Final report of Working Group 4:
Ergonomics of thermal effects

A COST Action TU1101 / HOPE collaboration

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I. Introduction

1. Background

The thermal effects related to wearing a bicycle helmet are complex and different studies have investigated single parts of this topic. A literature review was produced and published (Bogerd et al., 2015) 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 that 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.

The report of working group 4 (WG4) provides information about activities undertaken during the COST Action TU1101 "Towards safer bicycling through optimization of bicycle helmets and usage" to better understand the ergonomics of thermal aspects and to work towards the tasks defined in the memorandum of understanding (COST Secretariat, 2011)

Primary Task 5: Development of guidelines for thermally-optimized helmet designs

Secondary Task 3: Inform impact studies on which kinds of ventilation structures are useful and which are unnecessary

Secondary Task 7: Review of physiological and comfort effect of wearing bicycle helmets

All the chapters listed below include important aspects contributing to the primary task 5. Modelling and simulation tools (Chapter II) are becoming more and more important in research and development of new bicycle helmets but also in the development of guidelines, directives and norms. An example for the industrial application of models is given in Chapter III. The investigation of different forms of helmet coverings provides important information about the future direction for the development of helmet designs. Completely new helmet designs and the respective thermal properties are presented in Chapter IV. This chapter shows a different approach for finding new concepts of helmet designs. In Chapter V, new project initiatives are introduced to improve thermal aspects of helmets but also to include information and communication techniques (ICT) into helmets. Finally, the tasks of WG4 are summarized in Chapter VI, conclusions are drawn and an outlook is provided regarding the future development of helmets to comply with the requests of two-wheel commuters (including e-bikes, segway and others).

2. Reference

COST 4142/11 (2011) Memorandum of Understanding for the implementation of a European Concerted Research Action designated as COST Action TU1101: Towards safer bicycling through optimization of bicycle helmets and usage. COST secretariat, Brussels, Belgium.

II. Modelling in R&D

1. Local thermal discomfort by bicycle helmet use – a modelling framework

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1.1. Introduction

Low bicycle helmet wearing rates are suspected to originate, at least partly, from impaired thermal comfort due to accumulated sweat increasing skin wettedness at the head region (Bogerd et al. 2015). Furthermore, a recent survey among German cyclists on helmet usage (Otte et al. 2014, see also WG1 section of this Final Report) showed that complaints on excessive sweating (57%) dominated other ergonomics issues like impaired visual field (9%) or perceived head pressure (10%). As a development from COST Action TU1101 WG4, we introduce a modelling framework for assessing thermal comfort of bicycle helmet use (Bröde et al. 2013). We predict local sweat rate (LSR) at the head region as ratio to gross sweat rate (GSR) of the whole body and also based on sudomotor sensitivity (SUD), which relates the change in LSR to the change in body core temperature (ΔTre). We coupled those local models with models of thermoregulation predicting ΔTre and GSR. This allows for modelling head sweating in response to the characteristics of the thermal environment, clothing, level of activity, and exposure duration. We then validated the predictions of several local models (SUD, LSR/GSR) combined with different whole-body models against head sweat rates measured in the laboratory (Bröde et al. 2014; Bröde and COST Action TU1101 WG4 2014). Eventually, thermal comfort criteria were developed from head LSR by relating skin wettedness to the thermal properties of bicycle helmets. An example illustrates the application in a commuter cycling scenario.

1.2. Thermal comfort in the heat

Though helmets will have beneficial effects on user's comfort by increasing thermal insulation in the cold (Bogerd et al. 2015) or by attenuating heat gain from sun irradiation (Bogerd et al. 2008; Brühwiler 2008) this section focusses on the thermal discomfort originating from heat stress experienced when cycling in moderate to warm environments.

Thermal comfort largely depends on skin temperature and thermal sensation in moderate and cold conditions (Fanger 1972), but is more closely related to sweating and skin wettedness in the heat for both whole body (Gagge et al. 1967; Gagge et al. 1969; Gonzalez and Gagge 1973) and local body regions (Gerrett et al. 2013; Fukazawa and Havenith 2009). Skin wettedness (w) is defined as ratio of actual to maximum possible sweat evaporation and may be interpreted as the percentage body surface area covered by sweat (Gagge 1937). Comfort threshold values (wcrit) are somewhat higher for exercising compared to resting conditions and vary between 22% and 46% depending on exercise mode and body region (Gonzalez and Gagge 1973; Gerrett et al. 2013; Fukazawa and Havenith 2009). As sweat evaporation depends on sweat production, the accurate estimation of local sweat rate is of utmost importance for assessing head thermal discomfort.

1.2.1. Local head sweat rate prediction

Reviewing the literature (Bogerd et al. 2015), we identified six different models for the head region relying on the sudomotor sensitivity (SUD) (Machado-Moreira et al. 2008; Smith and Havenith 2011; Taylor and Machado-Moreira 2013). Three additional models quantify LSR as ratios to gross sweat rate (GSR) of the whole body: LSR/GSR=1 estimated LSR as equal to GSR (Taylor and Machado-Moreira 2011), and two further LSR/GSR ratios were taken from the literature (Smith and Havenith 2011).

Table 1 describes these nine local models and Figure 1 illustrates the coefficients separately for the frontal, lateral and medial head regions. Sensitivity is highest for the forehead in most cases, whereas it is much lower at the hairy medial region.

Model name	Description/Source
Local model as sudomotor sensitivity ($mg \cdot cm^{-2} \cdot min^{-1} \cdot °C^{-1}$)	
SUD1	45 min incremental cycling (50-100 W) in the heat (n=10) (Machado-Moreira et al. 2008)
SUD2	30 min treadmill running at 55% VO_{2max} @25°C (Smith and Havenith 2011), n=9 (frontal), n=4 (lateral, medial)
SUD3	30 min running at 75% VO_{2max} subsequent to SUD2 (Smith and Havenith 2011)
SUD4	Overall results from combined SUD2 & SUD3 protocol (Smith and Havenith 2011)
SUD5	cycling in the heat at 125 W (n=46) (Taylor and Machado-Moreira 2013)
SUD6	resting in the heat (n=49) (Taylor and Machado-Moreira 2013)
Local model as ratio LSR / GSR (n.d.)	
GSR1	LSR estimated as equal to GSR
GSR2	Conditions identical to SUD2 (Smith and Havenith 2011)
GSR3	Conditions identical to SUD3 (Smith and Havenith 2011)

Notes: n: sample size in experiments underlying the corresponding parameter

Table 1. Models predicting local sweat rates (LSR) at head via sudomotor sensitivities (SUD) and as ratio of LSR to gross sweat rate (GSR), respectively.

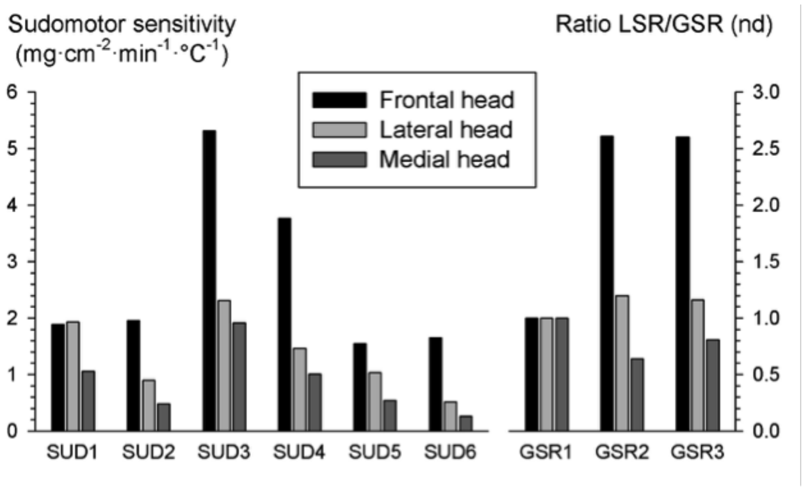

Figure 1. Local sweat sensitivities at the frontal, lateral and medial head expressed as sudomotor sensitivities (SUD) and as ratio of LSR to gross sweat rate (GSR), respectively. For abbreviations refer to Table 1.

1.2.2. Head sweating modelling and validation

In order to predict head LSR depending on the thermal environment, clothing, activity and exposure duration, we linked the local models (Table 1) with the whole body models "Predictive Heat Strain" (PHS) (ISO 7933 2004), the multi-node UTCI-Fiala model of thermoregulation (Fiala et al. 2012) and the still more complex "Fiala thermal Physiology and Comfort" (FPC) model (Fiala et al. 2010).

We compared the prognoses to published means with 95% confidence intervals (CI) of LSR measured at the frontal and lateral head during bicycle ergometer trials in the laboratory with varying air temperatures (16 – 28 °C), air velocities (0.1 – 3 m·s-1) and activity levels (power output 50 – 150 W) (De Bruyne et al. 2008; De Bruyne et al. 2010). The power output (W) was transformed to metabolic heat production (M) assuming a cycling gross efficiency (=W/M) of 20% with 17% and 23% applied in additional sensitivity analyses (Ettema and Loras 2009).

Results showed a substantial inter-model variability with an approximately ten-fold increase from the lowest to the highest predicted LSR in all studies. Models based on sudomotor sensitivity tended to overestimate frontal head LSR, whereas for two of these models (SUD2 & SUD5) predicted lateral LSR were predominantly within the experimentally observed 95% CI (Fig. 2A). Even for those two models, the absolute percentage error varied between 3% and 36%. The predictions based on GSR were lower than those from SUD and covered better the 95% CI for the lateral head region (Fig. 2A). But also for GSR based models the absolute percentage error ranged from 8 – 30% even in the cases when the predictions fell within the experimental 95% CI.

We further validated the predictions on individual measurements of frontal and lateral head LSR from 5 males and 4 females, who visited the laboratory for three times performing cycling exercise with varied workload while wearing a bicycle helmet (De Bruyne et al. 2008). The individual prediction errors were submitted to ANOVA to partition the error variance into relative components showing the influence of different factors (Fig. 2B).

The results indicated that gender, workload and assumed cycling gross efficiency were of only minor importance, whereas the head site accounted for about 10% error variability. The largest part, especially at the forehead, was due to the local models, whose influence on the error was comparable to inter- and intra-individual variability (Fig. 2B). Though PHS gave less accurate predictions than UTCI-Fiala and FPC (Fig. 2A), the local model determined overall performance (Fig. 2B), which was best for GSR2 and SUD2&SUD5 (Fig. 2A) that had been developed for exercising persons (Smith and Havenith 2011; Taylor and Machado-Moreira 2013).

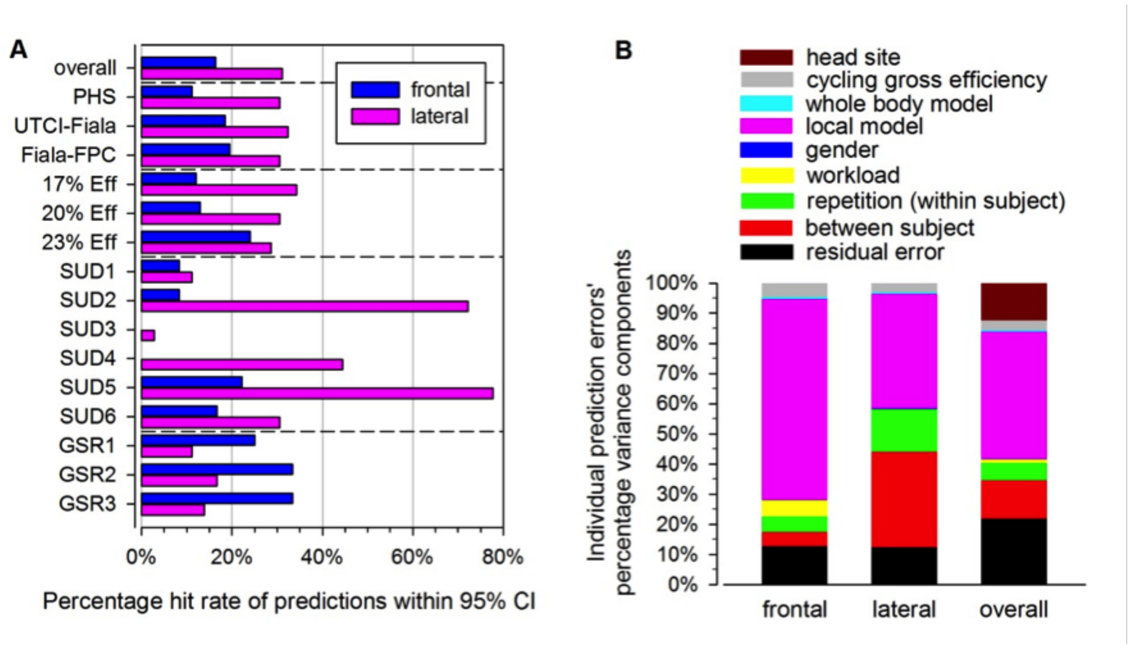

Figure 2. Validation of predictions for frontal and lateral head sweat rates showing the influence of different whole-body and local models as well as varied cycling gross efficiency (Eff) on the accuracy expressed as percentage of predictions falling within the experimental 95% confidence interval (CI) using published means (A), and as partitioning of the individual prediction error in variance components based on individual measurements (B).

1.2.3. Framework for modelling thermal comfort of bicycle helmet use

Based on the aforementioned concepts and elements, we propose a modelling framework for assessing the thermal comfort when wearing bicycle helmets consisting of the following steps:

a) Simulate whole body responses (ΔTre, GSR) in relation to the parameters of the thermal environment, clothing characteristics, activity level, and exposure duration.

b) Apply local model based on SUD or LSR/GSR ratios (Table 1, Fig. 1) to predict frontal, lateral, medial head LSR (in mg / cm^2 / min).

c) Compute head LSR as area weighted mean (Annaheim et al. 2013, see also Chapter III) $LSR_{head} = (1*LSR_{frontal} + 2*LSR_{lateral} + 4*LSR_{medial})/7$

d) Head skin wettedness (whead) can be calculated (Parsons 2014) by

$w_{head} = 0.06 + 0.94 * (E_{head} / E_{max})$,

where

$E_{head} = 2430\ J/g * LSR_{head} * (1/6)$ (in W/m^2)

with 2430 J latent heat per gram sweat evaporation and (1/6) a unit conversion factor and the offset 0.06 considering diffusive moisture transport

$E_{max} = (P_{sk,sat} – Pa) / R_{et,head}$

P_a, $P_{sk,sat}$: ambient and saturated skin water vapour pressure (Pa)

$R_{et,head}$: evaporative resistance of helmet & air layer for covered head area (m^2Pa/W)

e) Relate w_{head} to $R_{et,head}$ and compare to comfort threshold w_{crit} of head skin wettedness

This approach requires knowledge on the evaporative resistance of bicycle helmets (cf. the contribution of Kuklane et al. 2015, see Chapter IV), as well as on head w_{crit}, which is delineated below.

1.3. Thermal comfort limit values and example application

As indicated by the small sample sizes in Table 1, data on human head perspiration are scarce, and there are no reported values on head w_{crit} readily available, but have to be estimated, e.g. from the relationship of local comfort threshold values with local sweating sensitivity, as shown in Fig. 3A for local w_{crit} (Fukazawa and Havenith 2009) increasing with their corresponding LSR/GSR ratios, here taken as GSR2 from Table 1 (Smith and Havenith 2011). The LSR/GSR ratio for the covered head region was calculated as area weighted average of the frontal, lateral and medial head values (Fig. 1), and amounted to 1.09 yielding a head w_{crit} of 0.37. It should be noted that applying the GSR3 sensitivities from Table 1 or using averaged GSR2 and GSR3 values also yielded a head w_{crit} of 0.37.

Illustrating our approach, we coupled the UTCI-Fiala model (Fiala et al. 2012) with the local model GSR2 and simulated a commuter cycling scenario (de Geus et al. 2007) with a person wearing clothing insulation of 0.4 clo cycling 30 minutes with 125 W power output assuming 20% cycling gross efficiency at 20 °C air temperature, 40% relative humidity, in the shade with mean radiant temperature equalling air temperature and a (relative) air velocity of 6 m/s. Additional simulations were carried out for air velocities of 0.3 and 1.6 m/s representing conditions used when measuring headgear evaporative resistance (Fonseca 1974; Pang et al. 2014; Chen et al. 2006, Kuklane et al. 2015).

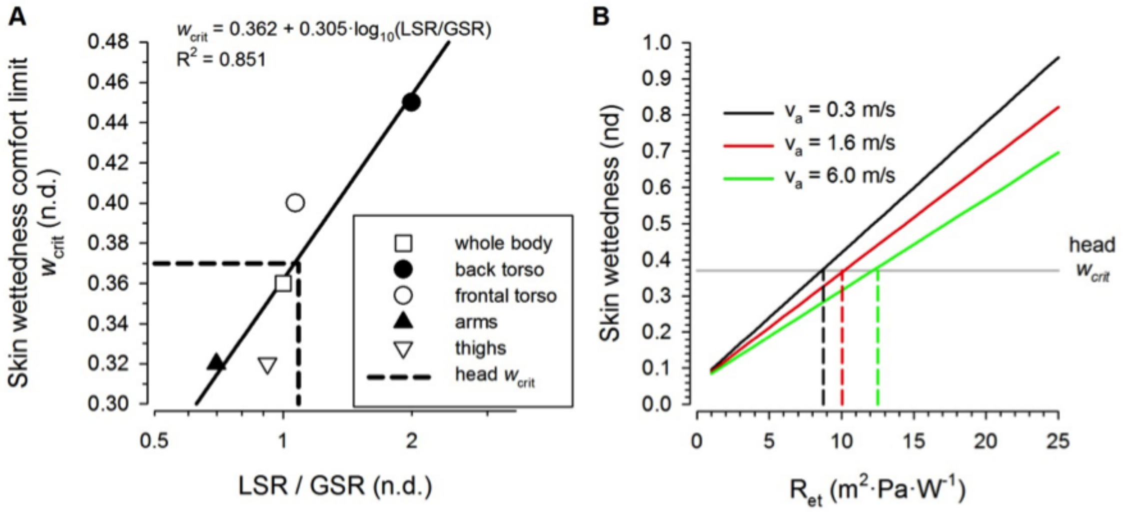

Figure 3. Regression of skin wettedness comfort limits (w_{crit}) for various body parts (Fukazawa and Havenith 2009) on sweating sensitivity GSR2 from Table 1 (Smith and Havenith 2011) with derived head w_{crit} (A), and upper limit values of evaporative resistance (Ret) for thermal comfort by comparison of head w_{crit} to skin wettedness calculated for different wind speeds (va) from a simulated commuter cycling scenario (B, see text for details).

Figure 3B shows the skin wettedness at the end of the simulated 30 min exposure compared to evaporative resistance. As sweat rate was reduced by wind, also skin wettedness decreased with increasing air velocity. The vertical reference lines indicate the upper R_{et} threshold to maintain thermal comfort at the head at different wind speeds, allowing comparisons to actual evaporative resistances of the bare head and/or bicycle helmets.

Wang et al. (2012) reported air layer evaporative resistance for the bare head measured by a thermal manikin, which was reduced from 32 m^2Pa/W at still air to 8 m^2Pa/W at v_a = 0.8 m/s. As even more reduction could be expected for higher wind speeds, the comfort threshold value 12.5 m^2Pa/W (Fig. 3B) will not be exceeded for cycling with 6 m/s (21.6 km/h) while not using a helmet. Evaporative resistance for different types of headgear ranged from 40 – 50 m^2Pa/W at still air (Fonseca 1974; Pang et al. 2014; Chen et al. 2006), but a four-time increase in evaporative heat loss by increasing wind speed to 5 m/s was found for military headgear (Fonseca 1974), and reduced Ret values between 10 – 15 m^2Pa/W were reported for bicycle helmets at va = 1.6 m/s (Kuklane et al. 2015, see Chapter IV). Thus, thermal comfort will most probably be attainable for the simulated conditions also for bicycle helmet use.

1.3.1. Section summary / Key facts

The concepts introduced in this section allow for the simulation, prediction and assessment of local thermal comfort associated with bicycle helmet use considering the (potentially time-varying) parameters of the thermal environment, exposure duration, activity level, clothing characteristics, and helmet's thermal properties.

However, due to the scarcity of data on human head perspiration we had been compelled to make certain assumptions during modelling. These points to the requirements for more research aiming to improve and validate the applied models, more specifically there is a need for:

- Improvement of local head sweating models, e.g. by considering the modifying effect of local skin temperature on sweating (Nadel et al. 1971).
- Biophysical testing of helmet's thermal properties using head-forms and thermal manikins, which should
    - tabulate the thermal insulation and evaporative resistance at still air, and
    - asses their reduction by wind speeds relevant for cycling, preferably by developing correction equations as available for whole body clothing (ISO 9920 2007) or air layer evaporative resistance (Wang et al. 2012).
- Human trials on head perspiration addressing
    - the measurement of head sweat rates and skin temperature and their relation to skin wettedness and thermal comfort perception, thus allowing for deriving experimentally head wcrit,
    - simultaneous measurements of GSR and ΔTre besides LSR, thus allowing for specifically validating the local models.

Finally, the principles presented in this section are easily transferable to considering local thermal comfort at other body regions as well.

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2. Towards Data-Based Mechanistic Models for Managing Thermoregulation

A. Youssef, P. Truyen, D. Fiala, P. Bröde, J.-M. Aerts

2.1. Introduction

The growing interest in heat transfer and thermoregulation in human beings has led to the development of many advanced and accurate thermoregulation models such as the 'Fiala thermal Physiology and Comfort' (FPC) model (Fiala et al., 2010; Fiala and Havenith, 2015). Today, one of the big challenges in this domain is the implementation of thermoregulation models in applications capable of real-time monitoring and control (i.e. management), e.g. in the assessment and management of thermal comfort of bicycle helmets (De Bruyne et al., 2008, 2010, 2012; Bröde et al., 2014; Bogerd et al., 2015). The most reliable models however are much too complex for real-time calculations and implementation.

In the reported research, it was aimed to make a first step for controlling human body core temperature (measured as rectal temperature, *Tre*, °C), using metabolic activity (*Qmet*, W) and mean skin temperature (*Tskm*, °C) as process inputs. More specifically, it was aimed at developing compact discrete-time data-based mechanistic (DBM) models describing the dynamic response of *Tre* to *Qmet* and *Tskm*.

2.2. Materials and Methods

2.2.1. Datasets

Three datasets, provided by the Leibniz Research Centre for Working Environment and Human Factors (IfADo) in Dortmund and by Ergonsim - Human Thermal Modelling in Marxzell, Germany were used during the course of this study.

Dataset (1) contains data from climate chamber experiments which have been carried out during the EU FP7 PROSPIE (Protective Responsive Outer Shell for People in Industrial Environments) project similar to the experiments of Niedermann et al. (2014). Six subjects were asked to perform a similar two-phase experimental protocol for 100 to 120 minutes in a climate chamber exposed to a mean air temperature (*mTair*) of 25, 30 or 40°C (representing warm to hot climates) at random relative humidity combined with solar loads and two different clothing ensembles. Each subject followed the same protocol starting with a short resting period followed by two times 40 minutes of treadmill walking at a set speed and gradient. This way, a constant metabolic rate (*Qmet*) is persisted. These two periods of exercise were separated by an obligated seated rest taking place outside the climate chamber at approximately 22 °C and 50% relative humidity (RH). The duration of this resting period was determined by the rate of decline in rectal temperature of the individual, with participants returning to the chamber once their rectal temperature (*Tre*) had dropped by 0.4 °C. It should be noted that the subjects work at incremental load in the second exercise period instead of the abrupt imposed step in working load at the first period of exercise. The climatic conditions were monitored by measuring air velocity (*mVair*), relative humidity (RH) and air temperature (*mTair*) which was approximately equal to mean radiant temperature (MRT). The mean skin temperature (*Tskm*) is calculated as the mean temperature of local skin temperature recordings at 7 sites (head, chest, lower arm, hand, thigh, calf and foot) using the Hardy-Dubois relationship. The core temperature of the rectum (Tre) results from simulations of the FPC model using Qmet and Tskm as well as using Qmet and environmental conditions as inputs.

Dataset (2) contains data of eight healthy male students (mean + SD: age 22.8 + 1.3 years, body height 1.81 + 0.06 m, body mass 75.1 + 6.6 kg, body surface area 1.94 + 0.11 m2) each performing two experiments in 20°C air temperature, 80% RH and facing an *mVair* of 0.5m/s (Bröde et al. 2008). The subjects wore their own briefs, socks and sport shoes, and a four layer clothing ensemble consisting of polypropylene underwear, a hooded Tychem C Standard coverall as intermediate layer preventing both wicking and evaporation, a cotton (CO) mid layer and an impermeable PVC outer layer. Trials were performed with the CO mid layer either dry (dry condition) or wetted using 618 + 16 g of water (wet condition). The sequence of those conditions was balanced across subjects who visited the laboratory at the same time of day.

The experimental protocol itself contained of a 30-minute resting phase followed by three phases inside a climatic chamber, each lasting 30 minutes and separated by a 3-minute period where the fully clothed person's weight was determined (Mettler-Sauter balance, Mettler, Germany + 5 g). The first exercising phase comprised of 2 minutes of treadmill walking at 4.5 km/h followed by 28 minutes of standing in the room. Treadmill work was performed during the whole second and third phase.

Metabolic heat production was calculated according to ISO 8996 (2004) from the analysis of O2 consumption (Servomex Series 1100, Servomex Ltd., UK) and CO2 production (UNOR Infrarot-Gasanalysator, maihak AG, Germany) of expired air collected with Douglas bags during the last 10 minutes of phases 1 and 3, respectively. Mean skin temperature *Tskm* was calculated as the average of thermistor recordings (YSI 427, Yellow Springs, USA) at eight body sites (forehead, left chest, right frontal thigh, left dorsal thigh, right scapula, right upper arm, left lower arm and left hand) according to a variant of the ISO 9886 scheme (ISO 9886, 1992). The clothing layer temperatures, on their turn, are measured by averaging the thermistor temperatures on six body locations.

The third dataset, dataset (3), contains simulated data taking place in four cities with a hot-dry (Dallas and New Delhi) or a warm-humid (Managua and Osaka) climate and at four workloads (1.7, 2.8, 3.9 or 4.9 Met; with 1 Met = 58.2 W/m^2). This way another 16 datasets are available for data analysis. A typical workwear ("KSU uniform": long-sleeved shirt, trousers, underwear, socks, shoes) was worn, assuming a 0.6 clo thermal insulation. Each time a 12-hour period is simulated with hourly cycles of 50 minutes of work (at different workloads) followed by 10 minutes of rest at 1.1 Met. A resting period of one hour is taken at noon. The entire experiment is run from 6 a.m. till 17:55.

The meteorological conditions are deemed "typical" for the considered regions and a shaded condition is assumed with mean radiant temperature equalling air temperature as well as an air speed of 1 m/s. As already mentioned, the physiological responses (*Tskm* and *Tre*) are simulated by the FPC model as it was adapted for the development of the Universal Thermal Climate Index UTCI (Fiala et al., 2012).

2.2.2. Mathematical Modelling

Data-based modelling was performed by means of constructing discrete-time transfer function (TF) models in the form of an output-error (OE) model (Young, 2011). In this thesis, rectal temperature (*Tre*) was modelled using one (SISO or single-input, single-output) or more (MISO or multiple-input, single-output) inputs. The general block diagram of such an output-error model is given as:

$$y(t) = \sum_{i=1}^{nu} \frac{B_i(z^{-1})}{A(z^{-1})} u_i(t - \delta_i) + e(t)$$

with $y(t)$ is the system output (*Tre*) at time instant t; $u_i(t-\delta_i)$ = i-th system input at time instant $t-\delta_i$ (*Qmet* and/or *Tskm*); δ_i is time delay for i-th process input; $A_i(z^{-1})$, $B_i(z^{-1})$= polynomials containing the model parameters using backward shift operator z which is a time shift operator: $z^{-s}\,x(t)=x(t-s)$; $e(t)$ is the prediction error at time instant t, and *nu* is the number of process inputs (*nu*=1 if SISO; *nu*≥1 if MISO).

The polynomials can be written as:

$$A(z^{-1}) = 1 + a_1 z^{-1} + a_2 z^{-2} + \cdots + a_n z^{-n}$$
$$B(z^{-1}) = b_0 + b_1 z^{-1} + b_2 z^{-2} + \cdots + b_m z^{-m}$$

with $a_1,\ldots, a_n$ and $b_0,\ldots,b_m$ the *a*- and *b*-parameters to be determined, while the amount of *a*- and *b*- parameters are respectively indicated as *n* and *m*. Model structures are indicated as [n m δ] for SISO models and as [n m_1 m_2 δ_1 δ_2] for MISO models with two inputs.

The simplified refined instrumental variable (SRIV) algorithm (Young, 1998) was used by the CAPTAIN toolbox (Taylor et al., 2007) to estimate the best possible or most parametrically efficient model for each [n m δ] or [n m_1 m_2 δ_1 δ_2] combination.

The models were evaluated by quantifying the confidence intervals of the model parameter estimates, the poles, the coefficient of determination (R_T^2) and Young's Identification Criterion (YIC).

2.3. Results and Discussion

SISO discrete-time transfer function (TF) models, using metabolic rate (*Qmet*) as the only input, were the most satisfying for datasets (1) and (2) in terms of accuracy, reliability and complexity, as indicated by the average selection criteria R_T^2 and YIC (mean + standard deviation): R_T^2 = 0.982 + 0.024 and YIC = -11.926 + 3.596 and R_T^2= 0.980 + 0.012 and YIC = -10.409 + 1.456 for datasets (1) and (2) respectively.

SISO results with input *Tskm* are equally good (significance level α=0.05) for the first interval in dataset (1) (R_T^2 = 0.996 + 0.012, YIC = -13.771 + 5.132). Rectal temperature estimation for dataset 3 on the other hand, was not that good, with low accuracies for the best inputs *Qmet* (R_T^2 = 0.6747 + 0.065) and *Tskm* (R_T^2 = 0.668 + 0.215).

Using the two inputs, *Qmet* and *Tskm*, improved the accuracy of the SISO models for each subject with clearly and significant better (R_T^2= 0.917 + 0.084, YIC = -8.787 + 2.476) results for dataset (3). These models, as well as those for the first interval of dataset (1), were preferred to their corresponding SISO models because of a higher value for YIC. Also for the second interval of the first dataset is this type of model found to be the best possible model since 'variable straigh-tening' had to be used to find satisfying SISO models (R_T^2=0.984 + 0.012, YIC=-7.935 + 1.024). It is very logical that the same inputs capable of good model construction for SISO are the same as for those giving little prediction error for MISO models. Using both inputs *Qmet* and *Tskm*, it was possible to obtain a mean R_T^2 above 0.9 for each dataset but not for every subject (41 out of 44 cases). Examples of modelling results are shown in Fig. 1 for the three datasets.

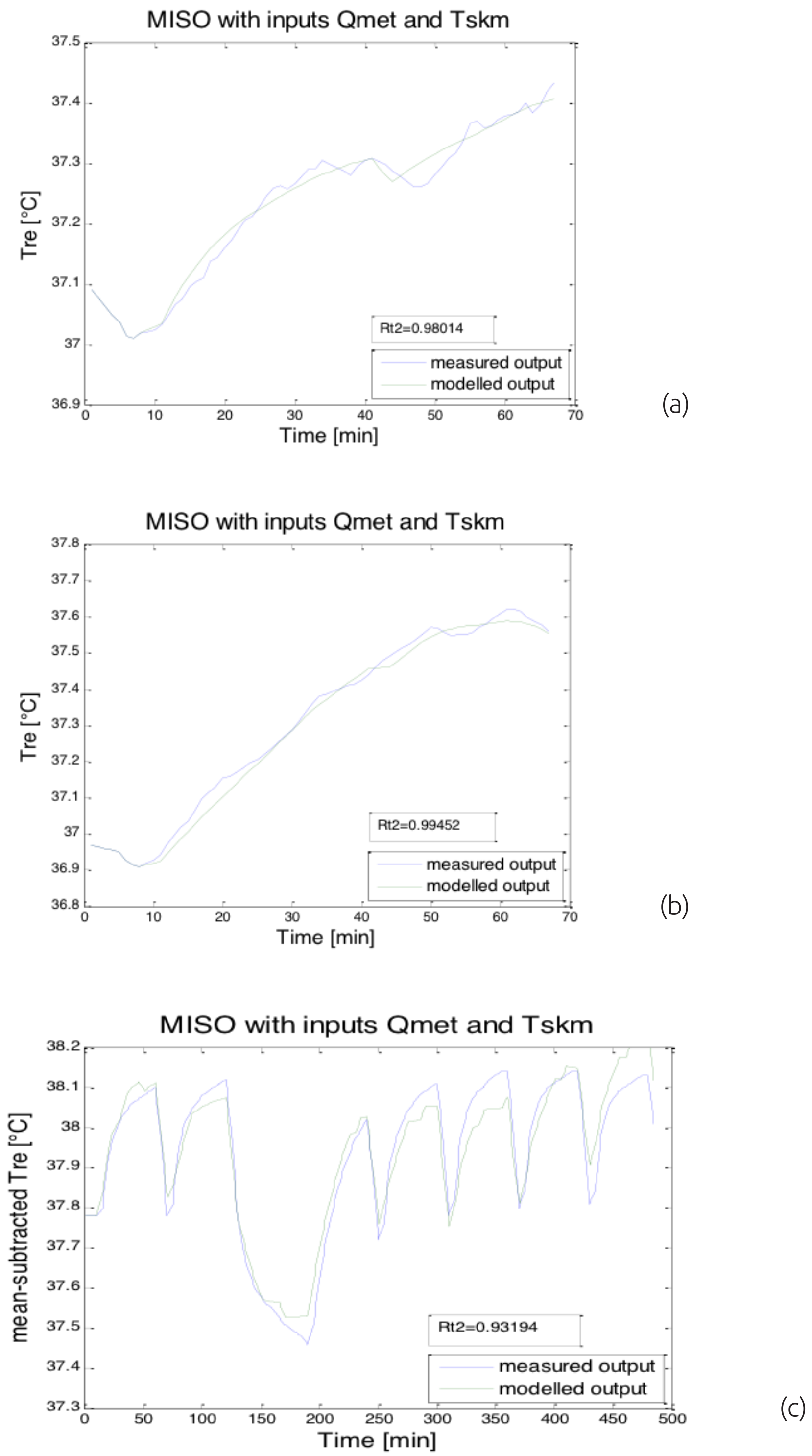

Figure 1: Examples of modelling results using both inputs Qmet and Tskm for modelling the output Tre for dataset (1), (a), dataset (2) (b) and dataset 3 (c).

First order models (n=1) were obtained for all SISO and MISO data-based models and subjects, whereas 2 instead of 1 b-parameters (m=2) were needed for SISO models using *Tskm* as an input in dataset 3 and at dry condition for dataset (2). Two b-parameters are also necessary to model *Tre* for the third dataset's subjects in response to all input combinations.

Mechanistic interpretation was based on the best obtained model or the first-order multiple-input, single-output (MISO) model for the third dataset using both *Qmet* and *Tskm* as inputs with the model structure [1 1 2 δ_1 δ_2]. Studying the human thermoregulation system and basic heat transfer processes revealed the presence of three parallel thermoregulatory mechanisms in the model affecting the rectal temperature Tre: the conversion of metabolic heat *Qmet* into a temperature effect (heat capacity) and two thermal resistances to heat transfer between the human body core and skin with opposite effects. The first impeding mechanism is a steady-state resistance linked to heat transfer processes of the passive thermoregulation system inside the body (blood circulation and heat conduction through the tissue layers). *Tskm* itself is also influenced by the surrounding environment by heat transfer mechanisms such as convection and radiation. The second one is a capacitive impedance related to a part of the active thermoregulation system, moreover to the process of sweating. The proposed mechanistic interpretation is verified by the fact that the obtained SISO models for *Qmet* and *Tskm* contain respectively 1 and 2 b-parameters so that they lack one or two of the parallel heat mechanisms for good rectal temperature estimation. Their corresponding lower accuracies confirm this. An example of such decoupling in mechanisms is shown in Fig. 2 for a case of dataset (3).

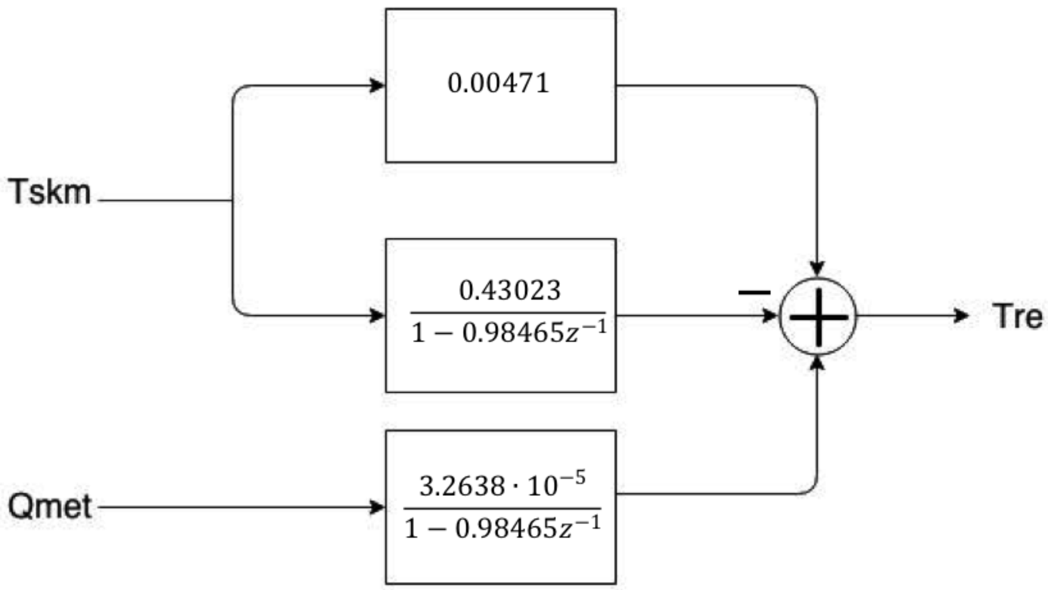

Figure 2: Block diagram of the data-based TF model for Tre in Dallas at 2,8 Met with inputs Tskm and Qmet.

2.4. Conclusions

In this work we investigated the use of compact data-based transfer function models for modelling core body (rectal) temperature in relation to metabolic activity and mean skin temperature as a basis for managing thermoregulation. We demonstrated that core body temperature could be modelled accurately using metabolic activity alone or both metabolic activity and mean skin temperature.

It was further demonstrated that the identified transfer function model structure with metabolic activity and mean skin temperature as inputs can be interpreted in a mechanistic way when linking it with mechanistic models such as the 'Fiala thermal Physiology and Comfort' (FPC) model.

Such data-based mechanistic models can be used in a next step as a basis for managing thermo-regulation of individuals in real-time. Linking the predictions of core temperature with local models for head perspiration (Bröde et al., 2014) they may also become useful in assessing and controlling the thermal comfort of bicycle helmets.

2.5. Acknowledgements

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3. Thermo-physiological Head Simulator

N. Martinez, A. Psikuta, S. Annaheim, J. M. Corberan, R. M. Rossi

3.1. Introduction

Specialized body parts manikins are an increasing trend as an alternative to full-body manikins. Beside lower cost, operation control is clearer for separate body parts. Due to a finer segmentation, they allow determining local thermal properties of garments or protective equipment with great detail. Likewise full-body manikins, they usually operate in steady-state mode following the set values of heat flux or surface temperature defined by the user. Although this methodology enables a reproducible comparison between protective clothing and gear valuable for clothing industry, it does not provide sufficient information about general/whole body human physiological response in different cases of use.

The prediction of the physiological state of the body is provided by a mathematical model of human thermal physiology and comfort. Although models are powerful tools to predict human thermal response, they are not capable of accounting for complex heat and mass exchange processes at the skin surface when the clothing is worn. Instead, the thermal devices could measure the overall effect of these processes due to the given actual gear and surrounding environment. Several attempts to couple thermal manikins (full-body manikins and cylinders) with thermo-physiological models have been successfully undertaken. They have proved to accurately evaluate effect of clothing and environmental factors on human thermal response [1]. Nevertheless, the partial coupling of a body part manikin with a mathematical model of the thermal physiology has not been addressed so far.

This project is a forerunner attempt to couple the body part manikin - a nine-zone thermal head manikin with one of the most advanced thermo-physiological models by Fiala et al. [2]–[4]. Because the head is the only body part being covered by gear and exposed to the environment, the rest of the body needs to be simulated virtually. Accordingly, the model is challenged to simultaneously accept different types of boundary conditions, such as measured surface heat losses at head-site and virtual environmental conditions for the rest of the body. The head manikin is required to closely reproduce the skin temperatures and sweat rates imposed by the physiology model in real-time including its dynamic changes. Therefore, in this first stage we aimed at the performance evaluation of the components of the coupled system in order to determine their limitations with respect to head simulation. In the next step the evaluation of the coupled system will be done to confirm its range of application. Finally, this thermo-physiological head simulator will contribute to the development and optimization of thermal and comfort aspects in new headgear concepts.

3.2. Material and methods

3.2.1. Thermal head manikin

A nine-zone thermal manikin representing the human head geometry was developed for this project especially with regards to the segmentation of the head geometry. This segmentation of the head was aimed at providing high spatial resolution for headgear research and corresponded to the typical zones of interest based on many years of Empa experience in headgear evaluation [5]–[9]. Therefore, the cranial zone includes 6 independent zones: right and left temple as well as serial fragmentation of the area in-between. Face, forehead and neck were the remaining independent zones with the forehead being the only zone partially covered by the headgear (see Fig. 1).

The surface temperature of the head manikin is typically controlled at a fixed setpoint similar to human skin temperature at thermo-neutral state (e.g. between 34°C and 36°C). The power needed to maintain this temperature over a steady-state period is recorded and allows the quantification of combined net heat loss through convection, conduction and radiation.

Zones
1 Forehead
2 Face
3 Left temple
4 Right temple
5 Crown
6 Upper Head Back
7 Lower Head Back
8 Occipital
9 Neck

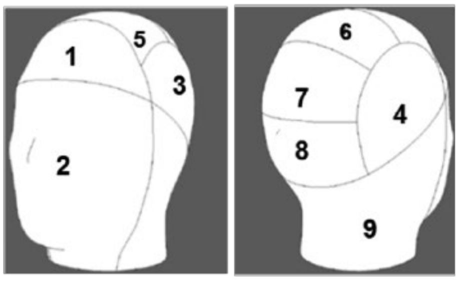

Figure 1 Nine-zone thermal head manikin with collocation and labelling of zones

3.2.2. Mathematical model of the human thermal physiology

The mathematical model of human thermal physiology by Fiala [2]–[4] was available for this project to be coupled with the head manikin. It consists of two interacting systems: the controlling or active system and the controlled passive system. It also incorporates the prediction of the overall perceptual responses according to ISO 7730:2005(E) [10]. The passive system is a multi-segmental and multi-layered representation of the human body and the dynamic heat and mass transfer that occur inside the body and its surface. The active system predicts thermoregulatory responses of the central nerv-ous system (see Fig. 2).

The model is already prepared to admit boundary conditions in three different formats, such as environmental parameters conditions (type 1), heat fluxes imposed on the skin surface (type 2) or skin surface temperature (type 3). These boundary conditions can be defined either globally or locally and eventually boundary conditions types can be mixed.

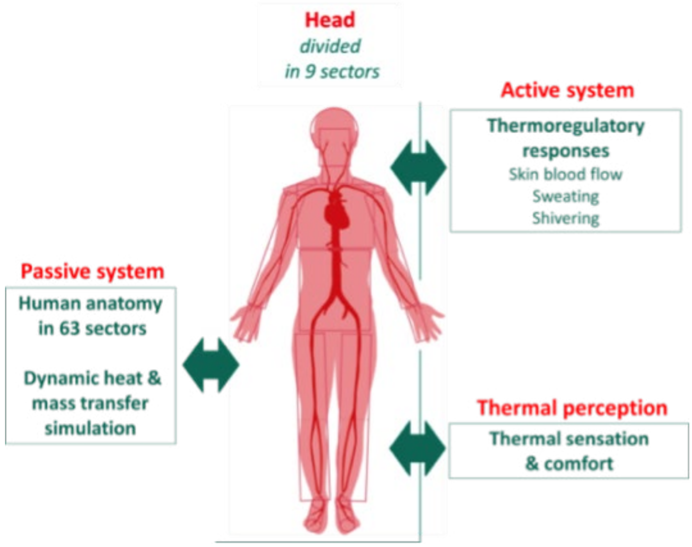

Figure 2 Mathematical model of the human thermal physiology by Fiala[2]–[4]

3.2.3.Evaluation of the thermal head manikin

Adding a physiological control to the thermal manikin will imply slightly different requirements for the manikin operation than these required by the manikin standards. Thus, its performance had to be determined under conditions corresponding to the course of a physiological simulation, namely:

- Head manikin independent zones will be controlled according to proposed division into head sectors of the mathematical model. Therefore, the nine zones of the head manikin were merged to get similar areas than head sectors presented in the mathematical model by Fiala [2]–[4].
- Non-uniform surface temperature over the entire head due to physiological response that can result in lateral heat losses by conduction or internal convection and radiation. For this purpose, two scenarios based on a matrix of simulations using the physiology model have been reproduced on the head manikin. They were selected for representing extreme non-uniform surface temperature at high heat losses rates and moderate non-uniform surface temperature low heat loss rates (see Table 1).
- Transient conditions requiring sudden change of surface temperature under which the thermal manikin responsiveness should match the physiology dynamics. To determine the capability of the head manikin to timely reach the surface temperature as required by the controlling mathematical model, the speed of reaction of the manikin (passive heating and cooling rates) was compared to rates of skin temperature changes predicted by the physiological model for certain scenarios. For this purpose, several typical and extreme exposures of the human body were simulated using the mathematical model by Fiala [2]–[4]. Results from 140 simulations for heating and 120 simulations for cooling including different environmental parameters to provide a wide range of cooling and heating rates were analysed. The maximal heating and cooling rates of the head manikin were determined.

Surface temperatures (°C)	*Scenario 1:* Extreme non-uniform surface temperature High heat loss rates	*Scenario 2:* Moderate non-uniform surface temperature Low heat loss rates
Forehead	30	34
Face	23	35
Cranial section (Left Temple, Right Temple, Crown, Upper Head Back, Lower Head Back, Occipital)	30	34
Neck	29	35
Environmental conditions	5°C/50%RH	25°C/50%RH

Table 1. Description of scenarios for testing lateral heat loss by conduction and internal convection and radiation

3.2.4. Evaluation of the mathematical model of the human physiology

The mathematical model of human thermal physiology by Fiala [2], [3] has been extensively validated [4] over 59 subjects' studies. Exposures included cold, moderate, warm and heat-stress provoking environmental conditions (-13 to 50°C ambient temperatures, 0.1 to 22 m/s wind speed, 0 to 600 W/m2 solar radiation). Moreover, a wide range of activity and clothing conditions (0.8 to 12 met, and 0.1 to 1.9 clo) were applied. Nevertheless, further validation is needed for local skin temperature prediction at head site.

Fifteen human data sets for cold, moderate and hot exposures have been selected to validate skin temperature at forehead. Rectal and mean skin temperatures were included as well. The agreement between model prediction and experimental data have been statistically assessed by the root-mean squared deviations (rmsd) and mean errors (bias).

3.3. Results and discussion

3.3.1. Evaluation of the thermal head manikin

The comparison of head geometries revealed a slightly bigger surface for the mathematical model (+3%) than for the head manikin. Merging the corresponding areas of the manikin for the different head parts, differences were 4.1% for the head, 6.1% for the face and -1.8% for the neck. With this zones assignment, head segmentation of head manikin considerably agrees with head sector proposed by the mathematical model by Fiala [2]–[4].

For extreme non-uniform surface temperature distribution and high heat loss rates scenario, non-uniform surface temperature proposed by Fiala model resulted in 28.3% more heat loss for forehead at steady-state when face was set at 23 °C with regards to situation in which both were set at 30 °C. For moderate non-uniform surface temperature distribution and low heat loss rates scenario, when surface temperature at neck and at face was set at 35 °C instead of 34 °C similar to physiological temperature distribution proposed by Fiala model, steady-state heat fluxes decreased by 9.2% in the neighbouring zones (forehead, left and right temples) due to face and neck were at 35 °C. Deviations above 5% from measured heat fluxes could result in some non-acceptable accuracy in the prediction of the physiological response at the coupled system [11].

First tests were done for heating up in still air conditions to check if the thermal head manikin was able to achieve skin temperature increases demanded by the mathematical model by Fiala [2]–[4]. An average temperature rise of 5.6 °C/min was observed when heating power was set at the nominal value of 800 W/m2. An average cooling rate of 0.7 °C/min was measured when the manikin was allowed to cool from initial surface temperature of 35 °C to the environmental temperature of 23 °C and 55% RH. Since the heating rate is dependent on the wind speed and cooling rate on both environmental temperature and the wind speed, a series of measurements will be conducted to build up a matrix of manikin cooling and heating rates. These results will be compared, and hence, the limitations of the manikin for physiological simulation determined.

3.3.2. Evaluation of the mathematical model of the human physiology

Table 2 shows the summary of the statistical analysis for the validation cases with regards to skin forehead, mean skin and rectal temperatures for exposures at cold, moderate and hot environments. All exposures were averaged in three groups such as cold, moderate and hot exposures.

Temperatures (°C)	Skin temperature at forehead		Mean skin temperature		Rectal temperature	
	rmsd	bias	rmsd	bias	rmsd	bias
Cold exposure	1.86	1.21	0.63	0.09	0.11	-0.08
Moderate exposure	2.49	-2.41	0.95	0.47	0.45	-0.33
Hot exposure	0.68	-0.42	0.72	0.42	0.17	-0.15

Table 2 Average statistical parameters (rmsd and bias) for local skin at forehead, mean skin and rectal temperature for cold, moderate and hot scenarios

Mathematical model prediction for rectal and mean skin temperatures showed a good accuracy regarding to subjects data. In case of local skin temperature at forehead, prediction cold and moderate exposures showed lower accuracy than in hot conditions. Different reasons could be responsible for this disagreement such as lack of description of thermal history of subjects prior to the exposure or presence of some additional insulation due to hair, displacement of the headgear over the sensors or allowance of moving the head during the data recording (e.g. away from the wind).

3.4. Conclusion

This is the first attempt in the scientific literature addressing the coupling of a mathematical model of the human thermal physiology with just one body part manikin (Figure 3).

In this first stage of the research, the performance of both components of the system has been evaluated in dynamic conditions such as actual physiological response to the environmental conditions, clothing and activity. Firstly, head geometry and size considerably agreed between head manikin and the mathematical model head sectors. This fact will allow the coupled system to provide coherent physiological control. Secondly, the responsiveness of the thermal head manikin has to comply with the rates of skin temperature change predicted by the physiological model foreseen for coupling and provide an accurate measurement of the heat power for each individual zone in cases with a non-uniform temperature distribution over the head surface. To meet this requirement for a wider range of scenarios, some technical adjustments were applied to the manikin. Thirdly, the physiology model used in this study performed acceptably well when predicting overall physiological response and with greater discrepancy to experimental data for forehead skin temperature.

Further steps aim at defining the physiological limitations and at validating the coupled system in a wide range of exposures. Because only head is physically simulated, the mathematical model has to simultaneously accept different types of boundary conditions, such as measured surface heat losses at head-site and virtual environmental conditions for the rest of the body. This work will be accomplished as discussed on the occasion of a PhD project conducted in relation to this COST action TU1101 (Multi sector thermophysiological head simulator for headgear research (2015) by N. Martinez). The thermophysiological head simulator will be a novel advanced method for headgear evaluation based on adding a physiological control to a nine-zone thermal head manikin.

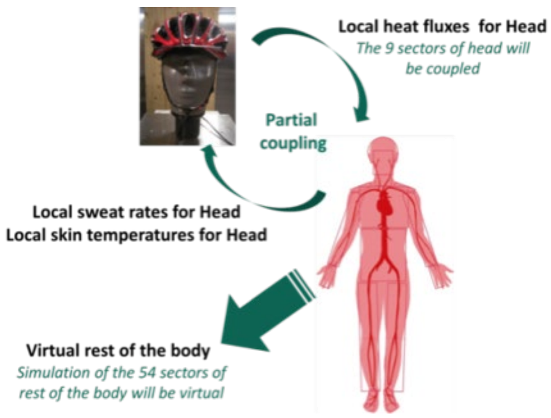

Figure 3 Representation of the partial coupling principle

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[10] ISO 7730:2005(E), "Ergonomics of the thermal environment- Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria," vol. 2005. (ISO), International Organization for Standardization, 2005.

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4. Standardization of test methods

G. De Bruyne, J.-M. Aerts, S. Annaheim, P. Bröde, A. D. Flouris, A. Hursa Sajatovic, K. Kuklane, R. M. Rossi, T. Sotto Mayor, C. P. Bogerd

4.1. Background

Recent studies show that thermal comfort is a major ergonomics concern in helmet use and still one the main reasons for cyclists to not wear a bicycle helmet. In the last decade some manufacturers have aimed to develop helmets with improved cooling capacity. Cooling effectiveness studies on bicycle helmets have shown that not all design parameters that are claimed by manufacturers to affect cooling effectiveness are relevant. Also, cooling effectiveness of bicycle helmets may be too complex to be evaluated by customers.

It is proposed to work towards a standard to assess the cooling effectiveness of bicycle helmets. An initial idea for the standard is provided here. This standard should not be mandatory, but it will allow to objectively informing customers on the cooling effectiveness of a bicycle helmet. The standard should be complementary with standards for full body thermal manikins. Additionally, it could be of interest to expand the standard to cooling effectiveness headgear if specific boundary conditions are application specific. This will make ventilation rating available to customers so that they will include this in their buying considerations. In this way it will become a direct priority of the manufacturers to maximize thermal comfort of helmets.

Finally, the standard to assess the thermal effectiveness of bicycle helmets should be complementary with safety standards for bicycle helmets (currently EN1078:2012).

4.2. Initial test conditions

4.2.1. Head sizing

EN960:2006 as used for eg EN1077:2007and EN1078:2012

4.2.2. Mannequin parameters: independent variables

- Two zones: face, skull (these are minimal requirements; higher resolution in local heat transfer results in more detailed information)
- Guard to avoid heat transfer from the face, skull to the support of the head form
- Skin Temperature setting: 35°C of all zones
- Simulated sweat production (water loss): none

4.2.3. Environmental conditions: controlled variables

- Temperature: 20°C
- Relative humidity: 50%
- Air Velocity: 3m/s, 6m/s, 9m/s (depends on different type of helmet [eg children, commuter, amateur cyclists])
- Solar radiation: none

4.2.4. Thermal sensitivity quantification: dependent variables

- Overall heat loss compared to nude manikin headform results (%) :

(example of costumer communication, not based on too much evidence)

  - 95-100%: excellent cooling capacity
  - 90-95%: good cooling capacity
  - 85-90%: moderate cooling capacity
  - 80-85%: poor cooling capacity
  - Less than 80%: extremely poor cooling capacity

4.3. References

EN 1078, 2012. Helmets for pedal cyclists and for users of skateboards and roller skates. European Committee for Standardisation (CEN), Brussels

EN960, 2006. Headforms for use in the testing of protective helmets. European Committee for Standardisation (CEN), Brussels

EN1077, 2007. Helmets for alpine skiers and snowboarders. European Committee for Standardisation (CEN), Brussels

III. Industrial application

1. Evaluation of thermal properties of coverings for bicycle helmets

N. Martinez, G. de Bruyne, R. M. Rossi, S. Annaheim

1.1. Introduction

The thermal head manikin described extensively in Chapter II.3 provides important information to evaluate the effectiveness of helmet concepts and designs on ventilation (convective cooling) protection from solar irradiation (radiant shielding). Based on the preliminary helmet tests with the head manikin, promising concepts and designs are identified and further developed. In this way, the thermal head manikin contributes to a shortening, and thus increased cost effectiveness, in the development of new bicycling helmet concepts and designs.

In this study, the effect of two helmet designs and additional helmet coverings on convective cooling and radiant shielding was investigated.

1.2. Materials and methods

1.2.1. Helmets

Two helmets (Genesis, Z1) and 3 different coverings for Helmet Z1 were supplied for testing (black, chrome and chrome with large vents). One of the covering was tested twice with the small holes placed at the front part open and covered with aluminium tape. Following six configurations were tested:

Helmet 1: Genesis

Helmet 2: Z1

Helmet 3: Z1 / black mat cover

Helmet 4: Z1 / chrome cover

Helmet 5: Z1 / chrome cover small vents

Helmet 6: Z1 / chrome cover large vents

Figure 1. Overview on the investigated helmet coverings

1.2.2. Experimental set-up

Figure 2 shows the position of the nine individual zones on the thermal head manikin.

Zone	Area [m²]
1. Forehead	0.0094
2. Face	0.0357
3. Left temple	0.0094
4. Right temple	0.0094
5. Crown	0.0095
6. Upper Head Back	0.0095
7. Lower Head Back	0.0095
8. Occipital	0.0095
9. Neck	0.0366

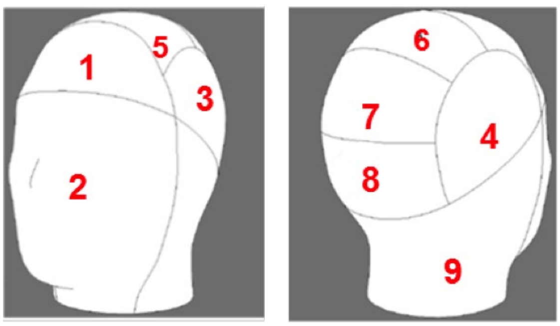

Figure 2. Position of 9 individual zones at thermal manikin.

1.2.3. Procedure

Helmets and covers were placed in the climatic chamber (York International) at 18 °C (±1 °C) and 50% relative humidity (±3%) during 12 hours for their conditioning.
For the experiment, each helmet was placed symmetrically on the headform (headform in upright position; inner part of the front brim 6.5 cm above of the tip of the nose). Heat losses from each individual zone of a 9-zone thermal manikin were continuously recorded during 12 hours for each helmet (one measurement for each helmet) at 18°C ambient temperature, 50% relative humidity and frontal wind speed of 6.22 ± 0.09 m/s. During the last 6 hours of each test, a radiant heat load (Infrared Lamp, 150W) was applied from the top of the head.

Averaged values of heating power for the last five hours of each test phase (light off and light on) was considered as the heat losses values for the sample under testing.

- Convective heat loss (W/m2) was calculated out of heat fluxes for each of the nine zones during the light off phase.
- Global heat loss (convection & radiation) (W/m2) was calculated out of heat fluxes for each of the nine zones during the light on phase.
- Radiant heat gain (W/m2) was calculated out of heat flux differences for each of the nine zones between phases with and without radiation.

Out of the individual values recorded at each zone, total convective heat loss, total global heat losses (convection & radiation) and total radiant heat gain values for the entire head have been calculated by area-weighted averaging of the heat flux measurements (equation 1).

$$Total\ Value = \frac{\sum Value_i * Area_i}{\sum Area_i} \quad (W/m^2) \tag{1}$$

where value corresponds to each of the three studied variables and the sub-index i indicates each of the nine individual zones.

1.3. Results

Total convective heat losses, total global heat losses (convection & radiation) and total radiant heat gain are shown in Table 1. The values are expressed as absolute values as well as relative values related to Helmet 2.

	Total convective heat losses		Total global heat losses (convection & radiation)		Total radiant heat gain	
	Heat loss (W/m2)	% of helmet 2	Heat loss (W/m2)	% of helmet 2	Radiant Heat gain (W/m2)	Radiant shielding (% of helmet 2)
Helmet 1	562.8 ±23.0	94%	542.4 ±22.5	96%	20.3	61%
Helmet 2	596.4 ±26.8	100%	563.3 ±19.4	100%	33.1	100%
Helmet 3	512.8 ±22.8	86%	500.4 ±18.3	89%	12.4	37%
Helmet 4	527.5 ±31.2	88%	502.9 ±18.2	89%	24.7	75%
Helmet 5	518.1 ±31.0	87%	503.1 ±25.0	89%	15.0	45%
Helmet 6	550.7 ±25.3	92%	532.0 ±25.4	94%	18.7	57%

Table 1. Area-weighted averaged total convective heat losses, total global heat losses (convection & radiation) and total radiant heat gain (entire head).

1.3.1. Evaluation of local heat transfer across the bicycle helmets

Convective heat losses, global heat losses (convection & radiation) and radiant heat gain were inves-tigated for each individual zone (Figures 3, 4 and 5, respectively).

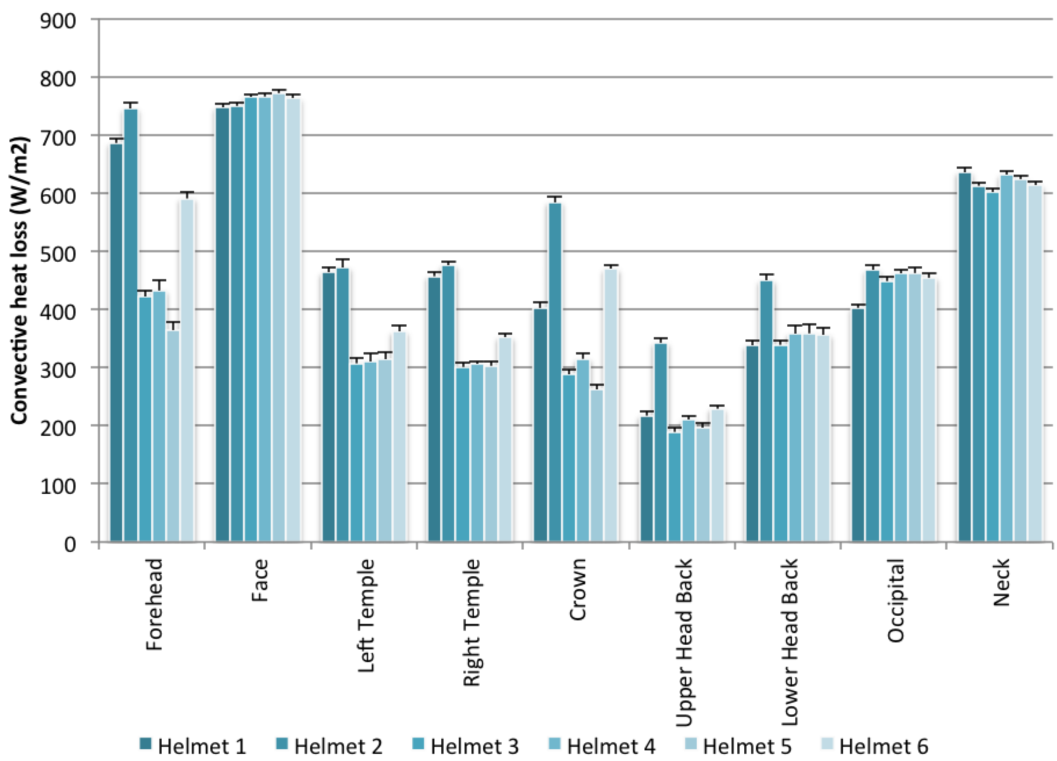

Figure 3. Convective heat losses by individual zone.

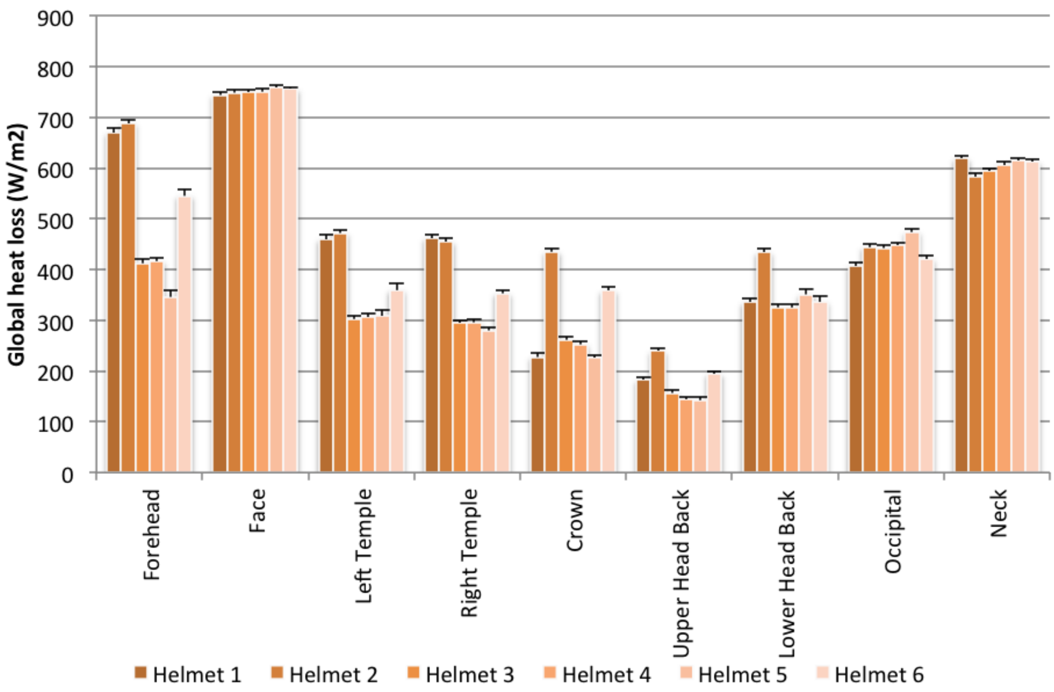

Figure 4. Global heat losses (convection & radiation) by individual zone.

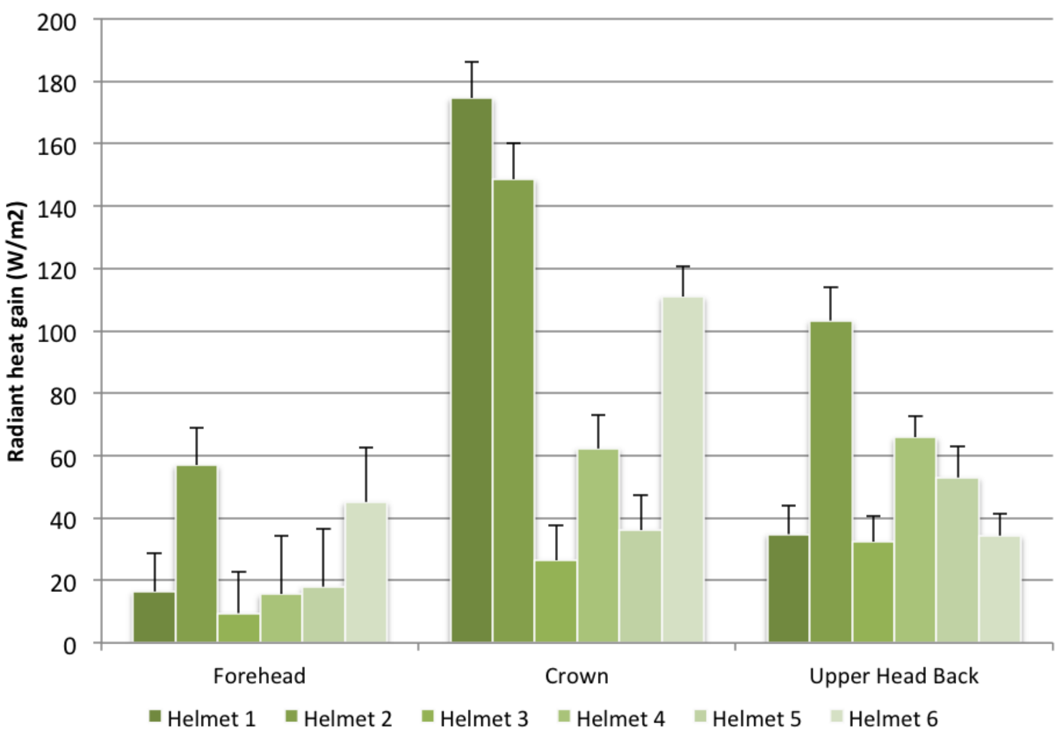

Figure 5. Radiant heat gain by individual zones.

1.4. Conclusions

1.4.1. Convective and global heat losses

Helmet configurations provided differences in total convective heat losses (Table 1). Helmet 2 provided the highest convective heat loss at head site on average. This is 6% higher than observed for helmet 1). By adding coverings to helmet 2, convective heat losses decreased to 87±1% for closed coverings (helmets 3, 4 and 5) but just to 92% for the covering with partial closing at the front (helmet 6).

In case of adding radiation, the amount of radiation rejected by a close covering produced a slight improve in the relative total global heat losses (convection and radiation) (helmets with close covering account not with 87% of the cooling regarding to helmet 2 but with the 89% on average for helmets 3, 4 and 5).

Looking at the convective heat losses of the individual zones (Figure 3 and Figure 4), helmet 2 showed improved heat losses with regards to helmet 1 mainly in the forehead, the crown and the upper and lower head part. Configurations including closed coverings (helmet 3, 4 and 5) resulted in similar convective heat losses at the following zones: forehead, left and right temples, crown and upper and lower head. For the covering with big vents on the top (partially closed, helmet 6), cooling at the forehead and the crown decreased by 20% regarding to helmet 2.

1.4.2. Radiant heat gain

The highest total radiant heat gain was found for helmet 2 (see Table 1 and Figure 5). The total radiant heat gain observed for helmet 1 was 61% compared to helmet 2. The addition of the different coverings further reduced the amount of radiant heat gain for most coverings. For helmet 4, total radiant heat gain was reduced to 75% of total radiant heat gain observed helmet 2.

The crown gained the highest amount of radiant heat. For this zone, helmet 2 showed better protective properties compared to helmet 1 (17% more radiative heat gain than helmet 2). The application of a covering reduces the radiant heat gain in the crown by different rates. Helmet 3 resulted in a radiant heat gain of only 18% related to helmet 2. The closed chrome coverings (helmets 4 and 5, irrespective of closed or open small vents) revealed a radiant heat gain of 24% and 42% of helmet 2. Helmet 6 provided less protection in case of the crown area (75% of helmet 2) than any other closed covering.

The results show that a bicycle helmet can locally enhance the heat loss on the head while riding in the sun with more than 800%. The use of chrome and blocking vents in case of solar radiation on top of a helmet, did not improve the cooling efficiency of the tested helmets.

IV. Innovative Helmet Designs

1. Better bicycle helmets for commuters: design solutions for ventilation

K. Kuklane, H. Aljaste, S. S. Heidmets

1.1.Background

The number of adult bicycle helmet users in Sweden has stayed over the years relatively stable around 20 % (Larsson, 2009). In Europe the number of helmet users varies between 1 and 40 % depending on country. Research has shown that the use of helmet considerably diminishes head injuries in the case of traffic accidents (Otte et al., 2008). In spite of that it is not fully clear what are the main factors why only a small number of bicyclists use a helmet.

Why helmet use is not popular? Several reasons could be pointed out: design, destroys the hair style, attitudes against helmet use, nowhere to put, too warm etc. Sweating, i.e. heat issues have been shown to stand for 57 % of complaints related to helmet use (Otte et al., 2014). Often the initial complaints are related to heat (Abeysekera and Shahnavaz, 1990). In cold additional insulation from the helmet may be a positive factor while compatibility issues with other clothing or items may rise.

As the professional bicyclists and most training/competing amateurs do wear the helmets then the aim for traffic safety should be increasing helmet use among commuters and bicyclists who do it just for fun. Therefore a project was initiated where main aim was to reduce initial thermal disturbance from a bicycle helmet while keeping in mind visibility, protection aspects, look, and issues related to wearing comfort etc. The work aimed for testing and comparing various design solutions that may lead to good helmet ventilation for commuters (Aljaste et al., 2014; Aljaste et al., 2015; Kuklane et al., 2013; Kuklane et al., 2015). Therefore, in order to promote creativity and avoid the helmets look like the one in supervisors mind, then the participating students were encouraged for wide freedom of action.

1.1.1. Important considerations

Openings

Ventilation allows increasing heat loss by convection and evaporation. If convection in hot conditions becomes negligible or even adds to heat gain then the only mean of heat loss will be evaporation. The best ventilation of the head is provided when there is no helmet on the head until you need it. Airbag based, "invisible" helmet (Haupt and Alstin, 2013) allows best ventilation, and certainly avoids issues related to hair style or improves fit with clothing. Simultaneously, it is known that headgear reduces solar load on the head (Bogerd et al. 2008), and therefore, covering the head may be an advantage in hot climates. Another aspect is the perceived safety of the helmet uses. Considering this the present work focused on "visible" helmets.

In order to allow ventilation over the head surface there should be openings available that allow air to enter the helmet. However, when the air can't exit then practically nothing can enter either. Outlet openings should be available, and so should the channels that connect inlet and outlet openings. The inlet openings should be designed to allow maximal air flow into the helmet (high air pressure in front). The outlet openings should allow maximal suction effect in the rear (low air pressure). Simultaneously, the protection properties of the helmet should not suffer from too large openings at most common impact surfaces (rear and front). Inlet openings at various distances from front should not be easily connected to each other – the air uses easiest way to leave the helmet if there is any pressure difference, and does not take a long way (= higher resistance) to pass over the head surface to rear. Similar is valid for outlet openings in the rear. Therefore wrongly placed openings may not improve ventilation (Liu and Holmér, 1997), and bigger openings may not lead to better cooling effect (Brühwiler et al., 2006; De Bruyne et al., 2012).

Placement of openings should consider helmet tilt (Brühwiler et al., 2004). This does depend not only on head position but also on bicyclist position on the bicycle. Latter will be affected by bicycle design, e.g. racing bikes, mountain bike and city bike. Mountain bikes are relatively popular in cities, and especially in young, active population. Both racing and mountain bikes do assume stronger tilt due to low position of handlebars. Large number of cyclist use classical or city bikes where posture is more upright. In city, where it is important to have a good overview of traffic and not only the track in front, the head position can be expected to be more upright.

Bicycling velocity

Tilt will also be affected by bicycling velocity. Higher speed leads to stronger tilt and lower one to more upright position of the body and the head. The bicycling velocities, and thus, air speed around a bicyclist can be estimated (Trafik i stan, 2013; Wikipedia, 2013):

1) 0.15 m/s – windstill condition, standing bicyclist with natural convection;
2) 1 m/s (3.5 km/h) – common air velocity under a calm day and quiet walking velocity;
3) 2.8 m/s (10 km/h) – relatively slow speed in the city;
4) 4.2-5.6 m/s (15-20 km/h) – average speed in the city;
5) 6.9 m/s (25 km/h) – quick city bicycling and average speed under long distance competitions (≈1000 km);
6) 11.6 m/s (42 km/h) – average speed under shorter distance competitions (≈120 km).

Bicycling velocity will be strongly affected by traffic situation and availability of bicycle routs. Even if maximum velocity may reach over 25 km/h the average can seldom be much above. Considering rush hours 15-20 km/h is more realistic. Bicycling at lower average velocity than that does not increase the heat generation by exercising body much more than walking. At such low speed it may be difficult to force air into the helmet anyway. If professional bicyclists often have short hair then average commuting population does not need to share that hair style, and the effect of hair needs to be considered when designing a helmet for them. Thus, a helmet for commuters needs to ventilate best in a speed interval of 15-20 km/h at the presence of hair.

The design of commuters' helmet does not need to depend on possible effects of additional air resistance from the openings and their design. It is not meant to be a competition helmet where hundredth of a second may decide a winner. Providing thermal comfort at common commuting velocities is of much higher priority.

Other factors to be considered

Impact protection is the main reason for using helmets. Any ventilation solution should not affect the protective performance of the helmet. Hygienic needs, e.g. cleaning, could be kept in mind, while at this stage these were of lower importance.

Visibility in the traffic is an important parameter to avoid collisions. The lights on the bicycle should be functional in the dusk and darkness. However, in all times the helmet could be used to make the bicyclist visible. In the tight traffic the head may be an only body part that could be seen by drivers. The choice of colours and patterns should consider the contrast with the background (Figure 1) (Gershon et al., 2012).

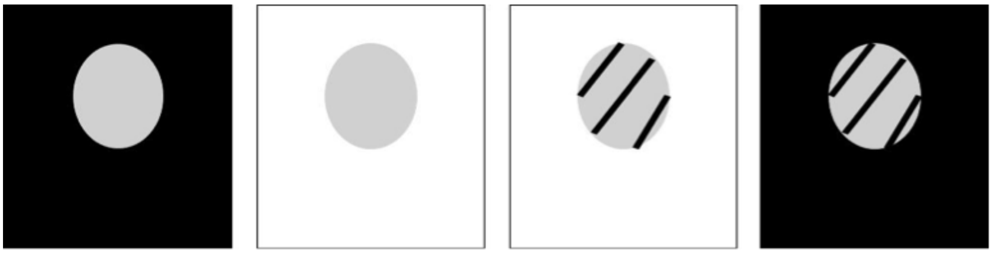

Figure 1. Object discrimination on different backgrounds.

Traditional, natural (Liu and Holmér, 1995) and modern (Kuklane et al., 2006) materials or their combinations could be used to make a helmet prototype. No manufacturing constraints were to be considered. The major requirement for the work presented here was good ventilation performance (final prototypes were tested on thermal head model). Also, an obvious decrease in protective performance was not expected to be present, however, in the following stages the best design solutions for ventilation could be checked and improved for impact protection, and tested.

Defining a user group for helmets was an important step that allowed defining design requirements. Background on the possible ventilation outcome depending on specification of openings in the helmet and air velocity around the users were considered essential start points for designing a thermally comfortable bicycle helmet. The aim was set to improve the thermal properties and ventilation of the helmets, specifically, for various groups of commuters and people who bicycle just for fun.

1.2. Methods

1.2.1. Design process

The basic inputs to start up the design process were covered in the background section. The introductory lectures were given at the Department of Design Sciences, Lund University, Lund, Sweden and at the Department of Product Design, Estonian Academy of Arts, Tallinn, Estonia. There were no students from Lund who picked bicycle helmet as their project topic while 15 students from Bachelor 3rd year, Master 1st and 2nd year in Tallinn followed the whole way (Figure 2).

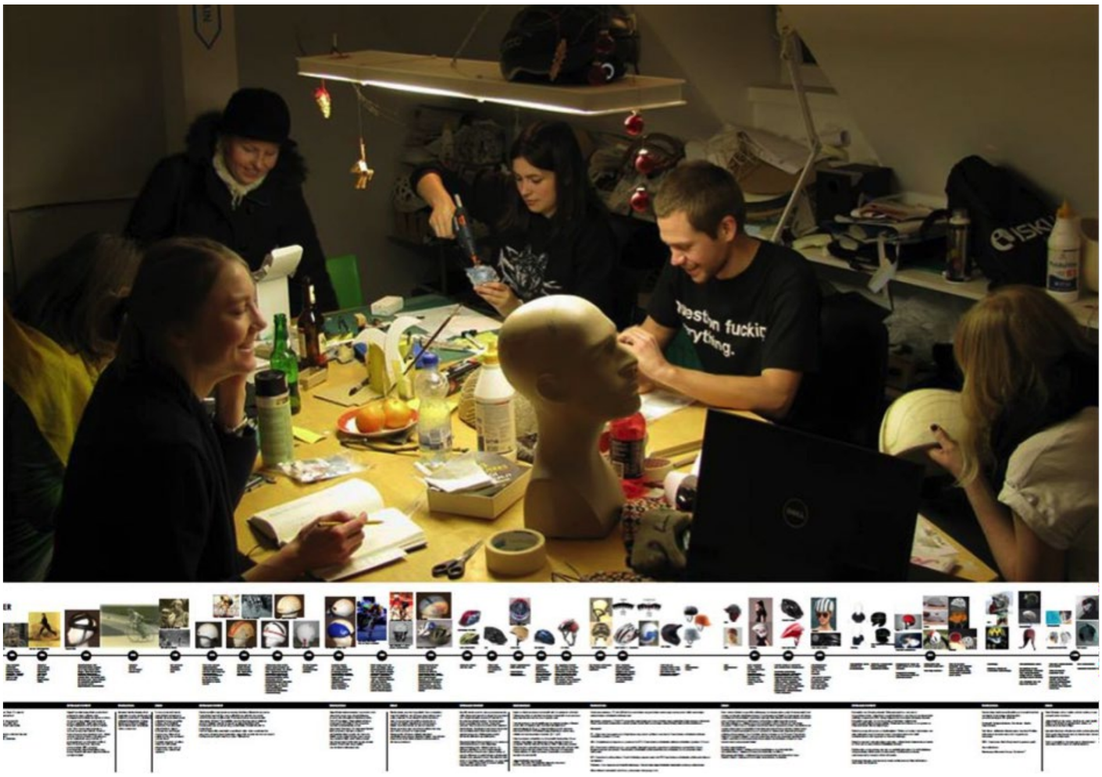

Figure 2. Students working with the project with a section of their summary of helmet development history and variation below that formed the basis for further work.

The work continued with the development of 15 full scale helmet mock-ups (Figure 3). In order to encourage the creativity for ventilation and allow the comparison of large variety of solutions the students were not restricted to consider the other properties except it was stressed that the mean-ing of helmets' use is protection. Design aspects should not compromise protective properties, but improve the look, heat dissipation, visibility and issues related to wearing comfort. Thus, the main objective of this task was to create a user friendly bicycle helmet that would not be rejected for perceived heat sensation. By improving the bicycle helmet design we may allow increasing the number of cyclists who regularly use the helmet. Improving traffic safety under bicycling is an important area, especially, considering the possible increase of bicycling as a sustainable mean of transport. As a summary, the major objective of the exercise was to come out with bicycle helmet solutions at the level of testable mock-ups. The way to solve this was by designing for cooling properties of the helmets through enhanced ventilation. The target groups were the commuters and people who bicycle just for fun. TK was prepared as a flexible helmet for racing and ventilation, thus, TKo is TK set on head rear to front (Figure 3). Design solutions could be divided into 2 segments: ones with air tunnels and the others with airy surface. The specific stages of this work are not covered in this report.

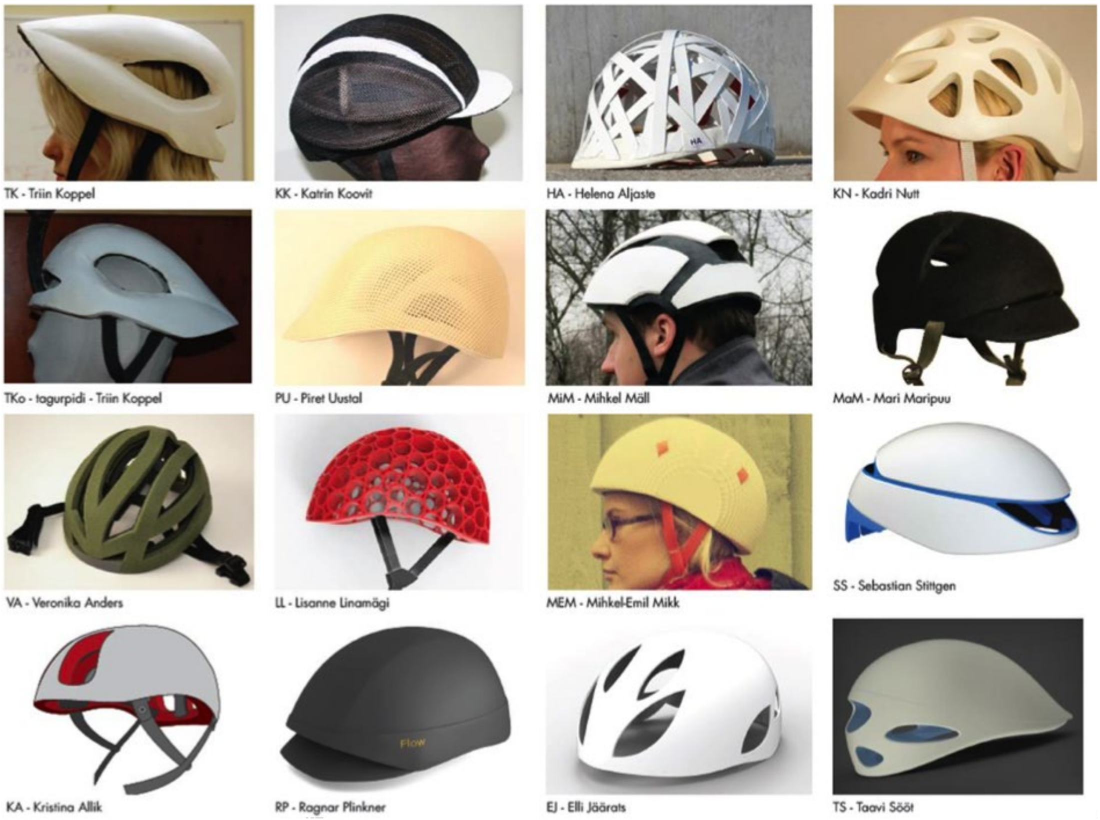

Figure 3. The tested helmets with codes and authors' names.

1.2.2. Insulation testing

The 1:1 scaled bicycle helmet mock-ups (Figure 3) were tested at the Thermal Environment Laboratory, Lund University for their dry heat transfer characteristics (insulation) in a wind tunnel on a thermal head manikin (Figures 4 and 5, Liu and Holmér, 1997). In addition, 3 helmets, one of the best, one average and one of the less well performing helmets, tested in a previous study (H5, H17, H20 of Brühwiler et al., 2006), and a common bicycle helmet available on the market (Etto) were tested in some conditions for comparison (Figure 4). As a reference point, a head model without any helmet was tested in the selected conditions (Figure 4).

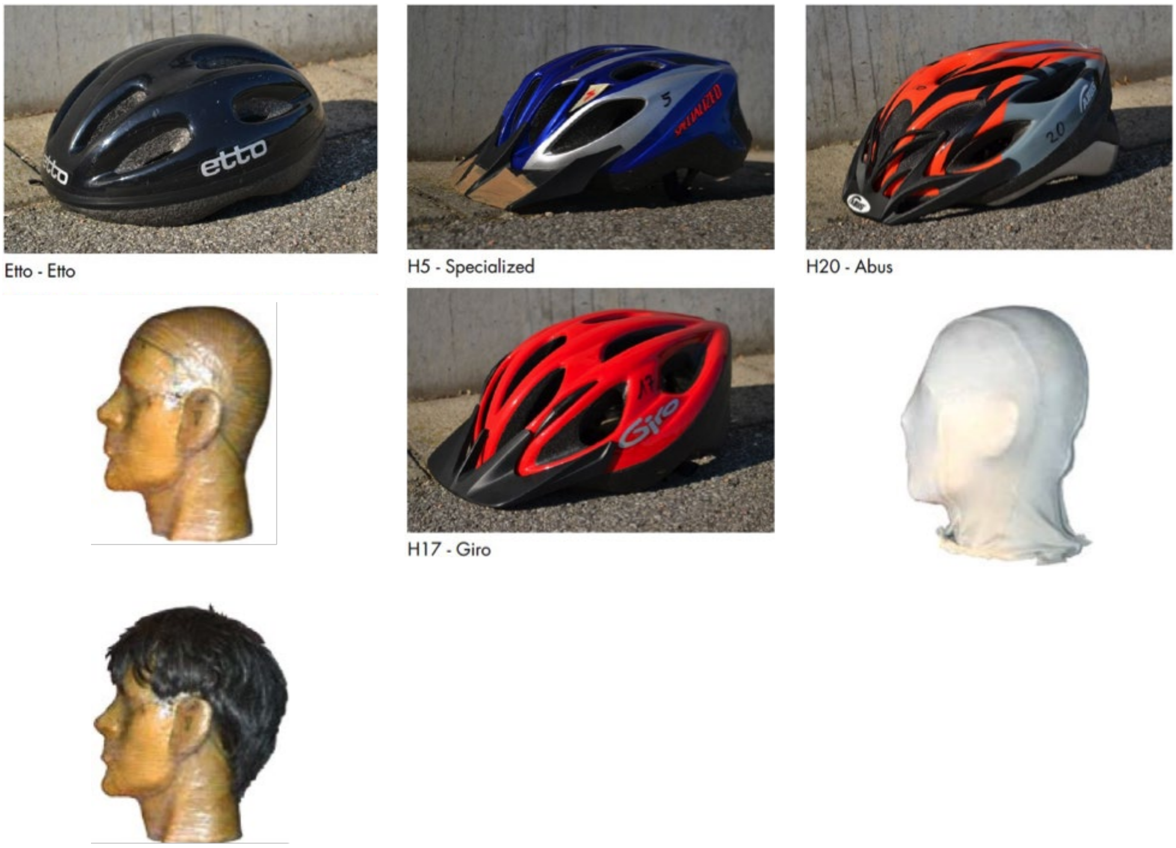

Figure 4. The tested helmets available on the market, and the head model as it is, with a wig and with a tex-tile “skin” for “sweating” tests.

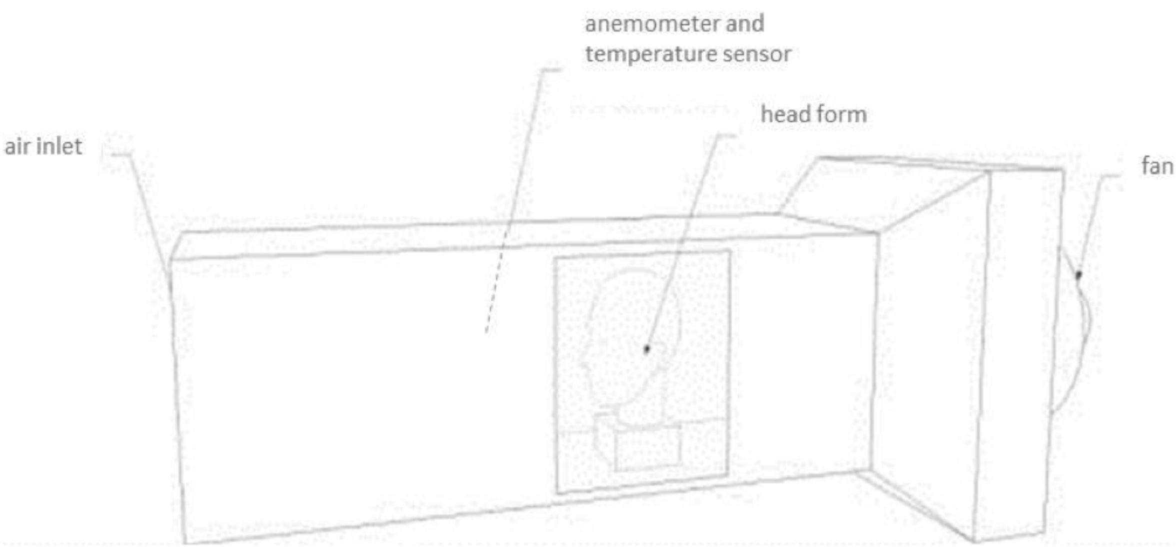

Figure 5. The measuring setup in wind tunnel. Air inlet was filled with 16 mm diameter and 50 cm long plastic tubes and fan was set on sucking air. Air velocity and temperature sensor was placed 30 cm in front of the head form.

The head form (Figure 4) consisted of six measurements sections: face, forehead, skull, neck, left and right ear. The head form was heated to a constant surface temperature of 34 °C, and placed upright (0° tilt angle) into the wind tunnel at room temperature (Figure 5). Air velocity was set to 3 levels. 0.2 m/s was resembling a standing person; 1.6 m/s as bicycling with pedestrian speed (about 6 km/h) with and without hair (a wig); 6.0 m/s as speedy bicycling (about 22 km/h) with a wig.

Each test lasted for at least 70 minutes. After choosing the air velocity and donning the helmet, the situation was allowed to settle. Stabilization time was about 40 minutes. The last 20 minutes of the stable state were used to record an average heating power to each section, and calculate insulation. More ventilation would lead to lower insulation and better head cooling, and vice versa. Forehead, skull and total insulation were selected for comparison.

The work was continued by modification of some mock-ups according to new ideas, in order to see if any change would improve or lower the performance (see section *Modifications of design helmets*). As sweating is a natural way of human temperature regulation then evaporation tests were needed.

1.2.3. Evaporative resistance testing

General settings and the helmets (Figure 3) were the same as for insulation tests; however, in this case the thermal testing conditions were different. The helmets were tested in the wind tunnel placed in a climatic chamber at 34°C and 40 % relative humidity (water vapour pressure in the air 2200 Pa) with the air velocities set to 1.6 m/s (≈6 km/h). Tests were performed on the head model without a wig only. Evaporative resistance was calculated from heat loss corrected for the difference in head surface to textile skin temperature (Wang et al. 2010). One (TK) of the 15 mock-ups was test-ed back to front, too (TKo). Furthermore, four commercially available helmets were included in the tests as well.

Figure 6. Some modifications of the design helmets ("n" means new solution of a helmet).

1.2.4. Modifications of design helmets

Based on the insulation and evaporative resistance test results, and observed high dependence of "the best" helmet on test conditions it was decided to modify certain solutions and retest them. The discussed modifications were to:

1) lift helmet with additional paddings higher from the head surface so that the channels were formed (MaM);
2) create edges at the openings in order to direct more air into the helmet (EJ);
3) break loose separated cells inside the helmet's supportive structure in order to allow air flowing over the head area (PU);
4) open or close some of the openings in order to observe the effect of the modification in comparison to the original design (RP).

Some of these modifications are shown in Figure 6. Modifications were marked with letter "n" – new. One helmet (PU) was changed several times (channels made deeper), and in the results are these ones marked with "n", "nn" or "nc". The retests for insulation were carried out without a wig at 1.6 m/s, with wig at 6 m/s and for evaporative resistance without a wig at 1.6 m/s. the procedures fol-lowed the ones described in the previous sections (*Insulation testing* and *Evaporative resistance testing*). A few additional helmets were modified for the comparison with special test prototypes that were created to study the effect of air channel construction and design elements on ventilation that is described in the next section.

1.2.5. Effects of Air Channel Construction and Design Elements

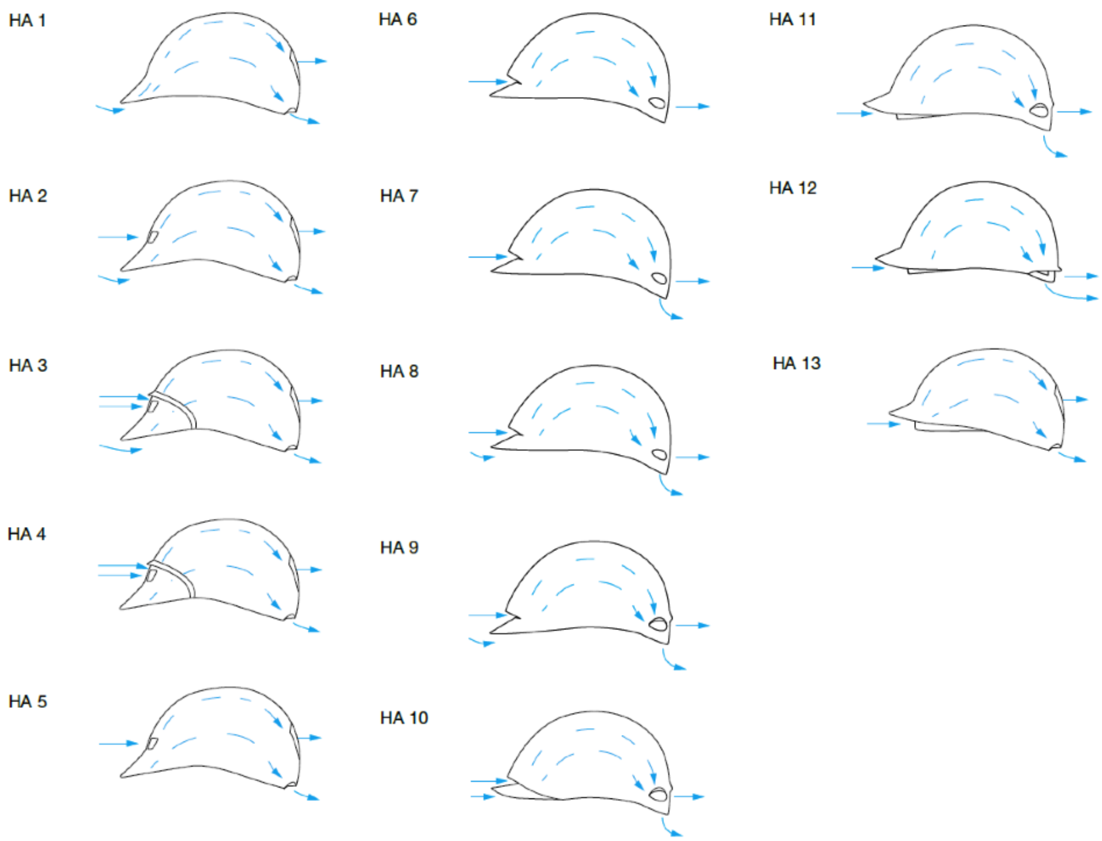

Figure 7. The alternative modifications of the design helmets with arrows showing the inlet and outlet locations and the expected flow paths.

The activities and results described here are a continuation of the above described research as a separate MSc. level thesis work by Helena Aljaste under supervision of Sixten Heidmets and Kalev Kuklane. It was a good opportunity to merge design process and evidence based studies. At the moment the work is on-going and the conclusions are not final at the moment of this report writing (August, 2015).

Two basic but in principle similar helmet mock-ups were prepared under the design process. These mock-ups were alternately tested and modified. Tests followed the conditions and procedures described in the previous sections. In addition, evaporative resistance was tested even with the wig. Due to the time limit all helmet modifications and reference helmets were not tested in all conditions. Also, some solutions were skipped on the way as no anticipated improvements were observed under the "test-modify-test" process. The tested alternatives differed by air inlet and outlet positions, their size and shape, and number of air channels, their cross section and position. Figure 7 shows the alternatives of the design helmets with arrows showing the inlet and outlet locations and the expected flow paths. In total there was 2 helmets from the market tested for reference, 4 selected helmet mock-ups from previous study and 2 new concept mock-ups with 13 modifications all together. Figure

7 shows the alternatives of the design helmets with arrows showing the inlet and outlet locations and the expected flow paths. The tested reference helmets were: Etto, H5, LLn (modified LL in 3D), PUn3 (last modification of PU), RP, SSn (SS with additional material reducing inlet and outlet size, see Figures 3, 4 and 6).

1.3. Results

1.3.1. Insulation testing

It is clear that if at the project start very high safety requirements would have been set, then the creativity on ventilation solutions might have been negatively affected. There would have been much less chances to find out how various factors work, how they interact and which ones are relevant. Forehead, skull and total insulation (m²°C/W) are compared in Figures 8-11. The results in the diagrams were sorted by skull insulation in ascending order.

The experimental condition with wind speed of 0.2 m/s represents a worst case scenario for heat dissipation, and is comparable with the situation of cyclists just standing (Figure 8), while in practice under such situation there would be present only minimal heat generation in the body. The helmets were put on the bald head. The best results were acquired from helmets KN, HA and TK, because of their airy structure and less contact area with head. The warmest helmets in this section were Etto and TS. These helmets covered the large part of the head, and the air channels did not work with the low air velocity.

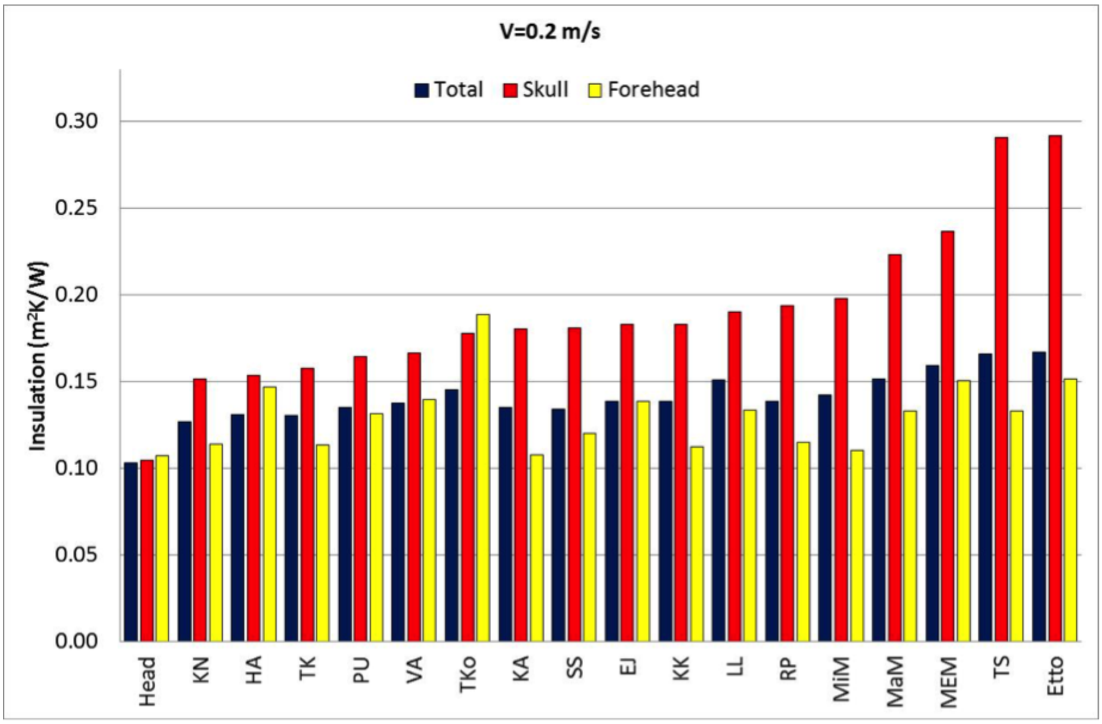

Figure 8. Helmets' insulations without a wig at air velocity of 0.2 m/s.

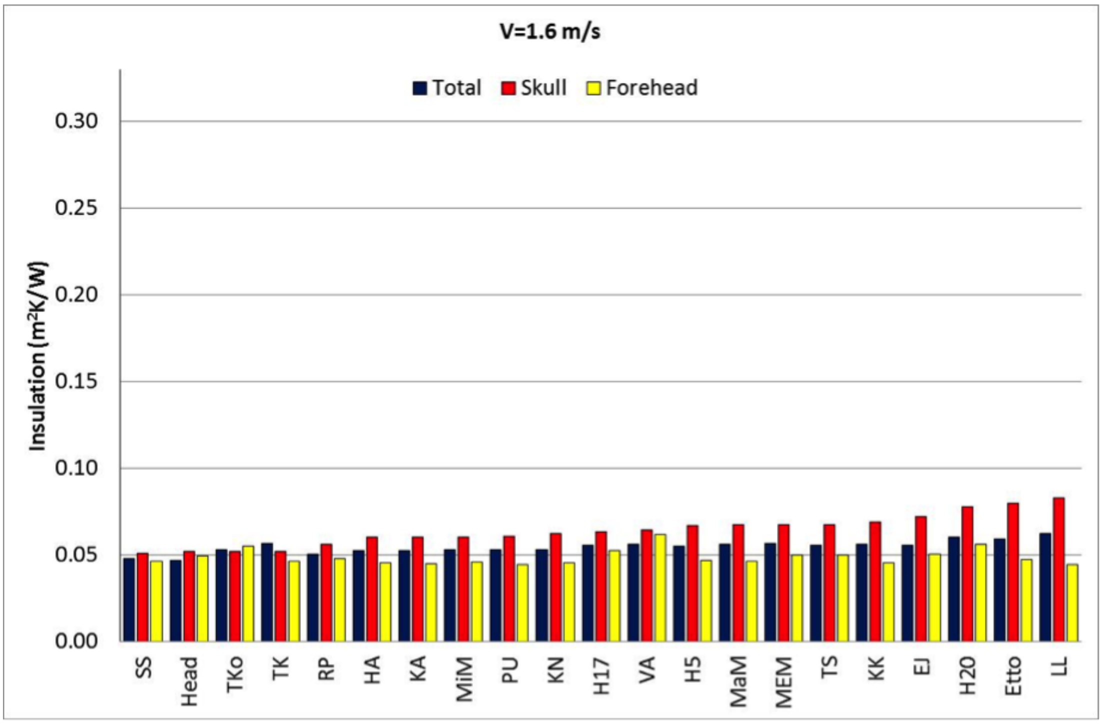

Figure 9. Helmets' insulations without a wig at air velocity of 1.6 m/s.

The air velocity of 1.6 m/s (6 km/h) is comparable with the speed of fast walking pedestrian (Figure 9). Helmets were donned on a bald head. The best helmets with this wind speed were SS and TK. The latter was tested in 2 positions - both front and rear side forward. All 3 helmet solutions had the largest vents, therefore the air flow was able to cool the head. Also, there was no hair to fill the vents. SS performed even better than the nude head. This could be related to forcing the air stream into the helmet and over the head surface. Three warmest bicycle helmets were LL, Etto and H20. It should be noted that more than half of the design helmets performed better than one of the best of the earlier study (H17, Brühwiler et al., 2006), although, the differences were not very big within this condition.

Figure 10 depicts also the results with air velocity of 1.6 m/s. This time a wig was donned on the head model in order to study the effect of hair. As expected the wig increased insulation. This time the best ventilation results were observed in TK and RP. TK was most probably showing a good performance because it's zigzag structure and open front which, however, became problematic with stronger wind. The RP helmet inner structure was designed to compress the hair down so the upper air channels stayed open. The poorest performance was observed in Etto and MaM.

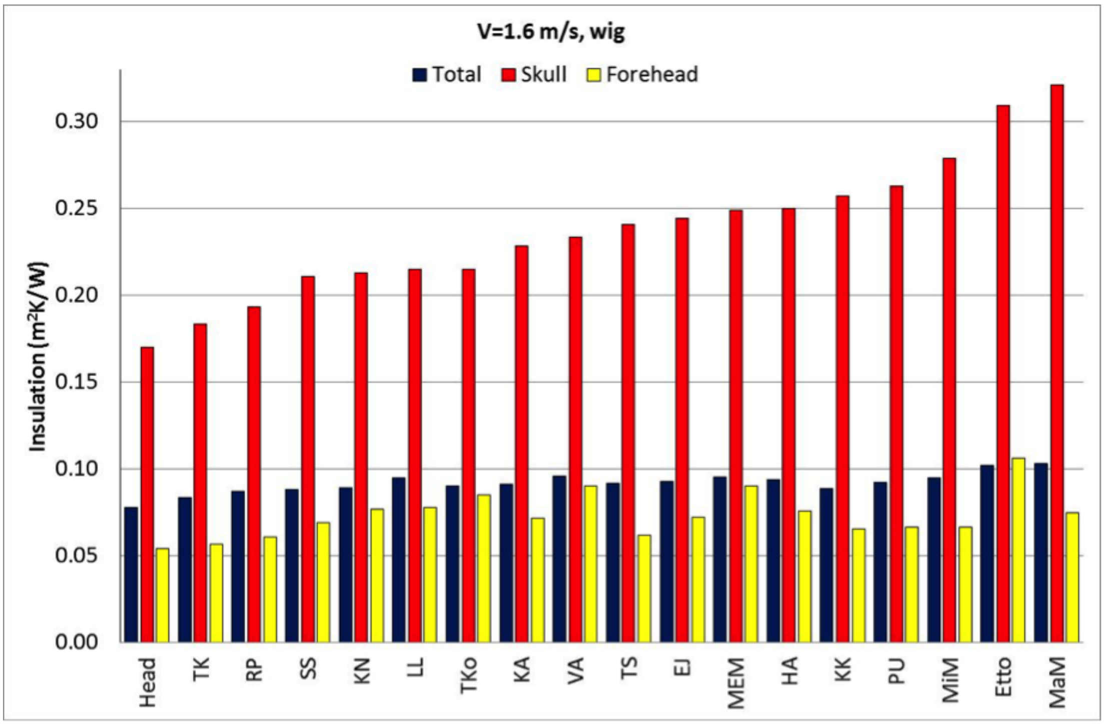

Figure 10. Helmets' insulations with a wig at air velocity of 1.6 m/s.

Wind speed of 6.0 m/s is the condition of cyclist riding at about 22 km/h speed (Figure 11). The head form had a wig. With this air velocity it was shown that less but strategic openings and systems with clear air channels were superior to the other solutions. The best bicycle helmet in this test was RP. This fully covering shell type helmet forced air to enter from the visor area in the front to cool the head. Good results were shown also by TK, but it may be related to weak positioning on the head, and should be improved with a proper system to fix it on the head. It fell backwards a couple of times during the experiment. The same helmets as with 1.6 m/s and wig condition had the lowest performance even with 6 m/s wind.

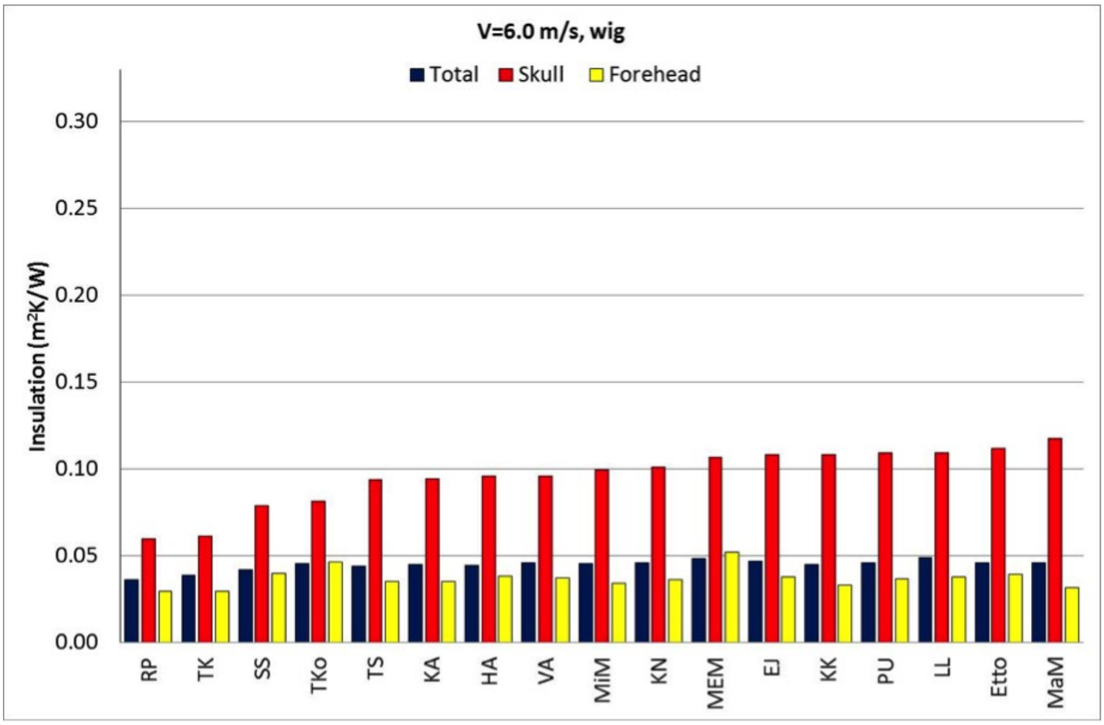

Figure 11. Helmets' insulations with a wig at air velocity of 6.0 m/s.

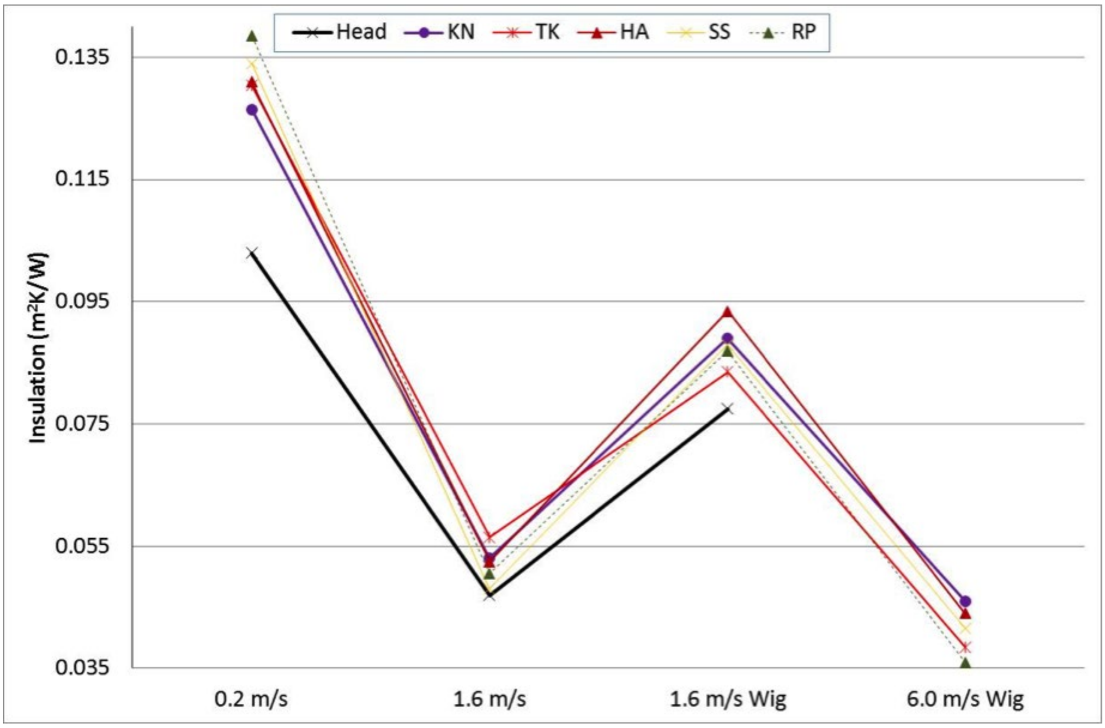

Figure 12. The changes of insulation in under specific conditions for the best ventilating helmets.

TS, which was the warmest with low wind, worked better with substantial wind. This could be related to that the air channels started working. On the other hand, PU helmet was much warmer with a wig and even stronger winds did not improve the results. The warmest in this experiment was MaM. MaM has vents that should guide air to enter, but the tight fit of the helmet did not leave any room for air flow.

Figure 12 summarizes the main findings of the study by comparing the best helmets of various conditions and reference condition of the bald head. It is clear that different helmets perform best in specific conditions. It means that selection of proper helmet needs to consider bicycling velocity and haircut. The reported tests in Figure 12 did not include any sweating simulation. The variation of performance did widen when this aspect was tested.

1.3.2. Evaporative resistance testing

As in the insulation tests so even in evaporative resistance tests of the helmets the prototypes dif-fered to great extent (Figure 13) and so did their behaviour. The order of the helmets in the "best function line" for evaporation was different from their insulation performance, as reported previous-ly (compare with Figures 8- 12).

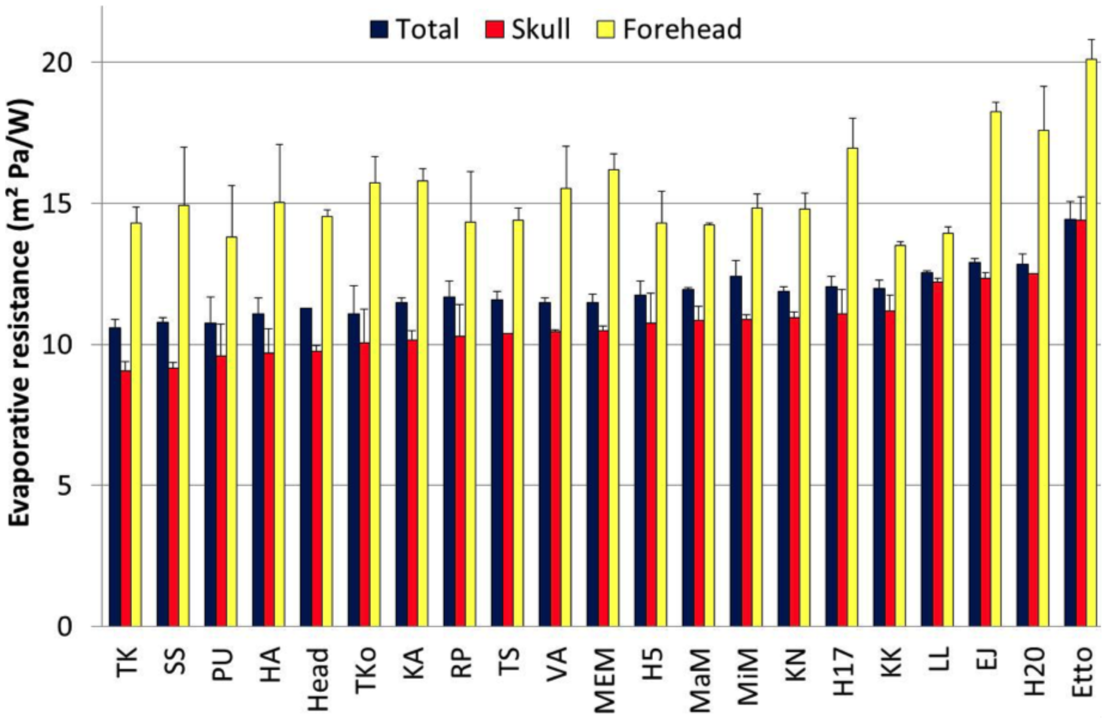

Figure 13. Helmets' evaporative resistances without a wig at air velocity of 1.6 m/s.

The best reference helmet from the earlier study (Brühwiler et al. 2006) stayed approxi-mately in the middle of the tested range while the poorest reference helmet was in the end of the line with an of-ten used one as the worst (Figure 13). Thus, in this test series the newer solutions performed much better from an evaporation viewpoint than commercially available helmets.

1.4. Modifications of the design helmets

From modifications we could learn if a solution improves or lowers the performance or if the combination effect would be marginal, and in which specific cases. In order to compare the insulation and evaporative resistance changes and the helmets' positioning on the "worst-to-best" performance line then in following figures the all previous results are redrawn (Figures 14-16).

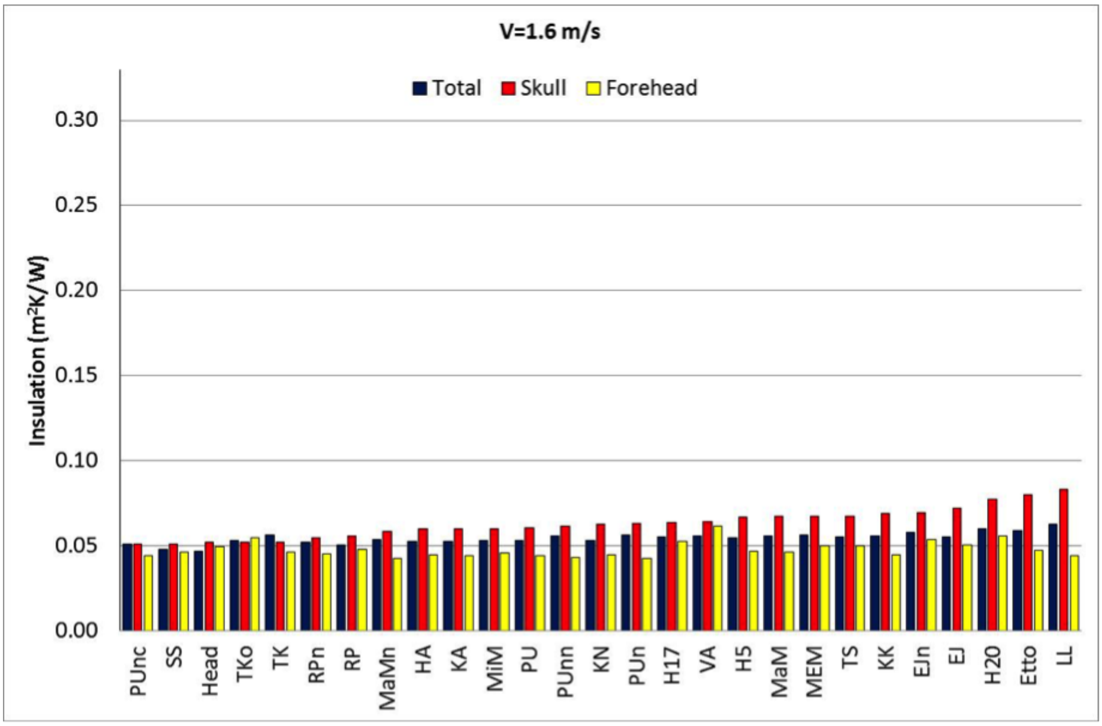

Figure 14. Helmets' insulation without a wig at air velocity of 1.6 m/s. Modified mock-ups are included.

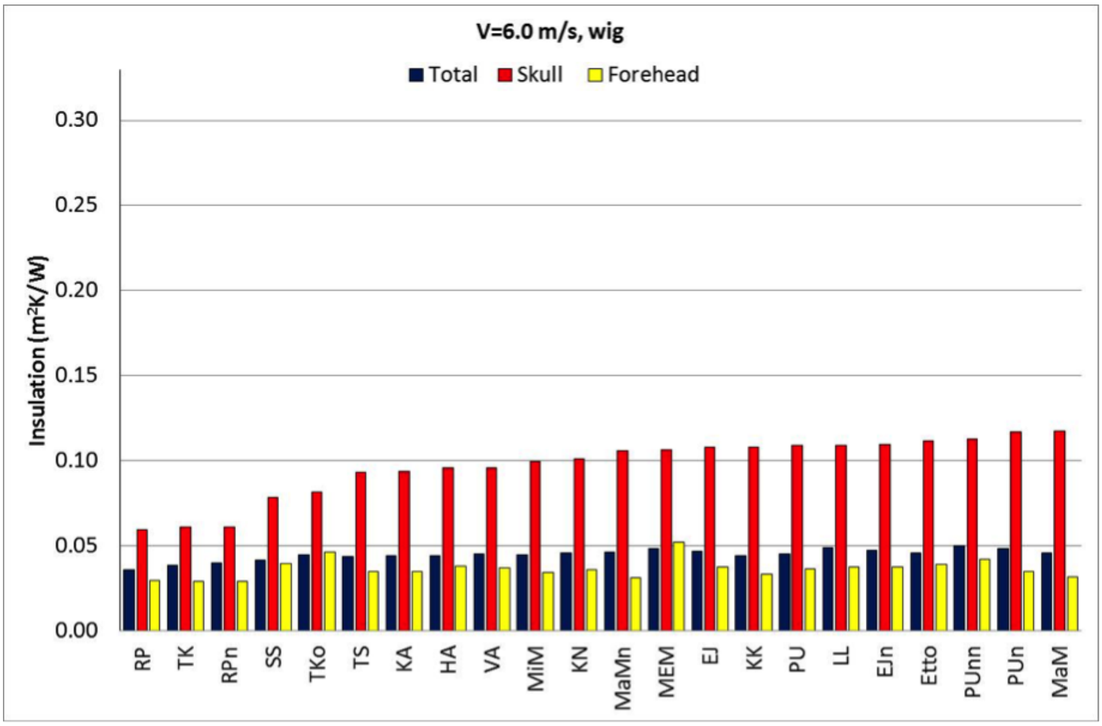

Figure 15. Helmets' insulation with a wig at air velocity of 6 m/s. Modified mock-ups are included.

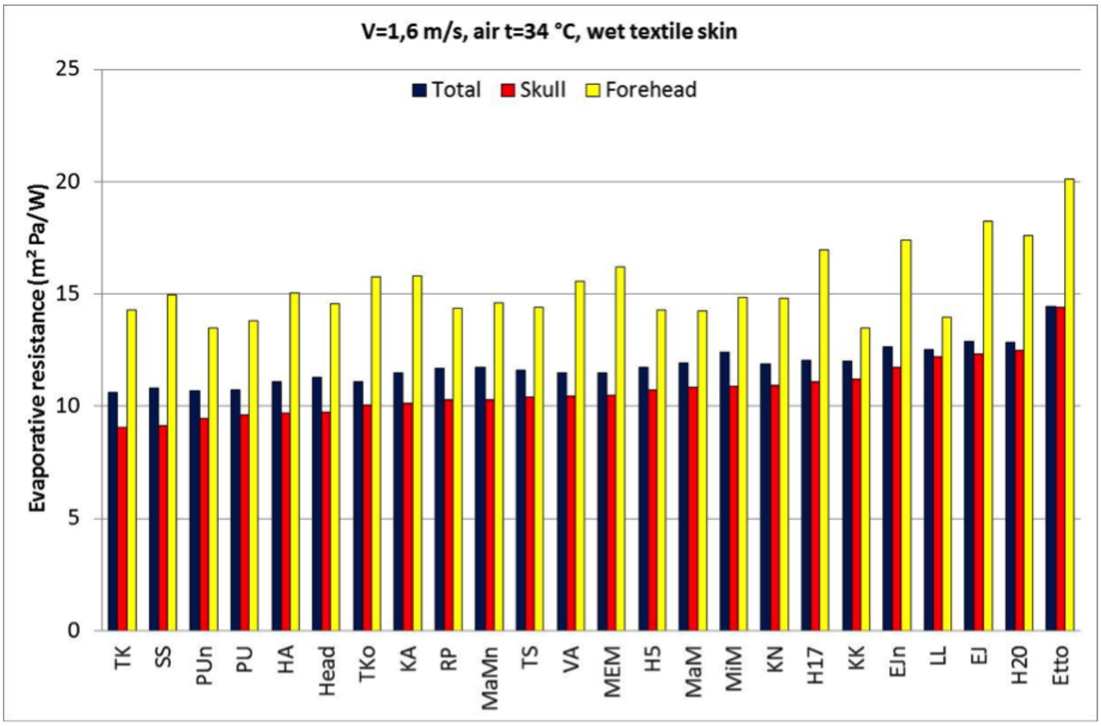

Figure 16. Helmets' evaporative resistances without a wig at air velocity of 1.6 m/s. Modified mock-ups are included.

As noticed before on original helmets that different conditions may affect solutions differently so happened also with the modifications. The biggest positive effect in all conditions was noted for MaM-MaMn (Figures 14-16). Creating channels and possibilities for the air to flow in helmets im-proves the ventilation. Referring also to the helmets RP and SS, and earlier studies (Brühwiler et al., 2006; De Bruyne et al., 2012; Liu and Holmér, 1997) it is clear that many holes do not always help – proper inlet and outlet with connecting channels seems to be a winning solution.

Modification of air inlets with design elements in the case of EJ – EJn gave a marginal effect. At lower air velocities without wig (Figures 14 and 16) the performance improved (increased heat loss) somewhat while at high air velocities with wig the performance dropped (Figure 15). Similar minor effect was observed also with RP – RPn insulation (Figures 14 and 15). Closing the additional opening on the top of the visor had no much effect if the major air flow was allowed in under the visor. The effects of visor have been studied earlier (Bogerd et al., 2008, Brühwiler, 2008, Brühwiler, 2009) but there seems to be space for more applied research on them.

In the case of PU – PUn – PUnn – PUnc with creating channels the changes could be as complicated. In some cases the performance was improved, in the others decreased. The last version (PUnc) with adding even the channels in the peak/under the visor the effect was enormously improved. Most interesting in the case of this helmet was a considerable change of positioning from medium-poor under dry to one of the best under wet tests (Figures 14-16). That leads to a need for a further evaluation on if one helmet works well (read: regulates) in cool (no sweating) and hot conditions (sweating). Also, the very poor performance with wig in dry conditions should be further evaluated under wet conditions with a wig (see next section).

Finally, as a summary of all dry and wet tests on this project's modified and non-modified helmets it can be said that depending on factors some helmets may position better or worse on the ranking scales but there are also these that keep their position. Some changes are positive for certain user situations and some do not make the user happy. Knowing the performance variation and the cause of the change allows designing for specific purpose. Also, this does indicate that the helmet must be chosen in relation to the intended conditions of use, i.e. cycling velocity, weather, amount of hair etc. In order to support any improvements the specific comments on each solution are given below. These cover even the suggestions related to impact testing etc. based on the feedback from various COST Action group members.

EJ: A helmet with very neat design that did not perform the best. With no hair it was one of the last for ventilation while with wig it improved the position to some extent but not above the average. The modification (additional elements directing the air into the helmet) did not help much (1.6 m/s dry and wet, no hair) or even deteriorated the performance (6 m/s and wig). This could be related to very good aerodynamic shape (air did not pass well into the helmet) or to too deep channels inside the helmet (air passed just under the helmet shell and nothing forced it towards the head surface). The failure of the modifications does support the latter case. In this case, a small bump on the shell surface in the helmet some cm into each air channel might redirect the flow and improve the results. This needs to be tested. The two largest front inlets of the helmet may be somewhat too large for the impact test. To keep the pattern an ornament or wall from corner to corner in the resembling of a leaf/skeleton leaf or flame could be applied.

HA: One of the best in calm condition but losing the position with medium air flow and wig and regaining it again with high air flow and certainly when sweating occurs. Eventually, it might need some additional bands to cover bigger openings and fixing band around the edge, and it would be interested to see its behaviour under the impact testing.

KA: A helmet that stays stable in its position through all test conditions. It has better cooling performance than an average helmet and leaves behind the best helmets tested by Brühwiler et al. (2006). No specific changes can be recommended from this point of view. On the strength side the openings in the front and in the rear may be needed to be split to avoid anvil pass during impact test. In this case the air channels may need to be adjusted and the ventilation should be retested.

KK: It was expected a better performance, but it behaved similar to a medium good helmet from Brühwiler et al. (2006) and positioned in the middle of the second half of the present design helmet series. Although, it did utilize the air permeable textile it did not function in this way. The reason could be the flexibility of the textile that under wind pressure might have taken the aerodynamic shape and allowed air motion over the helmet in the easiest way. That does lead the thoughts towards new textile materials with adjustable rigidity – for competition cases it requires less resistance and better aerodynamics from helmet adjustment while when bicycling for fun and enjoying cooling it may be rigid (comparable with PU). The underlying structure may need to contain more ribs to pass impact testing.

KN: The best helmet in calm condition and about medium in all other conditions still beating the best commercial ones of Brühwiler et al. (2006). Adding padding to lift it higher from the head surface may (see MaM) or may not (see PU) improve the performance. Only modification and testing may give the answer. The size of the openings and their depth is probably no issue for impact testing, however, it can be checked and hole size slightly modified.

LL: 3D printed helmet showing the near-future possibility of customisation of the production. It would allow ordering 3D drawings according to own head size (3D scanning), and then printing it out at home or special printing workshops. In the case of such helmet new 3D printing materials would be needed that can print part of the product in softer, flexible, more rubberlike material on inner side and then adding rigidity towards outer surface. Unluckily, under the tests the preparations for 3D printing and corrections of the file took too long, so that all tests could not be performed on hard version, and the paper model was not enough stable so only a few conditions could be tested and no modifications could be made. The helmet did position on the side with the poorest ventilation performance. Partly, it could be related to a net-textile that was placed inside the helmet for support, and did not allow the air to pass through the openings. It was the last with no wig at 1.6 m/s, while its position improved somewhat with higher air velocity and hair, and in wet tests. It may be expected that if applying buds, or padding or raising some inner (rubbery) surfaces along air flow line then the performance does improve considerably (this proved true under the additional tests described in the next section). With impact testing, especially, if material flexibility along its thickness can be varied, it is not expected to be a problem. As the spacing and size of the helmet "bubbles" is enough small then the anvil is most probably not reaching the head areas under the helmet.

MaM: A stylish helmet that probably has no impact testing issues. Possibly 1-2 vertical bars could be added to the rear opening. However, the ventilation was very poor, especially, when tested with a wig. Evaporation of moisture helped to improve the performance to some extent. Problem was that it did sit flat tight on the head. Adding some padding in the shape of air channels improved the cooling performance considerably above the average level. Eventually an inner layer with plastic buds would function, too.

MEM: Helmet was made of water resistant paper/cardboard. The ventilation solution did place the helmet into the second half among other helmets, quite close to the median. Adding evaporation dimension improved the position. It can most probably be improved when increasing the cross-section of internal air channels. If the low cost production can be organised while using recycled materials, then this could be a good solution even for rental bikes as one time use helmet. It can be believed that impact testing can be managed by this prototype already now. As the material allows gradual deformation, then severe impact would leave a contact pattern in the helmet, and the user will be more eager to change the helmet after an accident. With the deformation the contact area increases and the forces are also transferred to a broader surface, thus lowering injury risk at the local high impact area. From accident research viewpoint the deformations may give feedback on impact surfaces, severity, and protection needs etc. if the accident helmets are returned to provider or manufacturer. However, the material has to be waterproof – if it melts in rain or loses stability by sweating then it won't protect. Whatever to do then covering with a continuous plastic shell is not an option – all good points described above will be lost.

MiM: No expectations on issues with impact testing – with real materials the designed shape can be made enough strong. From cooling point of view it is an average helmet, performing better than the ones tested earlier and available on the market. It shows somewhat less successful performance for evaporation but is still better than the average helmet tested by Brühwiler et al. (2006). Helmet could be optimized with adjusting the air channels and openings.

PU: Original expectations were high for this solution. Laying pretty good in calm condition it dropped to middle with high wind and to end with the hair. The modifications did even worsen the performance (less heat loss = higher insulation than Etto – a common user helmet in Sweden some years ago). However, when moisture was introduced both original and modification turned into top 5 helmets. It means the helmet allowing help for active thermoregulation of the body: in cold with no sweating the helmet may keep heat while when getting warmer the heat loss would increase and may reach the required evaporation / sweating rate for comfort on the head. From this viewpoint, the performance seemed to be better than expected. The modifications introduced the improvements that actually increased the span from warmest to coolest position. Now, the wet tests were carried out without hair. What happens if the hair is present? An answer is available in the next section. There can't be seen direct problems with impact testing here – the 3D shell may take quite some of the impact by itself.

RP: One of the best helmets together with SS, allowing good ventilation by unrestricted air flow over the head surface. It was the best under the tests with wig. In wet condition quite some other helmets did pass RP performance. Modification did not improve the performance of this helmet but did not worsen it either. Inlet air opening in front was meant to be closed if ventilation is not desired (tested as RPn), e.g. during winter, and rear opening is not detectable at all. Helmet is expected to manage impact tests and at present any modifications of the openings is not recommended. As in SS (and also in some other helmets) the integration of wind protection for eyes and or other components could be possible.

SS: One of the very best helmets for ventilation with and, especially, without hair thanks to its novel solution of the padding system inside the helmet. It gave often the lowest insulation except during the calm condition. In 1.6 m/s condition without the wig the skull cooling in the helmet was even better than that on the bare head. This could be related to forcing air flow into the helmet and over the head surface. It is certainly worth of going on by this line. From strength /impact testing view-point probably the rear and certainly the front opening need to be separated by some bars. This is not expected to affect the ventilation too strongly. Possibly, a combination of RP and/or MaM visor solution could help, too. Closable front opening would allow reducing heat loss / increase insulation under cold season. Even integrated eye protection to avoid cold wind in eyes may be useful. The helmet shape does allow both easy shield for closing ventilation and integrating wind visor in or on the shell.

TK: Solution is interesting, and works well (both TK and TKo) for ventilation with and without wind and with and without hair (although, in wind case the helmet could be pushed to the back of the head), however, there are 2 major problems from safety side. If testing for impact then forehead is not protected at all and it will never pass, and if bicycling fast then the helmet is pushed into back of the head or totally off. It could be developed into a bonnet style of helmet for ladies that could be worn with a fancy dress and/or when bicycling velocity is not too high (about and less than 10 km/h). The solution for forehead protection / stopper avoiding gliding backwards needs to be developed, e.g. extension of the wind channel bottoms as ornamented details up to about the eyebrows' level. TKo may go its own way. At present the ventilation holes may be too large so that the shaped anvil for impact testing may pass through with its tip. However, if to utilize the RP solution (one inlet, minimal flow restriction and no additional holes) it could become a perfect competition helmet.

TS: A helmet in an original design resembling kepi does combine covering the forehead and inlet opening. Thus, the helmet is supported by forehead, does not fly off the head and allows air to enter the helmet. In calm condition the ventilation can't be seen while the positioning on rating line improves with increasing wind and added hair reaching the average level. Also, with moisture the helmet is positioned better than the average for cooling capacity and is performing better than any of the helmets tested by Brühwiler et al. (2006). Any issues affecting stress test results cannot directly be identified. If then only the largest rear opening should be split. For final product the inlet opening and the air channels may need to be optimized.

VA: Reminds the style of the first bicycle helmets. The helmet lays stable around average for all test conditions. No specific improvements can be suggested. Soft material feels good in hand. Outer layer could utilize material that turns rigid at impact. Any changes and impact resistance needs to be tested.

1.5. Effects of air channel construction and design elements on ventilation

1.5.1. Insulation

Forehead, skull and total insulation (m2K/W) are compared in Figures 17-19 below. The results in the diagrams were sorted by total insulation in ascending order.
The best ventilating helmets with wind speed 1.6 m/s and bald head were the ones from previous studies SSn, LLn, RP and Pun3 (Figure 17). One of the best ventilating helmets on the market H5 stayed in the middle and was better than the new mock-up and its variations.

The experiment with the same wind speed and with a wig gave a different result (Figure 18). The best ones were RP, HA12 and HA13. H5 positioned in the middle and most inefficient were Etto and Pun3. This result is not surprising and is fully comparable with the earlier results, e.g. see Figures 10 and 15. At 6 m/s wind and with a wig only 3 helmets were tested. There performed H5 better than HA12 and HA13 that had been better at 1.6 m/s (Figure 19).

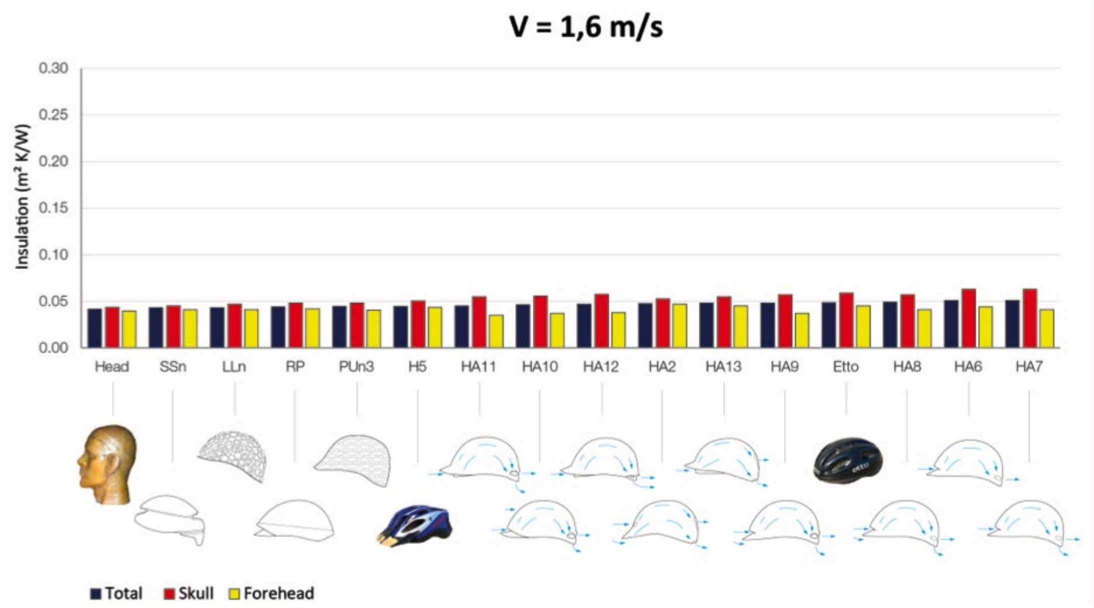

Figure 17. Helmets' insulation (m ²°C/W) without a wig at air velocity of 1.6 m/s.

1.5.2. Evaporative resistance

Evaporative resistance (m2Pa/W) of forehead, skull and total head were compared and sorted by total evaporative resistance in ascending order. Wind speed was set to 1.6 m/s. The experiment on bald head showed that more breathable helmets were Pun3 and LLn, while HA12 and HA13 showed average results and were still cooler than H5 (Figure 20). Figure 21 on the measurements of evaporative resistance with a wig showed that RP, LLn and SSn were better ventilating, and H5, HA13, HA12 were the warmest in this condition. Unexpectedly, Etto did perform better and did position in the middle of the ranking line.

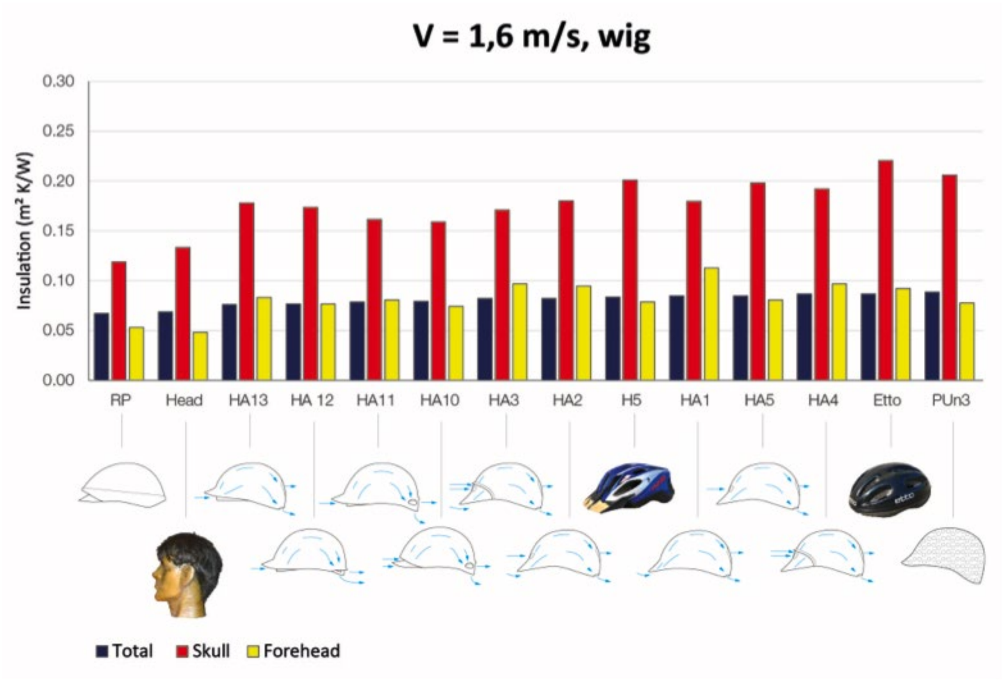

Figure 18. Helmets' insulation (m2K/W) witht a wig at air velocity of 1.6 m/s.

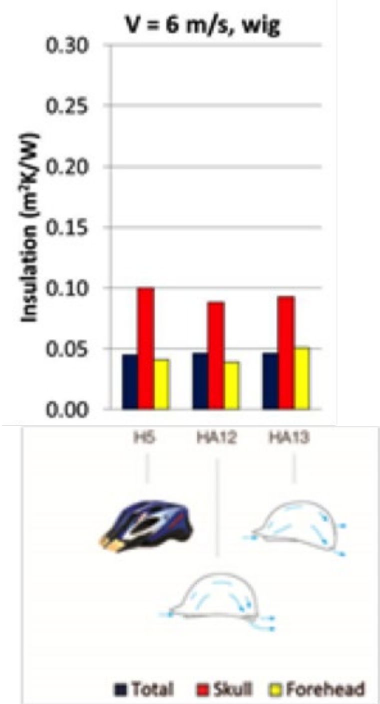

Figure 19. Helmets' insulation (m2K/W) with a wig at air velocity of 6 m/s.

1.5.3. Table of characteristics

In Table 1 the characteristics of each helmet are compared. It is mainly related to ventilation effects on different designs of air inlets and outlets.

On the whole, the characteristics that lead to better ventilating helmets are less contact with head and proper air channels with the strategically placed air inlets and outlets.

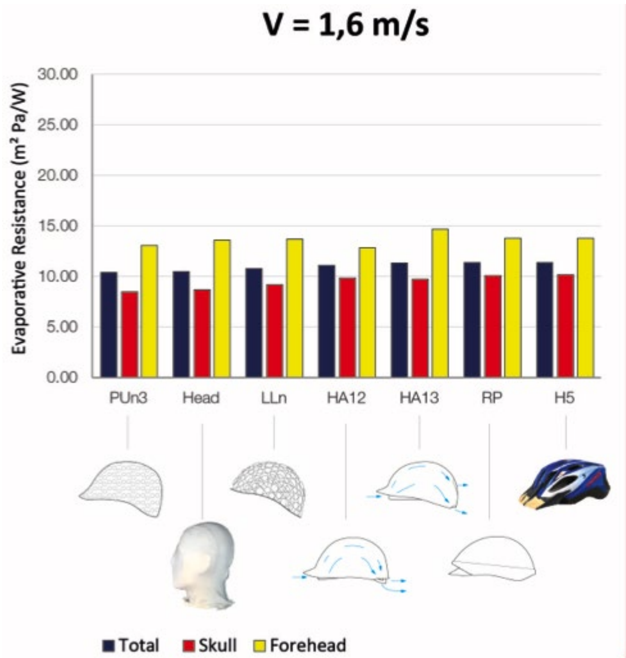

Figure 20. Helmets' evaporative resistance (m2Pa/W) without a wig at air velocity of 1.6 m/s.

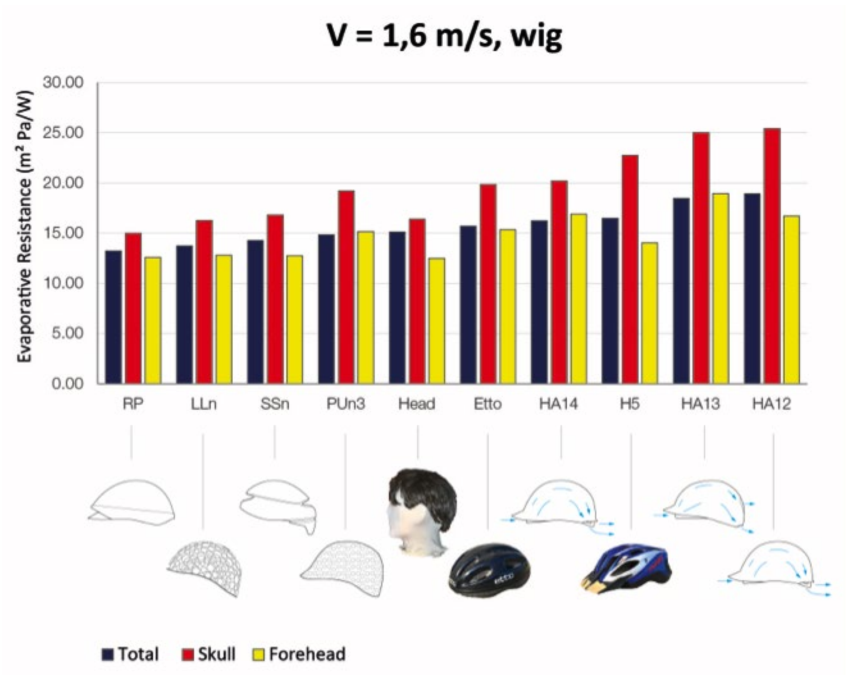

Figure 21. Helmets' evaporative resistance (m2Pa/W) with a wig at air velocity of 1.6 m/s.

Table 1. Helmet ventilation characteristics related to effects on different designs of air inlets, outlets and other design components

			AIR CHANNELS					AIR INLETS, AIR OUTLETS				SIZE				CONTACT WITH HEAD		IMPRESSION ON VENTILATION		IMPRESSION ON SAFETY			VISOR
Name	Producer/designer	Picture	Small	Large	Higher paddings	A distance between the head and the helmet	None	Airy, lot of openings	Openings in the front and back	Front	Back	Average openings	Large openings	Air catcher	Hõrendus õhu väljalaskel	Less	More	Airy	Airless	Protective	Somewhat protective	Not protective	
HA1	Helena Aljaste			✓					✓	1	4	✓					✓		✓	✓			✓
HA2				✓					✓	3	4	✓					✓		✓	✓			✓
HA3				✓					✓	3	4	✓		✓			✓		✓	✓			✓
HA4				✓					✓	2	4	✓		✓			✓		✓	✓			✓
HA5				✓					✓	2	4	✓					✓		✓	✓			✓
HA6				✓					✓	1	3	✓		✓			✓		✓	✓			✓
HA7				✓					✓	1	5	✓		✓			✓		✓	✓			✓
HA8				✓					✓	2	5	✓		✓			✓		✓	✓			✓
HA9				✓					✓	2	5	✓		✓	✓		✓		✓	✓			✓
HA10				✓					✓	2	5	✓		✓	✓		✓		✓	✓			✓
HA11				✓					✓	1	5	✓			✓		✓		✓	✓			✓
HA12				✓					✓	1	3	✓			✓		✓		✓	✓			✓
HA13				✓					✓	1	4	✓					✓		✓	✓			✓
HA14				✓					✓	1	3	✓			✓	✓			✓	✓			✓
PUn3	Piret Uustal						✓	✓									✓	✓		✓			✓
LLn	Lisanne Linamägi		✓			✓		✓								✓		✓			✓		✗
RP	Ragnar Plinkner			✓					✓	1	1		✓			✓			✓		✓		✓
SSn	Sebastian Stittgen			✓					✓	3	2	✓				✓			✓		✓		✗
Etto	Etto		✓					✓		4	4	✓					✓		✓	✓			✗
H5	Specialized		✓					✓		4	4	✓				✓		✓		✓			✓

Table 1. Helmet ventilation characteristics related to effects on different designs of air inlets, outlets and other design components

1.6. Conclusions

From the scientific viewpoint the study was successful – the task was set to find the most different ventilation solutions to be tested, and this was managed well. Various design helmets focused on specific solutions and/or their combinations, and these were used to study possible effects. The testing gave information on solutions that would fit best with low speed, high velocity and hair style. This would allow customisation to specific user needs. The designed helmets' cooling capacity was commonly better in practically any condition than a very common average user helmet, and on above half cases the solutions did function better than the best helmet that was tested earlier (Brühwiler et al., 2006).

The best helmet from the evaporation viewpoint was different from the best in terms of insulation. This means that a best solution for a commuter has to be defined by the user's bicycling activity, the weather conditions etc. The newly designed helmets' results can be used as the basis for improvement of helmet ventilation.

The specific design element study main result was that a well ventilating helmet is characterized by less contact with the head, and proper air channels with strategically placed air inlets and outlets. Large openings worked much better than a several small ones, yet, the care has to be taken as too large openings reduce the helmet protective capabilities. The shape and other design related modifications of the air inlets and outlets had minimal effect on ventilation.

Further, the best solutions should be chosen, and the design work with considering of impact testing should be continued. Also, any model development of the helmet performance prediction based on design and ventilation characteristics would be of interest.

The study showed that it is possible to find a better ventilation solution than available today. Reduction of thermal discomfort may lead to more helmet users and thus increased traffic safety.

1.7. Claim

All the design solutions belong to the authors and 3 of them: PU, RP and SS to the Termokatse OÜ who has bought the rights for these.

1.8. Acknowledgements

The design process was supported by Enterprise Estonia (Ettevõtluse Arendamise Sihtasutus, EAS). The testing was carried out during a training period supported by ERASMUS. Work was initiated within, and short term scientific mission (STSM) was financed by COST Action TU1101.

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V. Project initiatives

1. INTHEL.COM

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INTHEL.COM aims to improve the safety of the ever growing number of users of electrical bicycles (further referred to as 'e-bikes') through the development of an intelligent helmet system. The project addresses the following topics: updating knowledge on accident causation; improving the safety of vulnerable road users; demonstrating the effectiveness of the new helmet systems under real-life conditions; and, in the long term, contributing to the societal challenge of an ageing population as e-bikes are an excellent tool for keeping elderly people longer active; stimulating more women to use bicycles; and reduce the level of air pollution related to traffic congestion by motivating commuters to use (e-)bikes. The consortium exists of 16 partners of which 4 SMEs.

2. SmartHELMET

T. Sotto Major, A. D. Flouris, J.-M. Aerts, G. De Bruyne, K. Kuklane, R. Willinger

A project application was prepared and submitted to the H2020-MSCA-RISE-2014 (Marie Skłodowska-Curie Research and Innovation Staff Exchange (RISE)), having received funding under the grant agreement 645770. The project brings together academic partners and representatives from industry, covering different sectors of the development chain, from research to market (e.g. applied research, engineering capacity, product design and development, testing, innovation management, marketing / commercialisation and access to distribution/selling networks). The project will originate safer, smarter and more comfortable helmets, which will contribute to promote helmet acceptance and increase bicycle use.

VI. Final remarks

1. Conclusions

1.1. Literature review

The literature reviewed carried out in the WG4 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, 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.
- Wearing headgear does not affect physiological systemic parameters, e.g., body core temperature and heart rate, although it does affect local skin temperature.
- 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.
- Unfavorable thermal sensation or thermal discomfort are frequently returning arguments for not wearing headgear, which is mainly driven by skin wettedness under warm conditions.
- The head is among the most contributing bodyparts for whole body comfort and temperature perception under warm conditions, improving ventilation of headgear has been frequently and successfully applied for optimizing comfort.
- A causal influence of non-encapsulating headgear on the risk for heat stroke seems unlikely.
- Headgear could impair exercise tolerance time through increased discomfort.
- Headgear is unlikely to impair cognitive performance.
- Ventilation is relevant for forced convective heat loss as well as wet heat loss.
- Previous helmet design has not focused on reducing radiant heating.
- The effect of hair on forced convective heat loss is roughly 30%.
- Methods
    - CFD becomes more promising for evaluating helmet design with reducing cost of computational power.
    - Numerical models of human thermal physiology might facilitate active control systems for improved comfort of headgear.
    - Thermal manikin headforms are valid for determining effects of headgear on temperature perception of humans, whereas tracer gas methods can be utilized for quantifying airflow with a relevant spatial resolution.
    - Current efforts combine numerical models with biophysical models, making their predictions more accurate.
    - 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.

1.2. Local thermal discomfort by bicycle helmet use – a modelling framework

The concepts introduced in this COST Action allow for the simulation, prediction and assessment of local thermal comfort associated with bicycle helmet use considering the (potentially time-varying) parameters of the thermal environment, exposure duration, activity level, clothing characteristics, and helmet's thermal properties.

1.3. Towards Data-Based Mechanistic Models for Managing Thermoregulation

In this work we investigated the use of compact data-based transfer function models for modelling core body (rectal) temperature in relation to metabolic activity and mean skin temperature as a basis for managing thermoregulation. We demonstrated that core body temperature could be modelled accurately using metabolic activity alone or both metabolic activity and mean skin temperature.

It was further demonstrated that the identified transfer function model structure with metabolic activity and mean skin temperature as inputs can be interpreted in a mechanistic way when linking it with mechanistic models such as the 'Fiala thermal Physiology and Comfort' (FPC) model.

1.4. Thermophysiological Head Simulator

This is the first attempt in the scientific literature addressing the coupling of a mathematical model of the human thermal physiology with just one body part manikin. In this first stage of the research, the performance of both components of the system has been evaluated in dynamic conditions such as actual physiological response to the environmental conditions, clothing and activity. Firstly, head geometry and size considerably agreed between head manikin and the mathematical model head sectors. This fact will allow the coupled system to provide coherent physiological control. Secondly, the responsiveness of the thermal head manikin has to comply with the rates of skin temperature change predicted by the physiological model foreseen for coupling and provide an accurate measurement of the heating power for each individual zone in cases with a non-uniform temperature distribution over the head surface. To meet this requirement for a wider range of scenarios, some technical adjustments were applied to the manikin. Thirdly, the physiology model used in this study performed acceptably well when predicting overall physiological response and with greater discrepancy to experimental data for forehead skin temperature.

1.5. Evaluation of thermal properties of coverings for bicycle helmets

1.5.1. General heat transfer

In conclusion, the total convective heat loss is highly affected by replacing the helmet coverings reducing the ventilation of the helmet. Reductions were observed for partially closed (down to 92%) and for fully closed cover designs (down to 87%). The opposite was found when looking at total radiant heat gain, which was reduced down to 37% for closed helmet coverings but reached low values for partially closed coverings as well (57%). The assessment of helmet configurations based on global heat loss combines the heat transfer mechanisms, namely the convective heat loss and the radiative heat gain. Even though adding helmet coverings increases radiant protection, the reduction in convective heat was more pronounced and induced a reduction in total heat loss (down to 89%). Furthermore, no difference became apparent between reflective (chrome) and non-reflective (black) covers may due to the isolative properties of the EPS liner. These results indicate that radiant shielding is an important aspect but convective remains the most important dry heat transfer mechanism.

1.5.2. Local heat transfer

The assessment of local heat transfer revealed the forehead as being the section with most convective heat loss. The addition of closed coverings induced a similar reduction in convective heat loss for most of the sections. The partially closed covering resulted in reductions which were not that pronounced as for the closed coverings. The zones exposed the most to radiation were forehead, crown and upper head back. The application of helmets coverings mainly reduced radiant impact in the crown section (down to 18% of radiant heat gain found for uncovered helmet). The radiant shielding of the partial cover was not that effective in this section (down to 75%). As for general global heat transfer, a reduction was found for partially closed and fully closed helmet coverings.

1.6. Better bicycle helmets for commuters: design solutions for ventilation

From the scientific viewpoint the study was successful – the task was set to find the most different ventilation solutions to be tested, and this was managed well. Various design helmets focused on specific solutions and/or their combinations, and these were used to study possible effects. The testing gave information on solutions that would fit best with low speed, high velocity and hair style. This would allow customisation to specific user needs. The designed helmets' cooling capacity was commonly better in practically any condition than a very common average user helmet, and on above half cases the solutions did function better than the best helmet that was tested earlier (Brühwiler et al., 2006).

The best helmet from the evaporation viewpoint was different from the best in terms of insulation. This means that a best solution for a commuter has to be defined by the user's bicycling activity, the weather conditions etc. The newly designed helmets' results can be used as the basis for improvement of helmet ventilation.

The specific design element study main result was that a well ventilating helmet is characterized by less contact with the head, and proper air channels with strategically placed air inlets and outlets. Large openings worked much better than a several small ones, yet, the care has to be taken as too large openings reduce the helmet protective capabilities. The shape and other design related modifications of the air inlets and outlets had minimal effect on ventilation.

2. Outlook

2.1. Review

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:

- Modelling of the head's sweat rates as a function of spatial location and body core temperature.
- The effect of hair style on forced convection is not well understood and needs more investigation.
- Development of active control systems for improved comfort, models of the head's sweat rate might play a role in this.
- 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.

2.2. Local thermal discomfort by bicycle helmet use – a modelling framework

Due to the scarcity of data on human head perspiration we had been compelled to make certain assumptions during modelling. This points to the requirements for more research aiming to improve and validate the applied models, more specifically there is a need for:

- Improvement of local head sweating models, e.g. by considering the modifying effect of local skin temperature on sweating (Nadel et al. 1971).
- Biophysical testing of helmet's thermal properties using head-forms and thermal manikins, which should
    - tabulate the thermal insulation and evaporative resistance at still air, and
    - asses their reduction by wind speeds relevant for cycling, preferably by developing correction equations as available for whole body clothing (ISO 9920 2007) or air

layer evaporative resistance (Wang et al. 2012).

Human trials on head perspiration addressing

- o the measurement of head sweat rates and its relation to skin wettedness and thermal comfort perception, thus allowing for deriving experimentally head wcrit,
- o simultaneous measurements of GSR and ΔTre besides LSR, thus allowing for specifically validating the local models.

Finally, the principles presented in this section are easily transferable to considering local thermal comfort at other body regions as well.

2.3. Towards Data-Based Mechanistic Models for Managing Thermoregulation

Such data-based mechanistic models can be used in a next step as a basis for managing thermo-regulation of individuals in real-time. Linking the predictions of core temperature with local models for head perspiration they may also become useful in assessing and controlling the thermal comfort of bicycle helmets.

2.4. Thermophysiological Head Simulator

Further steps aim at defining the physiological limitations and at validating the coupled system in a wide range of exposures. Because only head is physically simulated, the mathematical model has to simultaneously accept different types of boundary conditions, such as measured surface heat losses at head-site and virtual environmental conditions for the rest of the body. This work will be accomplished as discussed on the occasion of a PhD project conducted in relation to this COST Action TU1101 (Multi sector thermophysiological head simulator for headgear research (2015) by N. Martinez). The thermophysiological head simulator will be a novel advanced method for headgear evaluation based on adding a physiological control to a nine-zone thermal head manikin.

2.5. Evaluation of thermal properties of coverings for bicycle helmets

The results indicate that there is a potential to improve total global dry heat loss by improving bicycle helmet designs. However, this is not only about increasing the radiant shielding properties of the helmet but to maintain or even improve the convective heat loss as well. For the development of new helmet designs with improved heat transfer properties, the thermal head manikin is a promising methodology which should be included in future development activities. The understanding helmet design effects on the local heat transfer will provide an important basis. Furthermore, the wet heat transfer (perspiration and evaporative cooling) has to be taken into account as well to provide a holistic concept of the thermal optimization of bicycle helmets.

2.6. Better bicycle helmets for commuters: design solutions for ventilation

Further, the best solutions should be chosen, and the design work with considering of impact testing should be continued. Also, any model development of the helmet performance prediction based on design and ventilation characteristics would be of interest.

3. Implications for industry

- The head is a body part showing exceptional thermoregulative and psychological responses and, thus, makes specific demands on products worn close to / at the head. Taking these thermal physiological aspects as well as psychological aspect into consideration will result in better ac-cepted headgear.
- Thermal properties of helmets have to be adjusted to the type of cycling activity, differing mainly in body posture and wind speed.
- Bicycle helmets showing improved radiant shielding properties contribute to an improved wearing comfort given that convective properties are at least maintained. Several concrete design improvements are done.
- Convective properties of headgear might be improved in case of many currently available bicycle helmets. Important are well positioned inlet and outlet vents as well as air channels connecting the two. The design should take into consideration that hair might not obstruct the air channels.
- The development of new helmet designs shall include different methodological approaches as computational modelling (CFD, data-based mechanistic models) for the development of new and effective helmet designs as well as experimental simulation for proof of concept and final adjustments to optimize helmet designs.
- Active cooling might be integrated in headgear.
- Dynamic vents or active cooling systems that can regulate the heat loss from the head might be controlled by models predicting thermal comfort at the head, aiming at an optimized thermal comfort.

4. Implications for the legislators

- The head is a body part showing exceptional thermoregulative responses and, thus, makes specific demands on products worn close to / at the head. If the demands are not approached, wearing comfort is decreased as will be the compliance of wearing helmets
- We propose to include minimal requirements regarding heat transfer in (bicycling) helmets in addition to protective properties to ensure wearing comfort and compliance of wearing helmets. However, a few as possible boundary conditions should be proposed regarding the design of helmets. Increasing number of restrictions reduce innovation in bicycle helmet design.

- We propose to initiate new standards regarding the evaluation and assessment of wearing comfort. This will make ventilation rating available to customers so that they will include this in their buying considerations. In this way it will become a direct priority of the manufacturers to maximize thermal comfort of helmets.

5. Feedback to the COST office

- Concept of COST network is interesting, provides a platform for new projects, for exchanging and developing new ideas, to initiate collaborations
- Supports the network of experts to provide a review
- The review provides an important basis for funding activities
- Dissemination is supported by COST: highly recognized review because of open access availability
- Increased visibility due to COST support (special sessions during conferences)
- Great contributions from students working on projects attributed to the COST action
- Swiss / (Turkish) model of funding favourable for other nations as well
- COST supports networking over different disciplines / different (research) aspects

- Working hours cannot be put on the COST action
- No reimbursement of VAT
- Information about open calls (H2020) related to activities of a COST action would be useful
- Useful feedback about progression of COST action hardly available (rapporteur never showed up during COST meetings)