutral conditions detected by the thermal receptors. According to this deviation, the effector systems are commanded to correct these deviations and with the simulation of the dynamic heat exchange between the body core and the environment through the different body (and clothing) layers, a new thermal state is achieved. The passive system of the Fiala model (Fiala et al., 1999) is consisting of 20 spherical and cylindrical elements. In this model, the head is represented by three elements: head (two sectors: anterior and posterior), face (anterior and superior) and neck (anterior, posterior and superior). As it is done for all the body elements, convection coefficients, surface emissivity and view factors for standing/sedentary posture are included in the model. The active system algorithms to predict the thermoregulatory reactions were developed by means of statistical regression (Fiala et al., 2001) based on data from a variety of physiological experiments covering steady-state and transient cold stress, cold, moderate, warm and hot stress conditions, and activity levels to up to heavy exercise.

Finally, also dynamic data-based modeling or system identification approaches have proven to be useful for modeling thermoregulatory responses. In contrast to the mechanistic models mentioned above, these purely statistical dynamic data-based models are especially suited to process real-time acquired data of a considered system and do not need a priori knowledge (Hulting et al., 2006). This approach has been applied successfully for modeling thermoregulatory responses in animal applications (Aerts and Berckmans, 2004; Aerts et al., 2003) as well as in human applications (De Bruyne et al., 2010; Rollins et al., 2006). The resulting model structures require typically less processing power compared to mechanistic models, thus they are well suited as a basis for actively controlling thermal processes under helmets as suggested by De Bruyne et al. (2010). They used this approach for modeling the transient sweat response of the human head under a safety helmet during cycling. Active control systems for improved comfort require the availability of real-time thermal physiological data which might be difficult to obtain experimentally. Models predicting these thermal physiological responses, therefore play a crucial role in the development of such active control systems.

4.2. Biophysical methods

4.2.1. Thermal manikins headforms

The application of anatomically formed thermal manikin headforms provides information about combined heat and mass transfer with and without the use of headgear. Several such headforms have been developed (Abeysekera et al., 1991; Brühwiler, 2003; Coment et al., 2000; Ellis, 2003; Fonseca, 1974; Hsu et al., 2000; Liu and Holmér, 1995; Osczevski, 1996; Reid and Wang, 2000; Reischl, 1986) of which some are commercially available, e.g., the headforms offered by Measurement Technology Northwest, (USA), and UCS d.o.o., (Slovenia). Studies were published using different types of thermal manikin headforms focusing on impaired heat and mass transfer for industrial helmets (Abeysekera et al., 1991; Hsu et al., 2000; Liu, 1997; Reischl, 1986) as well as sports headgear (Bogerd et al., 2008; Brühwiler et al., 2006, 2004; De Bruyne et al., 2012; Pang et al., 2013; Reid and Wang, 2000). The main differences among the headforms employed are the number of segments, providing local data on heat transfer, ability and technique of sweating, and the time to complete a measurement.

Thermal manikin headforms are equipped with heating elements and temperature sensors. The surface temperature of the headform is typically regulated at a fixed temperature, and the total power needed to maintain this temperature over a steady-state period is recorded. This heating power equals the total net heat transfer, which allows quantifying of combined heat loss by convection, conduction and radiation. In order to quantify the individual heat transfer pathways, measurements have to be carried out with conditions allowing only a particular heat transfer pathway while preventing the other pathways. The particular heat transfer pathway is then quantified by calculating the heat transfer differences between the different conditions. For instance, the effect of solar radiation was examined in the presence and absence of a radiation source (Bogerd et al., 2008; Brühwiler, 2008). Fig. 3 shows the effect of different headgear on net heat transfer according to forced convection only (NoRad condition) and forced convection in combination with radiation (Rad condition). The

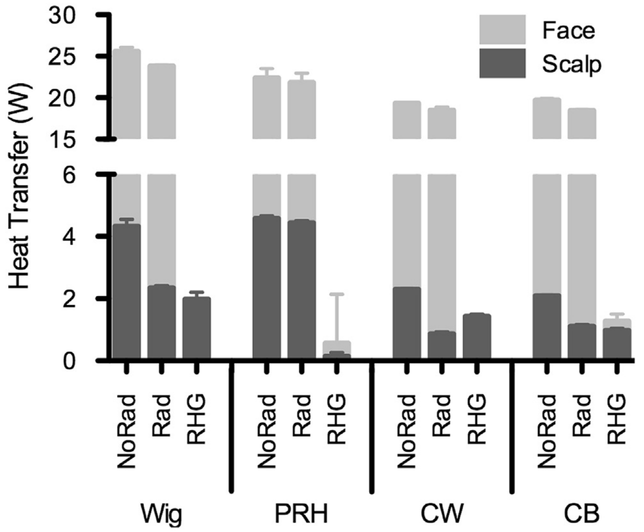

Fig. 3. Net heat transfer in two conditions (ambient temperature = 22 °C, relative humidity = 50%, wind = 4 m s^{-1}, with no radiation (NoRad) or radiation applied directly from above (Rad) using a 150 W lamp (T228, Osram, München, Germany)) for headgear such as a wig, a prototype rowing headgear (PRH), a white cotton cap (CW) and a black cotton cap (CB). Radiant heat gain was calculated as the difference between net heat transfer for NoRad and Rad (adapted from Bogerd et al., 2008).

difference in net heat transfer of the aforementioned conditions equals radiant heat gain (RHG).

Evaporative heat loss can also be simulated with many thermal manikin headforms by releasing moisture through outlets at a constant and controllable rate. However, the amount of outlets is limited, e.g., 25 in the headform described by Brühwiler (2003) and such density does not approximate the distribution of sweating glands by far. Furthermore, the low number of outlets may lead to an uneven moistening and, thus, evaporative heat loss which may induce heterogeneity of surface temperature and increased variability of heat loss. Thus, differences between various headgears are more difficult to detect. For this reason a tightly-fitting, highly wicking textile is usually put over the headform facilitating a more realistic distribution of simulated sweat.

Several studies have validated thermal manikin headform measurements against human perception of comfort and temperature. The most detailed study reports the vent-induced heat transfer given by the difference of open and closed vents of a motorcycle helmet (Bogerd et al., 2011). The vent-induced effects were compared to perceptual effect of opening (and closing) the vents. The results indicate a high correlation between temperature perception and vent-induced heat transfer. Interestingly, no meaningful relationship was found for thermal comfort and vent-induced heat transfer, likely indicating that comfort depends on more factors than just the thermal conditions of the local skin. In fact, a perception threshold can be derived in the range of 1.5–3.1 W for reductions in heat loss and of the order of 5.1 W for increases in heat loss (Bogerd et al., 2011; Brühwiler et al., 2004).

Compared to human participant trials, thermal manikin headform experiments provide more objective data at a lower variability, generally consume less time from an experimenter, and ethical considerations are irrelevant. Thus, headforms allow an efficient investigation of heat and mass transfer of headgear in steady-state conditions. However, the limitations related to the use of headforms include: (i) Restriction to experimental conditions where the heat loss from the head is substantially larger than the heat gain as current headforms can only heat, not cool. Thus, if the air and/or radiant temperature is close to or even larger than the head surface temperature heat transfer will not reach a steady-state. In such cases, headform surface temperature increases above the set-point and heating power is consequently turned off. (ii) Most headform studies have used a bald head, few attempts have been made to understand the role of hair (e.g., as a wig) on manikin measurements (additional details are given in Section 3.3). (iii) Manikin measurements are carried out mainly in steady-state conditions and transient conditions are therefore largely neglected. To overcome this lack, a thermal manikin has to be coupled with a mathematical model for thermal physiological responses, (as presented in Section 4.1.2). Such models will in addition provide data for a better understanding of the physiological responses as well as effects on temperature and comfort perception.

4.2.2. Tracer gas method

For moving activities, e.g., cycling and inline skating, airflow over the head is one of the main parameters influencing the thermal response of a human head wearing a helmet (Section 3.1). The quantification of local airflow of helmets can help explaining variations in heat loss (De Bruyne et al., 2012). Research on heat loss of helmets has often been performed using thermal manikin headforms (Section 4.2.1). An alternative method is using a tracer gas method that allows describing airflow under helmets without the need for measuring heat transfer. A specific tracer gas method was developed to specifically quantify airflow between a bicycle helmet and skull (De Bruyne et al., 2012; Van Brecht et al., 2008). The method uses CO_2 as a tracer gas (99% CO_2 and 1% N_2) that is injected upstream of the headform wearing a helmet (input) and sampled at several fixed positions (output). Local gas concentration is measured by pumping the gas sample via a multiplexer towards a CO_2 gas analyzer. Based on these measured input–output time series pairs, the local mean refreshment frequency, which is the inverse of the local mean age of air, was quantified using a data-based mechanistic modeling approach. The age of air concept is widely used to quantify air refreshments in buildings (e.g., Karimipanah et al., 2007; Sandberg and Blomqvist, 1985). It can be concluded that such tracer gas methods allow quantifying the global as well as local ventilation efficiencies in a convenient way. Therefore, these methods provide a good option for evaluating the effect of helmet design on thermal comfort.

4.3. Combined numerical and biophysical methods

To link biophysical parameters obtained from thermal manikins, i.e., heat flux or temperature (Section 4.2.1), with corresponding thermal physiological responses of humans (Section 4.1.2), thermal manikins are coupled with numerical models simulating the thermal physiological responses (Psikuta et al., 2008).

Thermal manikin technology is increasing the variety, complexity and accuracy of these devices for assessing thermal physiological responses due to clothing and environments. Various attempts to improve the prediction of human response by setting different heat fluxes or temperatures, spatially or temporally, did not succeed (Sakoi et al., 2007; Tanabe et al., 1994). Due to their passivity, thermal manikins are not capable of providing physiological data unless they are controlled or coupled by a mathematical model of human thermoregulatory system. On the other hand, existing thermal physiological models (Section 4.1.2) are limited to simulate accurately specific complexities at human–environment interactions (i.e., air turbulences, local fluctuations in air temperature and humidity, heat and mass transfer through multi-layered clothing systems) (Psikuta, 2009).

For evaluation of vehicle environments a multi-segmental sweating manikin controlled by a CFD implementation of a thermoregulatory model was developed (Rugh et al., 2004). In other cases, such control modes have been based on the two-node multi-segmental Pierce model and compared with traditional control modes (Burke et al., 2009; Foda and Siren, 2012; Psikuta, 2009; Psikuta et al., 2008).

In these cases manikins act as a heat transfer sensor, providing an input variable for the thermal physiological model. Some important technical challenges in coupling manikins with physiological models concern accuracy in heat flux measurements (especially in cases in which some heat gains may occur), variation in the manikin posture and the dynamic behavior and time response of heated and sweating systems during transients (Psikuta, 2009; Rugh et al., 2004). For body part manikins (such as the thermal head manikin) another challenge arises, namely the challenge of coupling the physiological model partially with only one body element whereas the thermal response of the rest of the body parts should be predicted virtually.

4.4. User trials

The present review identified a number of studies in which helmet-wearing effects have been assessed directly on human participants. These studies have focused on physiology (Section 2.2.2), comfort and thermal sensation (Section 2.3.1), and cognitive effects (Section 2.3.3). The advantage of such studies is the results are more closely related to the end-users, as compared to the more objective methods described above (Section 4.2). However, such generalizability comes at the price of higher intra- and inter-individual variances of studies involving human participants as compared to objective methods.

Several methods have been employed in user trials. Of special interest are the method of measuring heat storage (S, Equation (1)), ranging from direct calorimetric studies in controlled chambers (Reardon et al., 2006), water perfused suits (Hambræus et al., 1994; Webb et al., 1980), and partitional calorimetry systems (Flouris and Cheung, 2009; Hardy and Stolwijk, 1966). The latter are unique in measuring S accurately while allowing for exposure to various conditions including extreme ambient temperatures, exercise, and water immersion (Flouris and Cheung, 2010; Hartley et al., 2012). Also, partitional calorimetry systems can accurately calculate S for individual body segments, an important advantage for helmet optimization.

5. Design considerations

Some types of headgear are developed to protect the head against mechanical impact. These helmets need to meet criteria defined in safety standards. As a consequence the interplay among optimization of thermal properties, impact protection, and standards should be taken into consideration. For instance, given the present impact standards for bicycle helmets, a helmet with more ventilation openings will have less material. In order to meet the prevailing standards the stiffness of the material needs to be increased, potentially reducing the impact protection under practical conditions.

5.1. Radiative heat transfer

Radiative heat gain has received little attention in published work related to clothing (Bröde et al., 2010) and wearable accessories. Due to its position, the head is the most exposed body-part to heating from solar radiation, which can be as high as 1 kW m^{-2}. Although the head's surface area is relatively small, the head is one of the most important body parts for thermal comfort (Section 2.3.1), thus motivating several studies on this topic (Bogerd et al., 2008; Brühwiler, 2008; Brühwiler et al., 2006; Buyan et al., 2006; Diffey and Cheeseman, 1992; Ishigaki et al., 2001).

Bicycle helmets shield about 50–75% of the radiant heat gain (Brühwiler, 2008; Brühwiler et al., 2006) and standard baseball caps about 80% (Bogerd et al., 2008). However, these studies indicated that the optical surface area of the head's surface visible through the helmet and from the direction of the radiant source (e.g., the sun) is positively related to the radiant heat gain (Brühwiler, 2008; Brühwiler et al., 2006), indicating that the larger the vents, the less favorable the helmet will be for shielding against radiant heat gain. Initially, this poses a conflict between optimization for shielding against radiant heat gain and increasing the convective dry and wet heat losses (airflow over the scalp). However, the two can be combined by using a laminar system that creates an optically closed surface relative to the radiant source while only posing a marginal reduction in convective heat loss (Bogerd et al., 2008). A prototype based on this concept shielded 95% of radiant heat gain while reducing convective heat loss by only 9% (Bogerd et al., 2008).

Additionally, a relationship was established with the brim or visor of headgear. These help reducing the radiant heat gain in the face. Such a brim should have a width of at least 7.5 cm (Diffey and Cheeseman, 1992) and should have a low emissivity (Brühwiler, 2008). The latter study found a relationship between visor color and heat transfer at the scalp for bicycle helmets. Here the underlying mechanism is that the visor heats up and warms the air that flow over it before it passes through the helmet. This mechanism also applied to the general helmet color. Finally, others report that a tinted visor reduces facial heating with 1–2 W (Buyan et al., 2006).

5.2. Convective heat transfer

5.2.1. Passive ventilation

Convective heat transfer is a function of inlets, outlets, and channels guiding the air between in- and outlet, and a few other features of headgear. The driving mechanism of convective heat transfer is airflow, which moves from high pressure to lower pressure areas. Several studies indicated that the surface area of the vent in bicycle helmets is positively related to convective heat loss (Brühwiler et al., 2006; De Bruyne et al., 2012; Ellis, 2003; Woods, 1983). The vents at the low-pressure areas (rear) are also relevant. Brühwiler et al. (2006) found that blocking rear vents of bicycle helmets reduced the convective heat loss by 8–30%. Additionally, they found that blocking vents between the front and rear increases convective heat loss. This indicates that air tends to leave the microclimate if a lower resistance path is provided. Vents between the inlet and outlet provide such early exits, thus resulting in suboptimal heat loss (De Bruyne et al., 2012). Besides in- and outlet channels, a well-defined connection between these two is needed (Brühwiler et al., 2006; Ellis, 2003; Pinnoji et al., 2008).

The Hagen–Poiseuille equation was found to give a reasonable model for describing airflow through ventilation system of headgear (De Bruyne et al., 2012). In fact, a coefficient of determination of 0.83 was obtained between the percentage of well-ventilated area of the head under a helmet and estimated flow rate. The Hagen–Poiseuille equation was written per inlet for the different helmets as:

$$V = \sum \frac{\pi R^4 \Delta p}{8 \mu l} \tag{2}$$

where:

V = flow rate (m^3 s^{-1})
R = radius of a vent (m)

Δp = pressure difference between the front and the back of a duct ($N\ m^{-2}$).
l = length of a channel (m)
μ = viscosity of air ($N\ s\ m^{-2}$)

Equation (2) is relevant for bicycle helmet design as it stresses the importance of large vents. Vents with a radius of 2 cm are for example 16 times more efficient compared to a vent with a radius of 1 cm. Additionally, the equation also includes channel length. Airflow rate through a helmet is improved when the distance between inlet and outlet is reduced. In cases of no airflow relative to the helmet only natural convection can take place. To facilitate this, a microclimate thickness of at least 1 cm is needed (Hsu et al., 2000; Spencer-Smith, 1977). In this case the mechanisms described above apply to the top and bottom openings (Abeysekera and Shahnavaz, 1988).

5.2.2. Active ventilation

Active ventilation is defined here as a system requiring energy and part of the headgear that causes an airflow through the headgear. Such a cooling system could actively respond to the cyclists' sweat rate. Sweat rate can be measured based, e.g., on relative humidity of the microclimate air. Furthermore, since sweating is the main driver to dissipate work-induced heat production (Section 2.2.2), it is important to understand its transient behavior. De Bruyne et al. (2010) described the transient behavior of sweat production to a change in work rate when monitoring three sites on the head (center of the frontal area, left temple and right temple). It was found that time delay and steady-state gain of sweat production after a change in work rate was not different between a warm and a thermal neutral condition. However, the time constant of sweat production after a change in work rate was about 5–10 min, and lower in a warm condition, compared to a thermal neutral condition. An active cooling solution in bicycle helmet should therefore respond faster in warm conditions to a change in work rate, but not necessarily harder if the change in work rate is similar. So far no prototypes have been reported in the literature, active ventilation could be the first step towards more intelligent and personalized headgear.

6. Conclusions

Headgear increases head insulation and therefore is mainly problematic under warm conditions. Since the head is among the most sensitive regions for whole body thermal comfort, headgear causes discomfort and reduces the willingness to wear headgear under warm conditions. The interaction between sweat and textile parts of headgear can contribute to discomfort. In addition, there is a relationship between ratings of perceived exertion and (dis) comfort. Headgear does not affect physiological parameters other than the local skin temperature and local sweat rates.

The main heat transfer pathways for headgear are convection, evaporation, and radiation. These mechanisms and the interaction with the user are studied using either numerical methods, biophysical models and user trials or combinations of these methods. The heat transfer is a function of the environment, helmet parameters, and the user characteristics (e.g., hair). Existing empirical data indicates that current helmet designs can be improved. In most cases the ventilation systems can be enhanced, and the early exit of air flowing through such systems should especially be taken into consideration. Finally, the helmet's thermal performance may be improved if the radiant heat gain is reduced to negligible amounts, by making the helmet shield the head from the solar radiation, while maintaining its structure as open as possible for airflow. In brief, the literature reviewed in the present manuscript can be summarized into the following conclusions:

- Heat loss from the head can be as high as 1/4 to 1/3 of the total body heat loss in a warm climate (Section 2.1), whereas the proportion of surface area of the head relative to the whole body is 7–10%. This is explained by the lack of vasoconstriction of the head's skin, and the exposed position of the head (Section 2.2.1).
- Wearing headgear does not affect physiological systemic parameters, e.g., body core temperature and hart rate, although it does affect local skin temperature (Section 2.2.2).
- The reviewed literature shows considerable variation in head sudomotor sensitivity, although a consistent pattern of higher sweating sensitivity at the forehead compared to the lateral and medial head regions emerged (Section 2.2.2).
- Unfavorable thermal sensation or thermal discomfort is frequently returning arguments for not wearing headgear, which is mainly driven by skin wettedness under warm conditions (Section 2.3.1).
- The head is among the most contributing body-parts for whole body comfort and temperature perception under warm conditions, improving ventilation of headgear has been frequently and successfully applied for optimizing comfort (Section 2.3.1).
- A causal influence of non-encapsulating headgear on the risk for heat stroke seems unlikely (Section 2.3.2).
- Headgear could impair exercise tolerance time through increased discomfort (Section 2.3.2).
- Headgear is unlikely to impair cognitive performance (Section 2.3.3).
- Ventilation is relevant for forced convective heat loss as well as wet heat loss (Section 3.1)
- Previous helmet design has not focused on reducing radiant heating (Section 3.2).
- The effect of hair on forced convective heat loss is roughly 30% (Section 3.3).
- Methods
  - CFD becomes more promising for evaluating helmet design with reducing cost of computational power (Section 4.1.1).
  - Numerical models of human thermal physiology might facilitate active control systems for improved comfort of headgear (Section 4.1.2).
  - Thermal manikin headforms are valid for determining effects of headgear on temperature perception of humans (Section 4.2.1), whereas tracer gas methods can be utilized for quantifying airflow with a relevant spatial resolution (Section 4.2.2).
  - Current efforts combine numerical models with biophysical models, making their predictions more accurate (Section 4.3).
  - User trials are often used in the final evaluation of concepts optimized with more objective methods. This will remain necessary since the total headgear experience cannot be predicted in its entirety using objective methods (Section 4.4).

Based on the current analysis of the available literature, the following topics have the largest potential for future work regarding improving thermal properties of headgear:

- Modeling of the head's sweat rates as a function of spatial location and body core temperature (Section 2.2.2).

- The effect of hair style on forced convection is not well understood and needs more investigation (Section 3.3).
- Development of active control systems for improved comfort (Section 4.1.2), models of the head's sweat rate might play a role in this (Section 2.2.2).
- A laminar system that creates an optically closed surface relative to the radiant source only posing a marginal reduction in convective heat loss allow combining optimizing of airflow and protection against radiant heating (Section 5.1).

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