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PHYSIOLOGICAL AND COGNITIVE EFFECTS OF WEARING A FULL-FACE MOTORCYCLE HELMET

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For Carlo and Lia
For Nina

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Contents

Abbreviations

α	False-positive-ratio	
β	False-negative-ratio	
$\Delta\dot{Q}_F$	Vent-induced heat loss from the face section	[W]
$\Delta\dot{Q}_S$	Vent-induced heat loss from the scalp section	[W]
σ	Standard deviation	
A	Average	
C	Convective heat transfer	[W]
E	Evaporative heat transfer	[W]
EPS	Expended polystyrene	
h_c	Convective heat transfer coefficient	[$W\cdot{}^{o}C^{-1}$]
K	Conductive heat transfer	[W]
M	Metabolic rate	[W]
P_{H2O}	Water vapor pressure	[Pa]
PTW	Powered two-wheeler	
$\dot{Q}_F$	Heat loss from the face section	[W]
$\dot{Q}_S$	Heat loss from the scalp section	[W]
R	Radiant heat transfer	[W]
RH	Relative humidity	[%]

S	Body heat storage	[W]
SkBF	Skin blood flow	
T_a	Ambient temperature	[ºC]
T_c	Core temperature	[ºC]
$T_{headform}$	Surface temperature of the headform	[ºC]
T_w	Temperature of wind	[ºC]
v_w	Wind speed	[$km \cdot h^{-1}$]
W	Work rate	[W]

Summaries

Summary

Wearing a full-face motorcycle helmet is likely to cause a warm microclimate environment, due to its expected high thermal insulation, especially on the scalp. However, it is unclear how such helmets can affect the cognition, i.e. performance (e.g., sustained attention) and the perception (e.g., temperature perception or thermal comfort). Therefore, we studied the following aspects of wearing a full-face motorcycle helmet: i) the external thermal boundary conditions created by these helmets, ii) how diversely motorcycle helmets and their ventilation systems are influencing the temperature perception and thermal comfort, and iii) if wearing a motorcycle helmet can affect cognitive performance (Chapter 1).

In order to understand the external thermal boundary conditions created by full-face motorcycle helmets, 27 specimens were measured with all vents open or closed (Chapter 3). The average heat loss ($\dot{Q}$) was measured under controlled environmental conditions of 22.90 ± 0.05 ºC, and 50.4 ± 1.1 km·h^{-1} wind speed. In a follow-up study, similar measurements were conducted on a selection of helmets (Chapter 4) under the following conditions: i) a 30º forward head tilt angle, ii) a wig installed between headform and helmet, and iii) wind speed ranging from 0 km·h^{-1} to 79.8 km·h^{-1}. The results show large variations in $\dot{Q}$ among the different helmets, ranging from 0 W to 4 W for the scalp section and from 8 W to 18 W for the face section. Opening all the vents resulted in a vent-induced heat loss ($\Delta\dot{Q}$) exceeding 1 W in four and six helmets, respectively, for the scalp and face section. Only two and one helmet(s), respectively, exceeded a $\Delta\dot{Q}$ of 2 W. Qualitatively similar results were found under the other conditions.

To understand how $\Delta\dot{Q}$ is related to human perception, eight subjects (aged 28.0 ± 5.4 years) underwent two experimental trials in balanced order in a climate chamber with a temperature of 23.7 ± 0.4 ºC, or 27.5 ± 0.3 ºC (Chapter 5). During each trial, the acclimated subjects underwent 2 examination phases, each lasting approximately 20 min. To investigate the effects of the ventilation system, the vent configuration was changed in the scalp section, directly followed by a perceptual assessment of i) temperature, ii) airflow, iii) noise, and iv) thermal comfort. During the examination phase, four different helmets were assessed for about 5 min each at wind speeds of 39.2 ± 1.9 km·h^{-1} and 59.3 ± 1.4 km·h^{-1}. Having changed the helmet, the subjects sat still for 3 min; the vent configuration was then changed and the subjects were asked to evaluate their perception of an eventual difference. Similar assessments were performed for the face. The four full-face motorcycle

helmet models employed in this study presented conditions ranging from a high to a very low $\Delta\dot{Q}$. A multinomial logistic regression analysis was used to indicate the parameters which are important predictors for the response behavior of the subjects. $\Delta\dot{Q}$ in the scalp section ranged from -6.1 W to 6.1 W. $\Delta\dot{Q}$, subject and helmet were identified as the most important predictors of the response behavior. An additional analysis yielded estimates of the following parameters: i) perception thresholds, suggesting a higher likelihood of the subjects to perceive an opening of the vents compared to their closing; ii) helmet specific sensitivities, possibly caused by different internal airflow patterns; finally, iii) strong similarity in the perception of temperature and airflow for both scalp and face.

The above summarized results indicate that, the microclimate temperatures around the head are higher than the ambient temperatures, due to insufficient ventilation of these highly-insulating helmets. Since it is known that cognitive performance can be impaired by heat stress and also other helmet mediated effects (e.g., increased carbon dioxide levels), a study investigating the impact on cognitive performance while wearing a full-face motorcycle helmet was carried out (Chapter 6). Following three familiarization trials, nineteen subjects completed two experimental trials, wearing a full-face motorcycle helmet (HEL) or no headgear at all (CON), randomly assigned. The cognitive performance was assessed with a letter cancellation test (LCT), further with a task of simultaneous visual and auditory vigilance with tracking (VTT+AVT). During each experimental trial, acclimated subjects completed 30 min VTT+AVT preceded and followed by an LCT. In addition, the heart rate (HR) and heart rate variability (SDNN and pNN50) were measured during the VTT+AVT, and at the end of each trial, whole-body temperature perception and thermal comfort were assessed. All the trials took place in a climate chamber at an ambient temperature of 27.2 ± 0.6 ºC, a relative humidity of 41 ± 1%, and the v_w was 1.8 ± 0.2 $km\cdot h^{-1}$. HEL resulted in a larger displacement on the tracking task, with a median increase of 7.2% (25^{th} percentile -9.9%; 75^{th} percentile 23.7%) ($p = 0.021$). Furthermore, interaction effects were found between the intervention and time for the cognitive performance parameters for five out of 46 cases. pNN50 showed an intervention effect, with 17.5% (-26.9; 62.1), with larger values for HEL. Furthermore, HEL resulted in a less favorable temperature perception and thermal comfort ($p < 0.01$). Finally, most cognitive parameters showed a time effect during the 30 min VTT+AVT, indicating poorer performance towards the end.

Thus, the tracking performance was impaired by wearing of a full-face motorcycle helmet. In addition, these helmets cause a less favorable whole body temperature perception and thermal comfort, and increase pNN50, under the applied conditions. Furthermore, as expected, $\Delta\dot{Q}$ was the most important determinant for the perception of temperature, airflow and noise, although each helmet affected the sensitivity of the wearer in a slightly different manner. For temperature and airflow, perception thresholds were defined. Only three helmets of a sample of 27 state-of-the-art full-face motorcycle helmets exceeded these perception thresholds measured at 22.90 ± 0.05 °C and a wind speed of 50.4 ± 1.1 $km \cdot h^{-1}$. However, the number of helmets exceeding these thresholds will be slightly larger with higher wind speeds or lower ambient temperatures. This suggests that optimizing full-face motorcycle helmets for temperature perception and thermal comfort might reduce their detrimental impact on the cognitive performance and may thereby improve the traffic safety of motorcycle and moped riders.

Zusammenfassung

Das Tragen von Vollvisiermotorradhelmen führt aufgrund ihres hohen Isoliervermögens mit grosser Wahrscheinlichkeit zu einer Erwärmung des inneren Mikroklimas, und zwar speziell auf der Schädelhaut. Dennoch ist unklar, wie solche Einflüsse durch einen Helm die Wahrnehmung, bzw. die kognitive Leistung (z.B. ununterbrochene Aufmerksamkeit) und die Empfindungen (z.B. Temperaturgefühl und thermischer Komfort) des Trägers beeinflussen. Aus diesem Grund haben wir folgende Fragen untersucht: i) die äusseren, durch diese Helme verursachten thermischen Grenzbedingungen, ii) wie verschiedene Motorradhelme mit ihren Ventilationssystemen das Temperatur- und Komfortempfinden beeinflussen, und iii) ob das Tragen von Motorradhelmen die kognitive Leistung beeinflusst (Kapitel 1).

Um zu verstehen, wie die äusseren thermischen Grenzbedingungen durch Vollvisiermotorradhelme entstehen, haben wir 27 Muster mit offenen oder geschlossenen Ventilationsöffnungen gemessen (Kapitel 3). Dabei wurde die mittlere Wärmeabgabe ($\dot{Q}$) unter kontrollierten Umgebungs-Bedingungen von 22.90 ± 0.05 °C und einer Windgeschwindigkeit (v_w) von 50.4 ± 1.1 km·h^{-1} bestimmt. In einer zweiten Studie wurden die gleichen Messungen an einer Auswahl von Helmen gemacht (Kapitel 4): i) mit einer 30°-Neigung des Kopfes nach vorne, ii) mit einer Perücke zwischen Helm und Kopfmodell, und iii) mit einer v_w zwischen 0 km·h^{-1} – 79.8 km·h^{-1}. Die Resultate zeigten grosse Unterschiede zwischen den verschiedenen Helmen bei $\dot{Q}$. Die Unterschiede bewegten sich von 0 W – 4 W im Schädelbereich und zwischen 8 W – 18 W im Gesichtsbereich. Dabei bewirkte ein Öffnen aller Ventilationsöffnungen eine lüftungsinduzierte Wärmeabgabe ($\Delta\dot{Q}$) von mehr als 1 W bei vier Helmen im Schädelbereich, beziehungsweise bei sechs Helmen im Gesichtsbereich, wobei nur zwei Helme, beziehungsweise ein Helm eine $\Delta\dot{Q}$ von 2 W überschritt. Ähnliche qualitative Resultate wurden auch unter den anderen Bedingungen gefunden.

Da es unklar ist, wie eine $\Delta\dot{Q}$ mit der menschlichen Empfindung verbunden ist, wurden zwei experimentelle Versuche in ausgeglichener Reihenfolge mit acht Probanden (Alter 28.0 ± 5.4 Jahre) in einer Klimakammer bei einer Temperatur von 23.7 ± 0.4 °C oder 27.5 ± 0.3 °C durchgeführt (Kapitel 5). Bei jedem Versuch durchliefen die akklimatisierten Probanden zwei etwa 20-min Versuchsphasen. Um den Einfluss der Ventilation zu untersuchen, wurde die Einstellung der Belüftungsöffnungen im Schädelbereich geändert und das Empfinden mit einer

anschliessenden Befragung zu i) Temperatur, ii) Luftstrom, iii) Lärm und iv) thermischem Komfort erfasst. Während des Versuchs wurden vier verschiedene Helme jeweils für 5 min bei einer v_w von 39.2 ± 1.9 km·h^{-1} oder 59.3 ± 1.4 km·h^{-1} getestet. Nach dem Auswechseln der Helme sassen die Probanden für 3 min still. Dann wurde die Helmbelüftung geändert, und die Versuchspersonen zur Empfindung einer eventuellen Änderung befragt. Ähnliche Befragungen wurden zum Gesichtsbereich durchgeführt. Die vier Vollvisiermotorradhelme repräsentierten in dieser Studie die Bedingungen von einer hohen bis zu einer sehr niedrigen $\Delta\dot{Q}$. Multinominale logistische Regressionen wurden berechnet, um Parameter zu bestimmen, die Voraussagen über das Antwortverhalten der Probanden machen konnten. $\Delta\dot{Q}$ bewegte sich zwischen -6.1 W und 6.1 W im Schädelbereich. Proband, Helm und $\Delta\dot{Q}$ sind die wichtigsten Einflusswerte für die Voraussage des Antwortverhaltens. Eine zusätzliche Analyse ergab i) Empfindungsschwellen, bei denen die Probanden mit einer höheren Wahrscheinlichkeit geöffnete Lufteinlässe im Vergleich zu geschlossenen bemerkten; ii) helmspezifische Sensitivitäten, die eventuell durch unterschiedliches Verhalten des inneren Luftstroms verursacht werden und, schliesslich iii) eine grosse Ähnlichkeit beim Empfinden von Temperatur und Luftstrom auf Schädelhaut und Gesicht.

Folglich sind wegen der Wärmeisolierung dieser Helme die Mikroklima-Temperaturen um den Kopf herum höher als Umgebungstemperaturen. Da man weiss, dass kognitive Leistung durch Hitzebelastung und andere helmspezifische Einflüsse (z.B. erhöhte Kohlendioxyd-Werte) eingeschränkt wird, befasste sich eine Studie mit den Auswirkungen auf die kognitive Leistung beim Tragen eines Vollvisiermotorradhelms (Kapitel 6). Nach drei Angewöhnungsversuchen absolvierten neunzehn Probanden zwei experimentelle Versuche, wobei sie in zufälliger Reihenfolge einen Vollvisiermotorradhelm (HEL) und gar keinen Kopfschutz (CON) trugen. Die kognitive Leistung wurde mit einem Buchstabendurchstreichungstest (LCT) und einem simultanen visuellen und auditiven Wachsamkeitstest mit Tracking-Aufgabe (VTT+AVT) bestimmt. Bei jedem experimentellen Versuch durchliefen die akklimatisierten Probanden 30 Minuten VTT+AVT, mit vorausgehendem und nachfolgendem LCT. Zusätzlich wurden während dem VTT+AVT die Herzfrequenz (HR) und deren Schwankungen (SDNN und pNN50) gemessen, und am Ende jedes Versuchs das Ganzkörpertemperatur-Empfinden und der thermische Komfort bestimmt. Alle Versuche fanden in einem Klimaraum bei einer Umgebungstemperatur von 27.2 ± 0.6 °C, einer relativen Luftfeuchtigkeit von 41 ± 1 % und einer v_w von 1.8 ± 0.2

km·h^{-1} statt. HEL wies grössere Verschiebungen aus der Tracking-Aufgabe auf, bei einer mittleren Erhöhung von 7.2% (25. Perzentil -9.9%; 75. Perzentil 23.7%; $p = 0.021$). Ferner wurden Wechselwirkungen zwischen dem Eintreten und der Zeit für die kognitive Leistungsparameter bei 5 von 46 Fällen festgestellt. pNN50 zeigte eine helmspezifische Wirkung von 17.5% (-26.9; 62.1), mit höheren Werten beim HEL. Ferner ergab sich dabei eine ungünstigere Temperatur- und thermische Komfort-Wahrnehmung ($p < 0.01$). Schliesslich zeigten die meisten kognitiven Parameter einen Zeiteffekt während der 30 min VTT+AVT, was auf eine schwächere Leistung gegen das Ende des Versuchs hinweist.

Daher wurde die Tracking-Leistung durch das Tragen eines Vollvisiermotorradhelms beeinträchtigt. Dazu verursachen diese Helme unter den angewandten Bedingungen eine ungünstigere Körpertemperatur- und thermische Komfort-Wahrnehmung, sowie eine Erhöhung der pNN50. Ferner erwies sich $\Delta\dot{Q}$ wie erwartet als wichtigste Bestimmungsgrösse für die Empfindung von Temperatur, Luftstrom und Lärm, obwohl jeder Helm die Sensitivität des Trägers auf leicht unterschiedliche Weise beeinflusste. Für Temperatur und Luftstrom wurden Wahrnehmungsschwellen definiert. Nur drei Helme aus einem Muster von 27 modernsten Vollvisiermotorradhelmen überschritten diese Wahrnehmungsschwellen, die bei 22.90 ± 0.05 °C und einer v_w von 50.4 ± 1.1 km·h^{-1} gemessen wurden. Allerdings wird die Anzahl Helme, die über diese Schwelle hinausgehen, bei stärkeren Windgeschwindigkeiten oder tieferen Umgebungstemperaturen leicht ansteigen. Dies deutet darauf hin, dass eine Optimierung von Vollvisiermotorradhelmen in der Temperatur- und thermischen Komfort-Wahrnehmung deren negative Einwirkung auf die kognitive Leistung mindern und damit die Verkehrssicherheit bei Motorrad- und Motorfahrradfahrern verbessern könnte.

1. Introduction

The aim of this thesis is to investigate if thermally mediated effects of wearing a full-face motorcycle helmet, affect parameters associated with traffic safety. This is relevant since motorcycle and moped riders are overrepresented in traffic accidents. Motorcycle helmets are excellent thermal insulators, and are therefore likely to change the thermal boundary conditions at the head, unless the problem is specifically targeted in their design. The focus of interest lies on thermally mediated effects in warm environments since heat stress i) can negatively affect cognitive performance, and ii) causes thermal discomfort. It is known that impaired cognitive performance is the cause of 34% of all motorcycle and moped accidents; whereas thermal discomfort is a frequent reason given for not wearing a motorcycle helmet. Furthermore, a relatively large part of heat is lost through the head under comfortable room conditions for resting subjects. Thus, applying a thermal insulation to the head poses a larger impact to the body compared to insulating any other body part of equal surface area. In light of this, it is surprising that this thesis represents the first work pursuing this aim. However, also the mechanism by which full-face motorcycle helmets affect the heat stress on the head will be characterized (Figure 1.1). Differences between state-of-the-art helmets will be quantified and the first suggestions will be made for optimizing the thermal effects such a helmet imposes on its wearer. This introduction will start with a detailed description of the problem, covering traffic statistics and motorcycle helmet usage. Then the literature will be reviewed on i) the external thermal boundary conditions, ii) thermal physiology, and finally iii) cognition.

1.1. Traffic safety

1.1.1. Motorcycle and moped traffic accidents

Motorcyclists and moped riders accounted for 18 ± 2% of all traffic accidents on European roads from 1996 to 2005 (ERSO, 2007). These statistics are even more dramatic if expressed in deaths per 100 million person traveling hours (Figure 1.2), which is by far the highest for motorcyclist and mopeds with 440. For comparison, car passengers on average show 25 fatalities for the same time unit, based on EU statistics collected in 2001 and 2002 (Koornstra et al., 2003; WHO, 2004). Moreover, motorcycles and mopeds, collectively referred to as powered two-wheelers (PTW), are the only mode of transport showing a consistent increase of fatalities (ERSO, 2007). Traffic statistics in terms of fatalities are a reliable measure, since their definition is relatively unambiguous, and all the above-mentioned cases employed this criterion in their reporting.

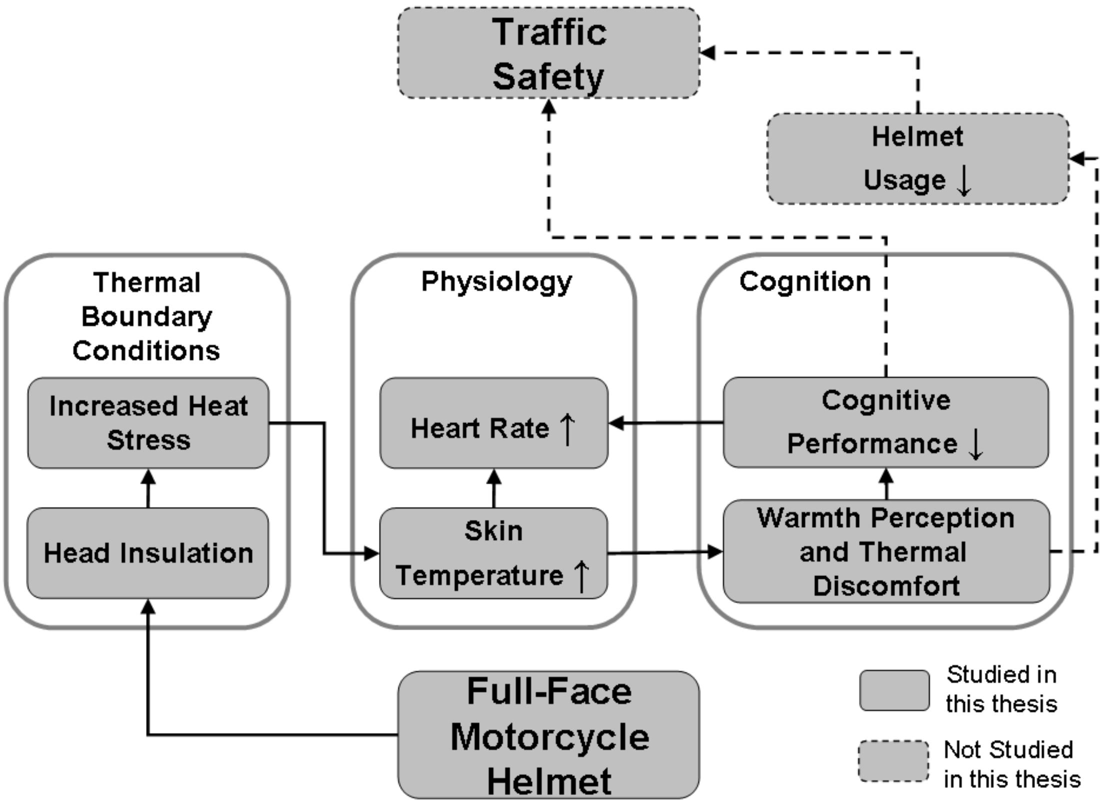

Figure 1.1: Organigram of the relationship between full-face motorcycle helmets and traffic safety. The written or symbolized directions indicate the hypothesized effects of wearing a full-face motorcycle helmet, relative to the nude head. In addition, the studied topics are indicated.

However, it is not necessarily the best means for comparing PTWs with other modes of transport, because PTWs are equipped with many fewer safety options than comparable modes, such as automobile driving. Therefore, a PTW traffic accident is more likely to result in a fatality. A comparison based on non-fatal accidents could be another approach, but no sufficient data are available. Taken together, PTWs are overrepresented in traffic fatalities. However, even more concerning is the consistent trend indicating that it is unlikely that the contribution of PTWs to the total traffic accidents will be reduced in the (near) future, in contrast to other modes of transport, if no special efforts are undertaken to understand this problem.

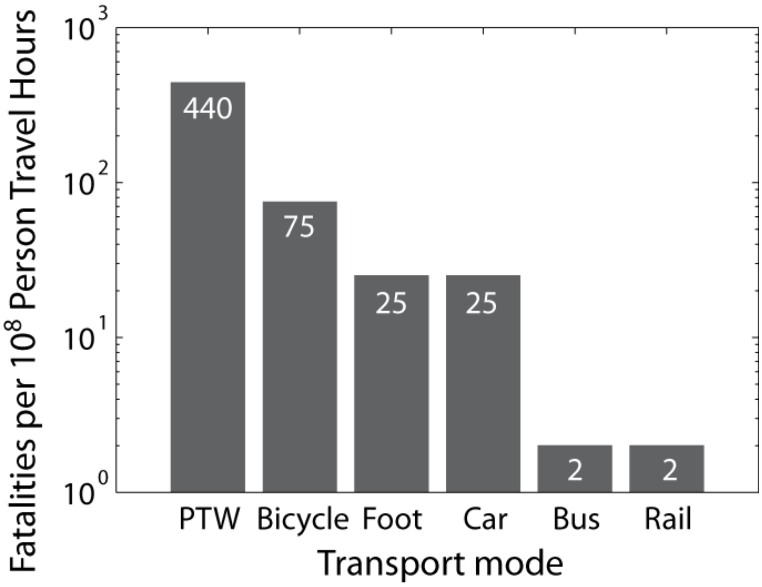

Figure 1.2: Fatalities per 100 million person travel hour, statistics obtained from 2001 and 2002 in Europe. PTW are powered two-wheelers including motorcycles and mopeds; data taken from Koornstra et al. (2003), pp 12 (table 2).

Relatively little traffic safety research has been conducted on PTWs, especially compared to cars (Shinar, 2007). Besides the safety option aspect mentioned above, PTWs cannot directly be compared to cars because of the much lower inherent stability of the former. Interestingly, in driving simulators, car drivers holding a PTW license are better drivers than car drivers not holding a PTW license (Horswill & Helman, 2003) with regard to hazard perception. It therefore is likely that PTW riders pay more attention in traffic situations, thereby attempting to compensate for their greater vulnerability. It seems intuitive to assume that PTW riders are occupied with more tasks than car drivers; or in psychological terms their typical cognitive load is higher than that of car drivers.

Between 1999 and 2000 a large European effort (MAIDS) was carried out, in which PTW accident sites were visited, usually allowing the experimenters access to all involved parties and witnesses (ACEM, 2004). In this study 921 cases were evaluated and, for each case, approximately 2000 variables were recorded. They found that 50% of all accidents were attributed to the collision partner, 37% to the PTW rider, and the remaining were explained by roadway and vehicle defects, and others, summarized in Figure 1.3a. Similar results have been found in a study carried out in Los Angeles (California) from 1975 through 1980 (Hurt et al., 1981). They attributed the accident cause in 51% of cases to the collision partner and in 41% to the PTW rider. The MAIDS study also evaluated the underlying accident cause

(Figure 1.3b). From the collision partner they found perception to be the cause of 72% of the accidents in which the collision partner was the primary factor. The low conspicuity of PTW riders and their vehicles are believed to play a large role in this (ACEM, 2004; Wells et al., 2004). However, when the PTW rider was found to be at fault, 92% of the cases were explained by i) perception failure, ii) comprehension failure, iii) decision failure, or iv) reaction failure. These four variables are associated with cognitive performance. Thus, for most PTW accidents in which the PTW rider is the primary cause, a cognitive failure is identified as the underlying cause.

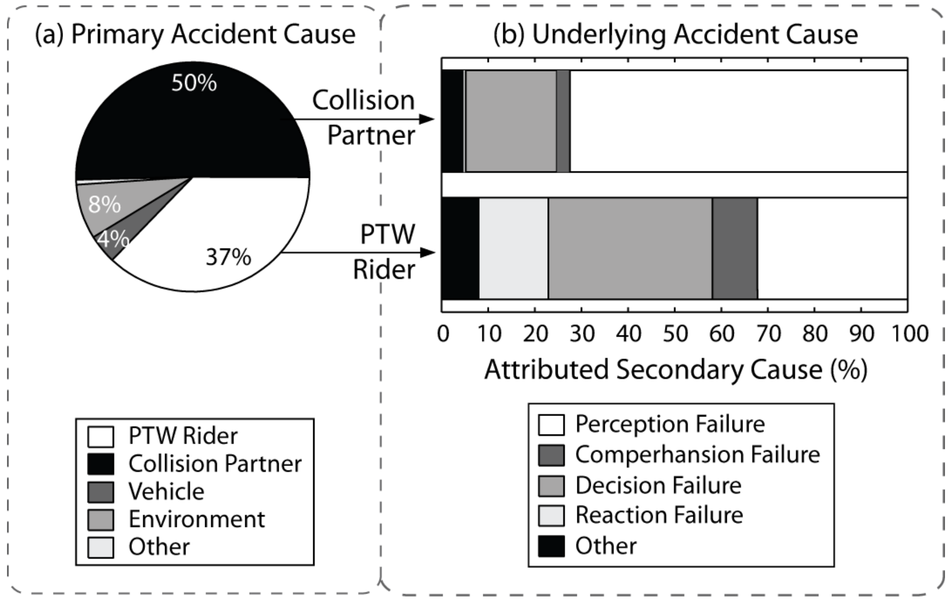

Figure 1.3: (a) Primary accident causes of powered two-wheeler (PTW) accidents. (b) For the collision partner (which was most often a passenger car) and the PTW rider, the underlying accident causes are indicated. Data for both figures are obtained from ACEM (2004); (a) pp 29 (Table 4.1), and (b) pp 30 (Figure 4.1).

1.1.2. Motorcycle usage

The most efficient means of reducing PTW fatalities is by wearing a certified motorcycle helmet (Shinar, 2007). Reported effectiveness of helmet use on PTW accident survival range from 22% to 50% (Deutermann, 2004; Keng, 2005; Ouellet & Kasantikul, 2006; Houston & Richardson, 2008; Liu et al., 2008). In addition, the use of such helmets reduces injury severity and medical cost associated with such accidents (Johnson et al., 1995; Rowland et al., 1996; Max et al., 1998; Chinn et al., 2003; Liu et al., 2008). This motivated the numerous efforts on optimizing motorcycle helmets for reducing injury severity during an accident (Mills &

Gilchrist, 1991; Richter et al., 2001; Chinn et al., 2003; Van Den Bosch, 2006). The safest type of motorcycle helmets include facial protection (Chinn et al., 2003) and are commonly referred to as full-face motorcycle helmets (Figure 1.4).

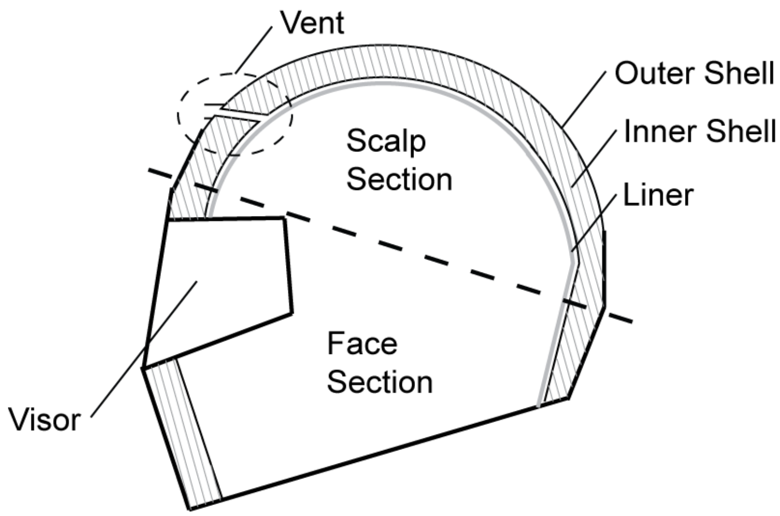

Figure 1.4: A side-view of a typical full-face motorcycle helmet, with important helmet features indicated. Reprinted from Bogerd and Brühwiler (2009); pp 162 (Figure 2) with permission from Elsevier.

Despite these convincing statistics, a substantial fraction of PTW riders do not wear helmets, ranging from 7.7% (ACEM, 2004) in Europe between 1999 and 2000, 40 ± 8% for the USA from 1994 to 2007 (Glassbrenner & Ye, 2007), and 25% in Taiwan between 1999 and 2001 (Keng, 2005). Unfavorable temperature perception or thermal discomfort are frequently returning arguments for not wearing a motorcycle helmet (Patel & Mohan, 1993; Skalkidou et al., 1999; Li et al., 2008a). This is intuitive, especially for the scalp, where these helmets are intrinsically excellent thermal insulators, as will be explained in more detail in Section 1.2. Reliable comparison of motorcycle helmet usage per geographical location is difficult, due to differences in climate and culture. However, Servadei and colleagues (2003) report helmet use in the Northern and Southern Italy of 93% and 60%, respectively. This could at least partly be due to higher levels of warmth perception and/or thermal discomfort in warmer climates. Finally, for industrial protective headgear similar complaints of thermal discomfort in warm environments are found (Hickling, 1986). As will become clear from Section 1.4.2, no studies are published on the effect of motorcycle helmets on temperature perception and thermal comfort. However, in this part the first indications were given that motorcycle helmets are likely to cause uncomfortably warm microclimates, especially in neutral and warm environments. Understanding the relationship between motorcycle helmets and their thermal impact could lead to the development of models with improved temperature perception and thermal comfort, and thereby increase the likelihood of motorcycle helmet usage.

1.2. External thermal boundary conditions

1.2.1. Characteristics of full-face motorcycle helmets

Figure 1.4 displays a side-view of a full-face motorcycle helmet. Full-face helmets cover the chin area and the rest of the head. At the level of the eyes a transparent visor allows visual perception of the surrounding. Characteristics of these helmets important for heat transfer of a head include its openings, as well as channels guiding air from outside the helmet through the helmet (inlet vents), over the head of the wearer, and finally through the helmet towards the outside of the helmet (outlet vents). Generally, all these helmets are equipped with at least one operable vent in the scalp section and at least one in the face section. In addition, the face section of the helmet is also equipped with a helmet-visor interface that might not be completely airtight, and a large opening below the chin. The space between the head and the helmet is also important, and will be referred to as the microclimate.

The largest part of the helmet with respect to volume is the inner shell (Figure 1.4). This shell is usually made from expanded polystyrene (EPS) foam with a thickness of the order of 3 cm. EPS in these helmets acts as shock absorbing material. However, EPS is also an excellent thermal insulator, with a thermal conductivity of 0.03 $W \cdot (m \cdot °C)^{-1}$ (Klodt & Gougeon, 2003), for typical EPS densities for this application (Gale & Mills, 1985). This is a factor of 1.25 larger than air, but 20 times smaller compared to water (Weast & CRC, 1986). Because of these properties (and its low cost), EPS is commonly marketed as a thermal insulator.

1.2.2. Theory

Heat loss ($\dot{Q}$) from the head can be discussed in terms of the heat balance, which is defined as (Blatteis et al., 2001):

$$S = M - W - E - C - K - R, \quad (1.1)$$

where S is storage of body heat, M is metabolic rate, W is work rate, E is evaporative heat transfer, C is convective heat transfer, K is conductive heat transfer, and R is radiant heat transfer. With respect to the head, the latter four affect $\dot{Q}$ and are directly affected by wearing a motorcycle helmet, and will define the thermal boundary conditions between the head and the environment. The driving forces for these $\dot{Q}$ pathways are summarized in Table 1.1, and will be discussed below, for the conditions relevant to this thesis. The interactions between the head and the rest of the body are here neglected, but will be covered in Section 1.3.1.

For E from the head the difference in water vapor pressure between the air layer just above the skin and of air layers further away from the skin are important (Parsons, 2003). The water vapor pressure (P_w) in the air layer just above the skin is usually considered to be constantly saturated, due to constant sensible or insensible perspiration (Parsons, 2003). Evaporation can only take place if air layers away from the skin are not saturated with water vapor, i.e. a gradient in P_w must be present. The air in the microclimate created by the helmet has to be constantly refreshed to prevent these air layers from becoming saturated with moisture. Thus, under these conditions airflow is the driving force for this $\dot{Q}$ pathway.

Table 1.1: The driving forces for heat transfer between the head and the surrounding, for all heat transfer pathways. The driving forces relevant for heat transfer from/to the head while wearing a full-face motorcycle helmet are indicated. Physiological steady state is assumed, in the presence of airflow at ambient temperatures larger than 23 ºC and smaller than 30 ºC and a relative humidity lower than 100%.

Heat Transfer Pathway	Driving Force	
	General[2]	Specific
Evaporation[1]	Water vapor pressure difference with the surrounding, and the wetness of the skin	Airflow: refreshing air
Convection	Temperature difference with a moving gas or fluid	Airflow: refreshing air
Conduction	Temperature difference with a solid material or a nonmoving gas or fluid in contact with the body	Negligible
Thermal Radiation	Temperature difference with surrounding. Fluids or solids have to be in direct visual contact, also their emissivity plays a role	Only plays a minor role in the face[3]

(1) Condensation is not considered to occur under these conditions. (2) More detailed information can be found elsewhere (Incropera & DeWitt, 2002; Parsons, 2003). (3) See Buyan et al. (2006).

C from the head under the relevant conditions is determined by the freedom of air to move over the head (Parsons, 2003). This movement can either be natural, when it is caused by temperature gradients within the air created by skin warming the air. Airflow can also be forced, when the air movement has another cause, such as caused by wind (Blatteis et al., 2001). If the air in the microclimate is not refreshed, then the temperature gradient reaches zero through natural convection. Forced convection is per definition directly coupled with air movement. Thus, also for C, airflow is the driving factor.

K between the head and a motorcycle helmet will occur in the first moments after putting on a helmet, because of its thermal inertia. After this, conductive heat transfer is expected to be negligible, because of the low thermal conductivity of these helmets.

R does not contribute noticeably to the total heat transfer with the skin where it is covered with EPS. Thermal radiation from an external source (e.g. the sun) might warm the outer shell, but its radiant and conductive components are very unlikely to penetrate through the full thickness of the EPS to an extent comparable to other processes under consideration. A similar rationale accounts for the thermal radiant $\dot{Q}$ from the head to the inside of the helmet. However, where there is no thick layer of EPS, particularly in the area of the visor, thermal radiation can contribute to the heat transfer.

1.2.3. Empirically-based results

$\dot{Q}$ from the human head during rest and when normally dressed at T_a of 25 ºC is of the order of 44 W; combined with the heat lost through respiration, this becomes 70 W (Rasch et al., 1991). Whole body heat loss under comparable conditions is of the order of 85 W measured by whole body calorimetry (Jay et al., 2008). Thus, in this situation approximately 80% of all heat is lost through the head. This percentage is likely to be an overestimation since the method employed in the former study was unlikely to strictly separate heat loss from the head from that of the rest of the body. However, this comparison indicates that a relatively large part of the heat is lost through the head. Furthermore, under heat stress the contribution of other body parts becomes larger and can finally result in an equal contribution with respect to that of the head when taking surface area into account. Nonetheless, applying insulation to the head, such as with a motorcycle helmet, can severely modify $\dot{Q}$ from the body, especially under the before-mentioned conditions. Before reviewing the thermal boundary conditions caused by headgear, the theory of heat transfer will be explained as applicable to a head wearing a full-face motorcycle helmet.

Brühwiler (2003) was the first to examine $\dot{Q}$ from a head while wearing a motorcycle helmet. He measured $\dot{Q}$ from the scalp and face using a non-sweating thermal manikin headform at an ambient temperature (T_a) of 20 ºC and a relatively low simulated wind speed (v_w) of 28 km·h^{-1}. The two helmets examined in this study yielded heat losses of roughly 0.5 W and 10 W, for the scalp and face sections respectively. The sum of about 10.5 W is slightly lower than results from the nude human head estimated at 14 W if sweating is neglected, under comfortable conditions with T_a = 25 °C and no applied v_w (Froese & Burton, 1957; Clark & Toy, 1975; Rasch et al., 1991). However, striking is the low contribution of the scalp section to the total $\dot{Q}$, indicating that the insulating effect of these helmets mainly affects the scalp section. In contrast, relatively high levels of $\dot{Q}$ were obtained from the face, suggesting a larger air movement in this area. Compared to the scalp this is intuitive and follows from the theory above.

The suggested unimpaired air movement in the facial microclimate while riding can be verified with literature on the accumulation of gas in this microclimate. Under wind-still conditions, microclimate carbon dioxide concentration reaches levels of the order of 2% (Aldman, et al., 1981; Brühwiler, et al., 2005; Iho, et al., 1980), which rates well above ambient air conditions of ~0.04%. However, only little v_w is needed to drive the carbon dioxide concentration below 0.5% (Brühwiler et al., 2005). This indicates that, with respect to carbon dioxide concentrations, air refreshment over the face is largely influenced by v_w. Therefore, it can be expected that modern motorcycle helmets reduced $\dot{Q}$ from the scalp under relevant conditions below values as measured in a conventional (office) climate. Furthermore, this reduction in $\dot{Q}$ seems mainly to be caused by a reduction in airflow, confirming the theoretical considerations above. Thus, only one study assessed $\dot{Q}$ of two older full-face motorcycle helmets (Brühwiler, 2003), and simulated only one riding condition. Therefore, additional measurements are needed to gain knowledge on $\dot{Q}$ of state-of-the-art full-face motorcycle helmets under a wider range of (simulated) riding conditions.

1.3. Thermal physiology

1.3.1. General effect of headgear

The effect of motorcycle helmets on human thermal physiology has not been previously reported. However, several studies have monitored the effects of headgear on multiple physiological parameters, for bicycle helmets (Gisolfi et al., 1988; John & Dawson, 1989; Sheffield-Moore et al., 1997; De Bruyne et al., 2008), equestrian helmets (Taylor et al., 2008), cricket helmets (Neave et al., 2004), football helmets (Coleman & Mortagy, 1973), and industrial protective headgear (Davis et al., 2001; Holland et al., 2002). None of these studies found a helmet-mediated effect on core temperature (T_c) or heart rate (HR), but did find an increased local T_{sk} where covered by the headgear. The reported minimum temperatures underneath headgear range from 26 ºC to 36 ºC, with maximum temperatures ranging from 30.5 to 36.5 ºC. The variation within these lower and upper limits seems mainly due to differences in T_a

and assumed airflow over the skin under the headgear, possibly in combination with sweating. For instance, the lower range reported [26 ºC – 30.5 ºC] is obtained with subjects wearing a bicycle helmet (De Bruyne et al., 2008). In this study an environment with T_a = 20 ºC and v_w = 9 km·h^{-1} was created. Airflow over the skin underneath this headgear is expected to be relatively high, since modern bicycle helmets only reduce airflow over the head by about 7% to 35% (Brühwiler et al., 2006). However, motorcycle helmets are less open than bicycle helmets. Therefore, one can speculate that T_{sk} underneath a motorcycle helmet will be in the upper range of those reported here, and that T_c is left unaffected, as well as heart rate.

Only focusing on the head and neglecting the rest of the body would be an oversimplification, mainly because blood flow facilitates a very effective means of heat transfer throughout the body (Nybo et al., 2002; Zhu et al., 2006). Thus, a reduced heat loss caused by a helmet is not likely to affect S in formula 1.1, since the reduced heat loss from the head will be compensated by an increased heat loss from other body parts. Therefore, a brief overview will be given on the physiological status of the rest of the body under conditions relevant to riding.

A PTW rider participating in traffic may be required to wear a motorcycle helmet, but in addition often wears additional protective clothing, even though these are not mandatory. Such clothing reduces injury severity of traffic accidents (ACEM, 2004). Similarly to motorcycle helmets, protective clothing in general reduces $\dot{Q}$ from the body (Havenith, 1999). In cool climates this is an advantage. However, in warm climates this might cause heat stress, an idea which is strengthened by frequent complaints about thermal discomfort given for not wearing motorcycle protective clothing (Koch & Brendicke, 1998). An important consideration is at which climates the average protective clothing causes uncomfortable warm conditions. Woods (1983; 1986) investigated the effect of motorcycle clothing on skin and core temperatures under riding conditions, mainly focusing on cold climates. The highest ambient temperatures in these studies ranged from 16 ºC to 23 ºC. At these temperatures one subject drove on separate occasions a distance of 80 km on a motorway and 8 km on urban roads. On the motorway the ‘generally-permitted speed’ was ‘near’ 112 km·h^{-1}. The heat transfer was calculated from the difference in S between the start and end of the motorcycle ride. Under these conditions a reduction in S was observed, but only if the minimum of protective clothing was worn (Figure 1.5), quantified as a clothing thickness of the order of 5 mm (Woods, 1986). It is unclear at which exact speeds the subject was riding, if these results can be generalized to a larger population, or what kind of protective clothing was worn.

It must also be realized that this study was carried out in the 1980's, and that it is likely that the thermal insulation of modern motorcycle summer clothing have decreased since then, motivated by the desire of riders (customers) for more favorable thermal comfort (Koch & Brendicke, 1998). It therefore remains unclear at which combinations of riding speed and T_a the protective clothing causes heat stress to the wearer.

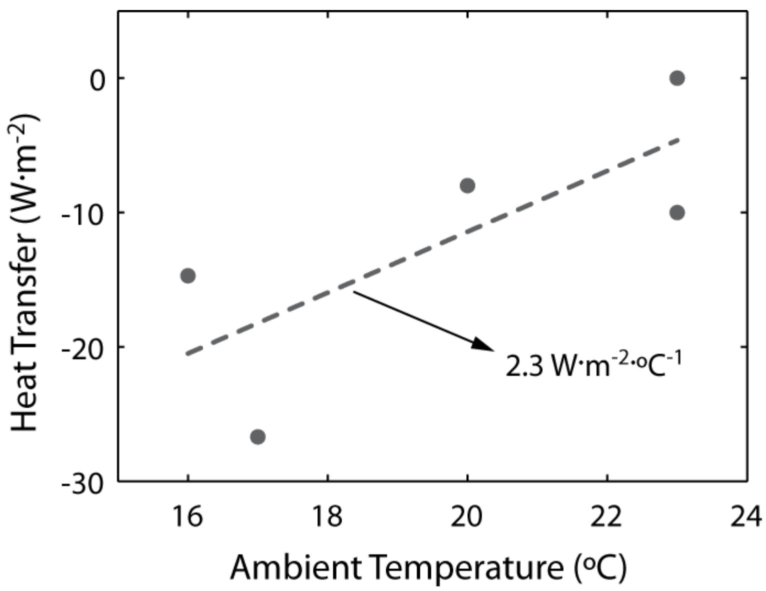

Figure 1.5: Heat transfer facilitated by motorcycle protective clothing while riding a motorcycle on a motorway. The dashed line indicates the linear regression, with a slope as indicated. Data obtained from Woods (1986), pp 458, (Figure 2). More information is given in the text.

1.3.2. Effect of changing local skin temperature at the head

1.3.2.1. Skin blood flow

Tur et al. (1983) measured basal skin blood flow (SkBF) of 52 body sites under stable comfortable conditions. They found a cluster of eleven sites that showed high SkBF compared to the remaining 41 locations. In the group of high perfusion rates were all nine sites on the head, with the remaining two sites located at the hand and finger. Also others found the skin of the head to show the highest basal SkBF (Stücker et al., 2001). Unfortunately, such spatial comparative studies have not included the scalp and solely focused on the face and neck. Furthermore, others found that, in contrast to other body parts, the head does not exhibit large fluctuations of SkBF due to exercise induced hyperthermia (Froese & Burton, 1957; Roberts et al., 1977; Rasch et al., 1991). This indicates that SkBF of the head, and its vasomotor activity, behave differently compared to other body parts. However, most studies on SkBF have focused on the forearm. It is therefore unclear how these results translate to the head, justifying only a brief overview of the literature.

Local SkBF can be affected by thermal and non-thermal factors (Charkoudian, 2003). Important thermal factors are core temperature and local changes of T_{sk} (Charkoudian, 2003). Of special interest to this thesis is the effect of local temperature fluctuations on the local SkBF under normothermic conditions. Most studies have clamped the average whole body T_{sk} at a temperature of 33 – 34 ºC and then either increased or decreased the local T_{sk}. From these studies it seems that if T_{sk} is in steady-state at 34 ºC and the subject is exposed to a lower temperature, a linear relation between local SkBF and the local forced T_{sk} is found, if for each exposure the time is constant. One study investigated the effect of warming and cooling (Charkoudian et al., 1999). From this study the following sensitivities can be derived for cooling below 34 ºC and warming above 34 ºC: ~0.4% of the maximum SkBF per ºC, and ~9% of the maximum SkBF per ºC, respectively. Furthermore, the maximum SkBF is obtained after a 30 min application of 42 ºC coming from a T_{sk} of 33 – 34 ºC (Taylor et al., 1984). This indicates that application duration is also an important determinant for SkBF. Thus, for the relation between local T_{sk} and local SkBF the magnitude of the temperature stimulus is of importance, as well as the duration of application. Furthermore, the effect of reducing local T_{sk} below 34 ºC affects SkBF in a lesser extend than increasing the temperature above 34 ºC.

Finally, the results presented in this part were measured while T_c was within its normal range. However, if the core temperature exceeds this range and hypothermia or hyperthermia occurs, then the core temperature becomes a stronger determinant of SkBF (Rowell, 1977). It has been found that the fluctuations of the core temperature away from the normothermic condition contribute twenty times more to SkBF than fluctuations in T_{sk} (Wyss et al., 1974).

1.3.2.2. Sweat production

The forehead is characterized by one of the highest densities of (eccrine) sweat glands compared to other body parts (Thomson, 1954; Montagna et al., 1962). Correspondingly, the sweat production of the forehead, normalized for surface area, is also among the body parts with the largest values (Hertzman et al., 1952). Recently, two studies have measured spatial differences in sweat production on the head, mainly focusing on the scalp (De Bruyne et al., 2008; Machado-Moreira et al., 2008). One of these studies reports the sweat rates measured on ten different sites on the scalp and forehead under normothermic conditions, with an increased but unreported average T_{sk} (Machado-Moreira et al., 2008). They reported sweat rates for the forehead of 1.2 $mg \cdot cm^{-2} \cdot min^{-1}$, which was a factor 4.5 larger than the average sweat rates at all other sites. This difference remains while subject exercise at different cycle ergometer work rates. However, De Bruyne et al. (2008) did not find spatial differences in sweat production of the scalp during cycling exercise. The application of wind projected towards the front of the subjects in the latter study was given as the reason for this discrepancy.

Fluctuations in T_{sk} can also affect local sweat rate (Nadel et al., 1971; Nadel et al., 1973; Cotter & Taylor, 2005). Cotter and Taylor (2005) dressed subjects in a water-perfusion suit at a temperature of 36.7 ºC. A temperature stimulus was then applied to a 274 cm^2 skin area at each of ten sites. For all ten sites they found that cooling the skin below the steady-state by 11 ºC for 5 min caused a decrease in average sweat rate of 26%, mild cooling for 10 min (4 ºC) 7%, and mild warming for 10 min (4 ºC) 16%. Furthermore, it was found that the face exhibited the strongest effect of local T_{sk} on local sweat rate. Moreover, compared to other body parts the face was a factor 2 – 3 more sensitive to cooling with 11 ºC. However, differences in spatial sensitivities were less profound for mild cooling and mild warming. Finally, as found for SkBF, also the core temperature is a stronger determinant for the sweat rate than T_{sk} (Nadel et al., 1971; Wyss et al., 1974).

Thus, sweat production of the forehead is among the highest of all body parts. But it remains unclear if sweat production of other sites of the head also exhibit such large values as the forehead. Furthermore, local sweat rate can be affected by local fluctuations in T_{sk}.

1.4. Cognition

The effect of a motorcycle helmet on cognition will be differentiated into two aspects of cognition, i) temperature perception and thermal comfort, and ii) performance, such as reaction time and attention. However, before these are discussed, a brief review will be given on thermoreceptors, since these are involved in the relationship between T_{sk} and brain tissue.

1.4.1. Thermoreceptors

Two classes of thermoreceptors can be found in the human skin, warmth sensors and cold sensors (Hensel, 1981; Pierau, 1996). The latter are found in higher densities, and the former at greater depths of the order of 100 – 500 µm. Cold receptors transport their afferent signal over thin myelinated Aδ fibers. Warmth receptors are mainly located at a depth of 2000 – 2500 µm, and communicate through slower unmyelinated C fibers (Ivanov et al., 1982; Pierau, 1996; Romanovsky, 2007). The temperature sensitivity of these receptors is facilitated by a specialized group of transient receptor potential ion channels (TRPs; Dhaka et al., 2006; Romanovsky, 2007). Subgroups of TRPs are defined by the different absolute temperature range in which they become activated upon changes in temperature (Pierau, 1996; Romanovsky, 2007). Cutaneous thermoreceptors are therefore mainly sensitive to temporal temperature dynamics.

1.4.2. Temperature perception and thermal comfort

Even though the head only makes up a small part of the total skin area, for a similar stimulated skin area it ranks among the body parts that exhibit the largest influence on whole body temperature perception (Hardy & Oppel, 1937; Stevens et al., 1974; Crawshaw et al., 1975; Zhang, 2003; Arens et al., 2006a; b) and whole body thermal comfort (Zhang, 2003; Pellerin et al., 2004; Cotter & Taylor, 2005; Arens et al., 2006a; b). Cotter and Taylor (2005) found that the sensitivity was a factor 1.5 larger than the next most sensitive body part (the back). The sensitivity of the face was 2.5 times larger compared with the average sensitivity among all other evaluated body parts, although not all body parts showed significantly different sensitivities compared to the face if parametric statistics were employed. In another very extensive study, it was concluded that, in addition to a relatively high sensitivity of the head, the rate of T_{sk} change has a large influence on temperature perception and thermal comfort (Zhang, 2003; Arens et al., 2006a; b). Motorcycle helmets are expected to cause increased T_{sk} of the head, especially of the scalp. It is therefore not surprising that thermal discomfort is often given as a reason for not wearing a motorcycle helmet (Patel & Mohan, 1993; Skalkidou et al., 1999).

The ventilation systems of motorcycle helmets suggest that they might also cause local temperature changes in the microclimate by opening or closing vents. One study measured the threshold for temperature perception on nine different skin sites on the head, including one site on the scalp (Fig. 1.6; Essick et al., 2004). They applied warming or cooling with a Peltier-regulated thermode with a surface of ~1 cm^2. The thermode applied a temperature change of ±0.35 $°C·s^{-1}$ once a steady-state T_{sk} of 32 °C was reached at the corresponding site. The results indicate that the scalp is at least a factor of two less sensitive compared to the face. In the same study qualitatively similar results were found for cooling the skin. It can therefore be concluded that there are spatial differences in temperature perception thresholds on the head, and that the scalp is the least sensitive. However, Katsuura et al. (1996) applied a constant amount of cooling to three different sites on the head with a similar surface area; the forehead, the back of the scalp, and an area around the ears. Each subject sat on a chair during 90 min in a climate chamber with a constant T_a of 40 °C and RH of 50%. Cooling applied at all three sites resulted in more favorable whole body temperature perception and thermal comfort. But no differences were found among the three cooled sites. This tends to indicate that, once the thermal threshold is exceeded, the effects on these perceptual parameters are similar. However, concerning full-face motorcycle helmets there is a need for understanding their impact on temperature perception and thermal comfort. Of special interest are differences among helmets which might lead to the understanding of which helmet characteristics exert a positive effect on temperature perception and thermal comfort.

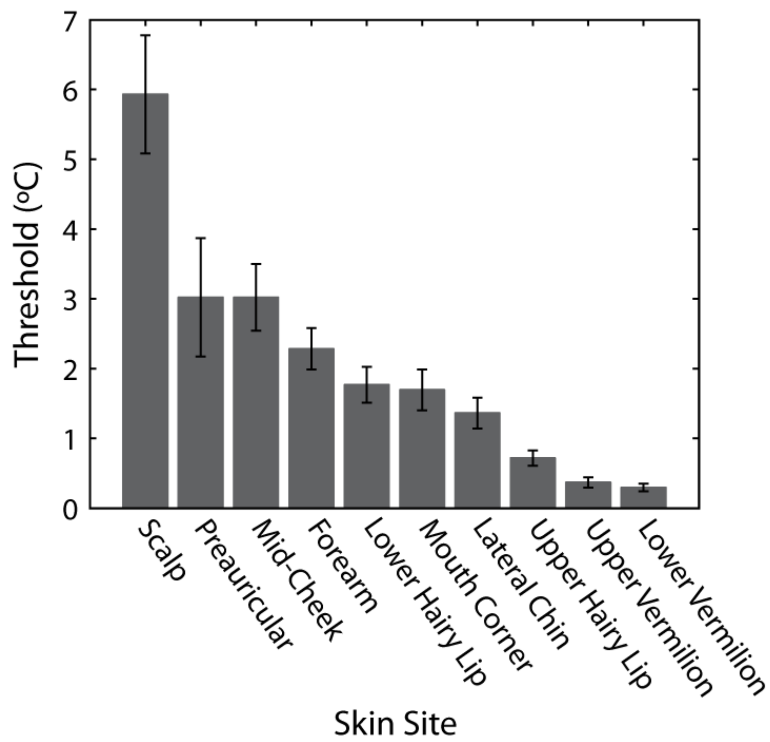

Figure 1.6: Temperature perception threshold for warming a 1 cm^2 skin area with a rate of 0.35 $°C·s^{-1}$ at different sites; data taken from Essick et al. (2004), pp 165 (Figure 4).

1.4.3. Cognitive performance

Cognitive tests allow studying of cognitive processes relevant to traffic participation, in a safe and controlled surrounding, as are employed by many (e.g. Daanen et al., 2003; Ball et al., 2006). Several studies have warmed the head of resting subjects in a thermal neutral environment, with and without manipulating the thermal state of the rest of the body (Holt & Brainard, 1976; Hancock & Dirkin, 1982; Hancock, 1983). These studies used the same helmet instrumented with electrical heaters on its inner surface, achieving an increase in tympanic temperature of the order of 1 °C (Holt & Brainard, 1976). One study reported a shortening of reaction time by heating the head, reported on the $p < 0.1$ level (Holt & Brainard, 1976). Hancock and Dirkin (1982) found increased reaction times and a decrease in errors on a choice reaction test. Such an effect could simply indicate an attention shift from one task to the other; a follow-up study was therefore carried out. In that study, subjects completed significantly more mathematical problems in a given period while wearing the heated helmet (Hancock, 1983). These three studies also evaluated cognitive performance while wearing the helmet without the heating elements turned on. However, only one found an effect, in the form of an increased reaction time (Hancock & Dirkin, 1982). Others have focused on the effect of externally cooling the head of subjects in neutral and warm environments (Konz & Gupta, 1969; Nunneley et al., 1982; Simmons et al., 2008). None of these studies found a significant effect on cognitive performance. Finally, one publication investigated the effect of sports headgear on cognitive performance in combination with exercise (Neave et al., 2004). They found impaired performance on vigilance and increased reaction times while wearing a standard cricket headgear during cricket practicing, but only after combining cognitive parameters. Vigilance refers to the ability to sustain attention for a prolonged period of time (Lezak et al., 2004). Thus, two studies found an effect of passive (non-heating) headgear on cognitive performance (Hancock & Dirkin, 1982; Neave et al., 2004); in contrast, two other studies did not find such an effect (Holt & Brainard, 1976; Hancock, 1983). Thus the relation between headgear and cognitive performance as found in previous work is unclear. A larger body of literature is available on the effect of a warm environment on cognitive performance, while the headgear configuration was kept constant within each study. Below this literature will be reviewed in order to better understand warmth-mediated effects on cognitive performance.

Impairments of some aspects of cognitive performance have been reported to occur in warm environments (Ramsey, 1995; Johnson & Kobrick, 2002; Pilcher et al., 2002; Hancock & Vasmatzidis, 2003; Hancock et al., 2007). This body of literature contradicts on which aspects of cognitive performance are affected in warm environments. However, a reduction in both vigilance performance and more complex dual task performance is generally reported. For example, Vasmatzidis et al. (2002) submitted twelve subjects to an extensive test-battery in six different thermal environments. Among other tests their subjects carried out a visual and an auditory vigilance task. They found that the performance on both vigilance tests was impaired if the combined T_a and RH exceeded 28 ºC wet bulb globe temperature (WBGT). WBGT is a single coefficient, especially suitable for representing heat stress experience by a human (ISO7243, 1989). Also others have found impaired vigilance performance in warm environments (Wyon et al., 1979; Wyon et al., 1996; Færevik & Reinertsen, 2003). However, some studies report no adverse effect of a warm environment on vigilance performance (e.g., Tikuisis & Keefe, 2005). However, most of these reviews indicate that vigilance performance is likely to be impaired in warm environments, although it remains unclear if local heat stress affects cognitive performance. Combining the literature on headgear and heat stress, it is clear that full-face motorcycle helmets have the potential of negatively affecting cognitive performance. Given the importance of cognitive performance to traffic safety (Section 1.1.1), it is of importance to investigate its relation with wearing a motorcycle helmet.

So far this introduction has focused solely on thermally-mediated effects of full-face motorcycle helmets with special interest to warm environments. However, there are indications that a motorcycle helmet can lead to other disturbances, caused for instance by its weight, reduced vision, discomfort caused by suboptimal fit, odor and gas accumulation, or a claustrophobic effect in those who are sensitive to this. These and more factors might also play a role in the effect on cognitive performance of wearing a motorcycle helmet. However, because of the scope of this thesis, these disturbances will not be treated in this thesis.

1.5. Goals and approach

Above the problem is described, the relevant literature is reviewed, and it is indicated were knowledge is insufficient or absent. This thesis aims to contribute at completing this knowledge.

It is unclear what thermal boundary conditions are created by state-of-the-art full-face motorcycle helmets. Therefore, a large sample of modern helmets will be collected from different manufacturers. These helmets will then be submitted to thermal manikin headform measurements, the goal of which is to quantify thermal parameters (Chapters 3 and 4) under a wide range of simulated but realistic conditions, and in addition, to quantify the effect of the ventilation systems integrated into these helmets.

The literature indicates that wearing a full-face motorcycle helmet is likely to affect T_{sk} where it is covered by headgear. However, it is unlikely that T_c or HR will be affected. Therefore, the effect of these helmets on T_{sk} of the head will be quantified under simulated but realistic riding conditions (Chapter 5). Especially focusing on the scalp, where the thermal conditions are expected to be the most unfavorable. However, literature and theory indicate that it is likely that the helmet-mediated reduction in $\dot{Q}$ from the head can be compensated by an increased $\dot{Q}$ from other body parts. Therefore, T_c will not be measured. HR and heart rate variability (HRV) will be registered, mainly since these two parameters can be utilized as objective measures for cognitive stress (Chapter 6).

Temperature perception and thermal comfort will also be assessed. Here special attention will go to the differences among helmets and the effect of the ventilation systems equipped on these helmets. This will allow detailed investigation of the relation between perception and $\dot{Q}$ measured on a manikin. In this analysis other parameters will also be involved, e.g., T_{sk} and helmet type, so that important parameters for subject perception can be identified. Furthermore, this will reveal if motorcycle helmets affect cognition (perception) (Chapter 5).

It remains unclear if wearing of a full-face motorcycle helmet affects cognitive performance. Therefore, a study will be carried out to investigate this. Cognitive performance will be assessed with auditory and visual vigilance tasks, since these tasks have been proven sensitive to heat stress. Other cognitive skills will also be evaluated (Chapter 6).

2. General methods

Here general methods not detailed in the following chapters are described.

2.1. Climate chamber and wind tunnel setup

All studies reported in this thesis took place in the same climate chamber, with inner dimensions of 3.0 x 6.8 x 2.0 m^3 (width x length x height). In this chamber, a framework was placed holding a small wind tunnel and a tray table at its exit, on which a headform or a computer screen could be placed (Figure 2.1). The wind flowed toward the position of the headform from the front, as shown.

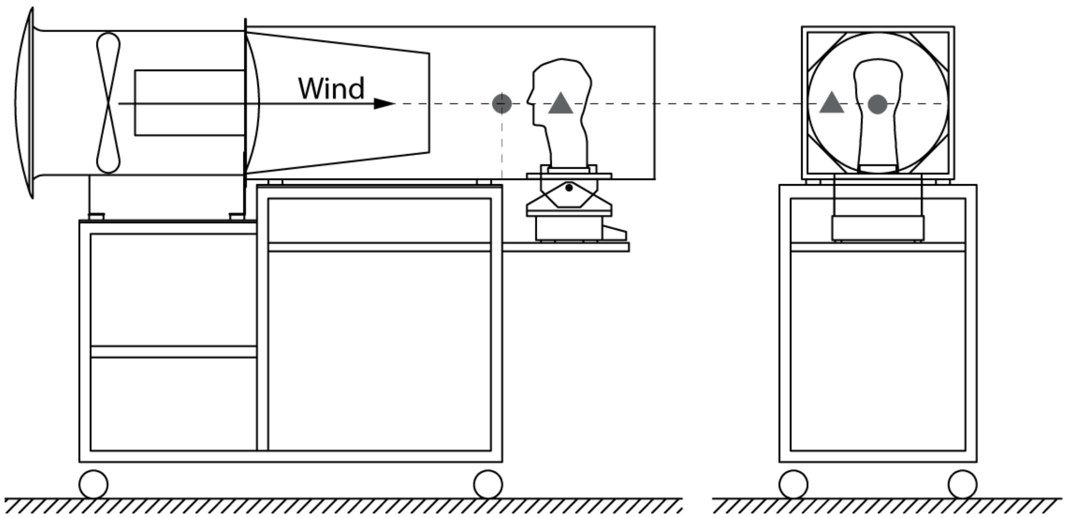

Figure 2.1: The framework holding the wind tunnel as a side-view (left) or front-view (right). A headform or the head of a subject could be positioned at the exit of the wind tunnel. The wind flowed toward the headform as indicated. Wind temperature (●) and wind speed (▲) were measured on the indicated locations.

During measurements in this setup, both wind temperature (T_w) and wind speed (v_w) were measured. T_w was measured in the middle of the air stream at a point about one-third of the distance from the exit to the source (Figure 2.1). For this purpose, a PT100 temperature sensor with an accuracy of 0.01 ºC was employed (PT100, Roth+CO, Oberuzwil, Switzerland) connected to a reader (HD 2127.2, Delta Ohm, Caselle di Selvazzano, Italy). The sensor was fixed along a wire running from the bottom of the tunnel housing until the top. The ambient temperature (T_a) was measured by a second PT100 temperature sensor positioned on the ceiling about 2 m away from the setup, outside the air stream. T_a, T_w, and v_w, were on average registered once per trial.

A handheld anemometer was used for measuring v_w (MiniAir2, Schiltknecht, Gossau, Switzerland). When measuring v_w this sensor was positioned at the level of the ear, and the maximum reading was searched by rotating the anemometer over its horizontal and vertical axis, and by displacing it between the wall of the housing and the headform. During this process, the sensor of the anemometer always remained at the level of the ear as indicated in Figure 2.1. The average v_w over 6 s was obtained from the sensor orientation giving the highest wind speed. This method was used since it was believed to give values more closely related to effective realistic conditions compared to measuring in front of the headform (such as for the temperature sensor). This is because the headform forces the wind through the much smaller volume between the headform and the housing, which is not expected to occur in a similar fashion in reality in which there is no wind tunnel housing. However, the employed method does not correspond to the ideal case, but is the optimal choice for this setup. A study by Brühwiler et al. (2005) can be seen as a validation of v_w against motorcycle riding speed in traffic. They measured v_w in the same manner as described here in the same setup and climate chamber. Facial microclimate carbon dioxide concentration was measured in the laboratory conditions and during outdoor motorcycle riding. They found similar carbon dioxide levels in both conditions if the riding speed was increased with a factor of 1.3 to 1.4 over v_w, for v_w of 36 $km \cdot h^{-1}$ and 62 $km \cdot h^{-1}$, respectively. The nature of the difference between v_w and driving speed is not clear, but could be attributed to the method of measuring v_w in the setup.

During all measurements in the climate chamber, both T_a and T_w were registered (Figure 2.2). From Figure 2.2 it can be concluded that the temporal stability of the temperature was high, since the standard deviations (σ) did not exceed 0.23 ºC. During these measurements v_w ranged from 2 to 59 $km \cdot h^{-1}$. In addition an effect on T_w of v_w was discovered and quantified. This relationship is caused by heat produced by the engine of the fan, and was best described with a quadratic equation ($r = 0.99$, and $p < 0.001$), as shown in equation 2.1 for $T_a = 22.90 \pm 0.05$ ºC:

$$T_w = 0.0005 \cdot v_w^2 - 0.012 \cdot v_w + 21.99 \qquad (2.1)$$

Hence, T_w was 2.3 ºC higher, when comparing the lowest v_w of 2 $km \cdot h^{-1}$ studied here to the highest, at 79.8 $km \cdot h^{-1}$.

The spatial distribution of the temperature was also investigated. For this purpose temperature was measured on five points inside the wind tunnel housing, in a plane perpendicular to the direction of v_w at the level of the sensor measuring T_w

(Figure 2.1). Spatial variations of 0.07 ºC and 0.09 ºC were measured at v_w of 50.0 km·h^{-1} and 79.8 km·h^{-1}, respectively. It was concluded that these variations are negligible. However, helmet and headform placements were standardized to ensure a position of the head and helmet as similar as possible, as explained in Section 2.2.

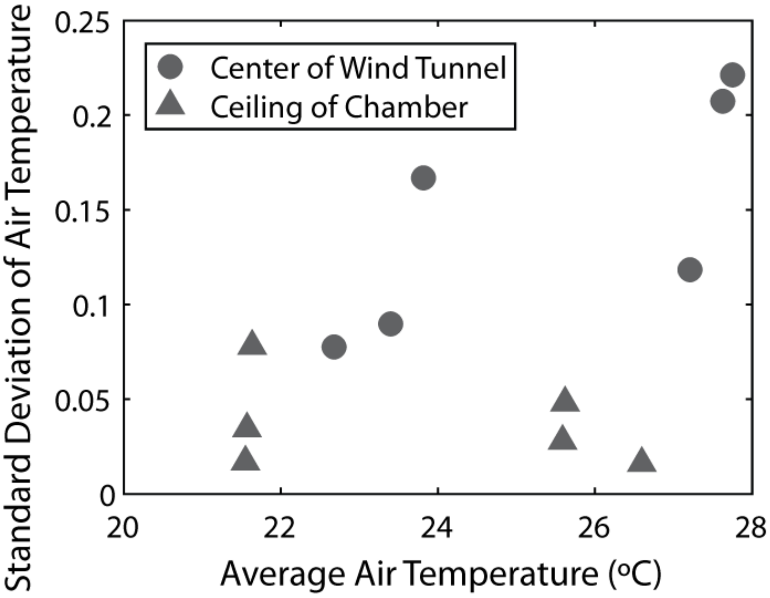

Figure 2.2: Standard deviation of the air temperature with respect to the average air temperature, measured at the center of the wind tunnel (● see Figure 2.1) also referred to as wind temperature. In addition, the readings for the ambient temperature are given, measured at the ceiling of the climate chamber (▲). Each data point consists of at least 27 separate readings.

2.2. Thermal manikin headform

In two studies a thermal manikin headform was used to assess heat transfer from the scalp and face sections facilitated by different helmets (Figure 2.3). This headform was constructed according to average head dimensions, with a head circumference of 57 cm. The surface temperature of the headform was regulated at a fixed temperature, and the power needed to maintain this temperature in a 20 min steady-state period was recorded. This heating power equals the heat loss ($\dot{Q}$), since no external heat was received by the headform, as will be explained later. Values for the scalp ($\dot{Q}_S$) and face ($\dot{Q}_F$) sections were obtained separately. The neck section of the headform was also heated to prevent conductive heat transfer to the support. Finally, the support could be rotated forward, enabling a head tilt between 0º and 30º relative to the wind direction.

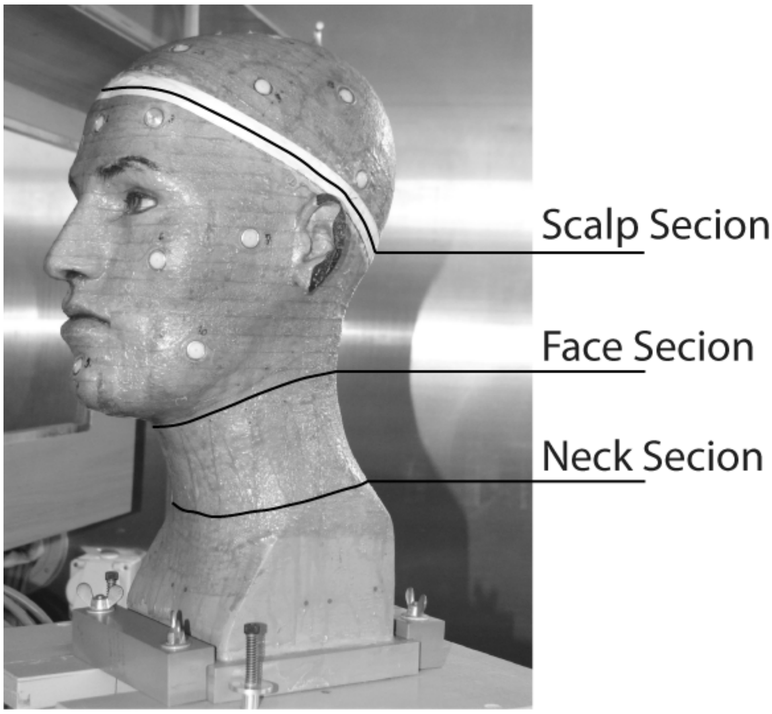

Figure 2.3: The thermal manikin headform, with the three separate sections as indicated.

Multiple helmets were assessed on this headform under different conditions, and generally each helmet was measured in three sessions, for each condition (unless indicated otherwise). In one session all vents were consecutively all open and all closed in random order. New helmet placements were made between sessions. All helmets were placed based on a broadly used impact test standard (ECE324, 2002), with a specified space of 3.9 ± 0.2 cm between the bridge of the nose and the upper edge of the helmet facial opening. In order to increase reproducibility, a plastic frame was used which standardized the position and orientation of the facial opening of the helmets with the headform. All measurements were carried out with the lights of the chamber turned off. A scarf covered the neck section to avoid an unnecessarily large forced convective heat loss there. This also simulates a realistic situation, since many motorcyclists wear such protection. Finally, a wooden form was used to ensure a reproducible position and orientation of the headform relative to the housing of the wind tunnel during each measuring session.

It was assumed that in this setup the total heat transfer consists primarily of convective heat loss, since the scalp section is completely covered by the comfort liner and a ~3 cm thick layer of expanded polystyrene foam leaving no other heat pathways. The main difference in the face section is the facial opening, which is covered by a visor made from a transparent material, and therefore facilitates radiant heat flow. Although the chamber lights were turned off during headform measurements, a window with direct view on the headform could allow some radiant heat transfer. In order to quantify this, measurements on three helmets (110, 130, and 201) were carried out, with and without aluminum foil covering the total surface of the visor. The results indicated that the radiant contribution to the heat transfer in the face section was -0.1 ± 0.2 W, or -1 ± 3%, falling well within one σ of the results presented in this thesis obtained with the headform. Thus, radiant heat transfer is negligible under the given conditions.

Some heat transfer inevitably takes place between the sections, although special care was taken to insulate the sections from each other, especially between the scalp and face sections (Brühwiler, 2003). It is likely that a high heat production of a given section corresponds to higher internal temperatures around the same section. Since conductive heat transfer is driven by temperature differences, a difference in heat production between two sections might cause conductive heat transfer. In order to investigate this, two sets of measurements were carried out. All conditions were kept constant while i) different levels of radiant heat were applied only to the scalp section, or ii) different levels of textile insulation were applied only to the face section. As a result the heat production of one section changed. Since all conditions were kept constant, the section that was not modified should show an unchanged heat production, if there is no heat transfer between the sections. However, if the heat production in the unmodified section does not stay constant, then it is likely that heat transfer between the sections takes place. The combined results are displayed in Figure 2.4. The results indicate that there is a significant relation between the differences in heat production of the two sections. From this relationship it can be derived that a difference in heat production of 1 W is expected to cause a heat transfer between both sections of 0.023 W. In this work, the largest difference measured between the scalp and face sections is of the order of 16 W, in this case a heat transfer between the sections of 0.4 W might occur. This should be taken into consideration when making comparisons among helmets. However, the largest part of this work compared differences within a helmet, caused by interventions. Typical differences in heat production between the scalp and face sections caused by such interventions are of the order of 1.5 W (e.g. for tilting the headform as reported in Section 4.3.1). These interventions affect heat transfer between sections of smaller than 0.1 W. Such fluctuations are much smaller than typical σ obtained for these measurements. Therefore, the results presented in this thesis are not corrected for heat transfer between the scalp and face sections. Finally, the heat transfer between the face and the neck sections is not characterized. It is likely that this relationship is similar to that found for the scalp and face, but will depend on the insulation between the face and the neck sections.

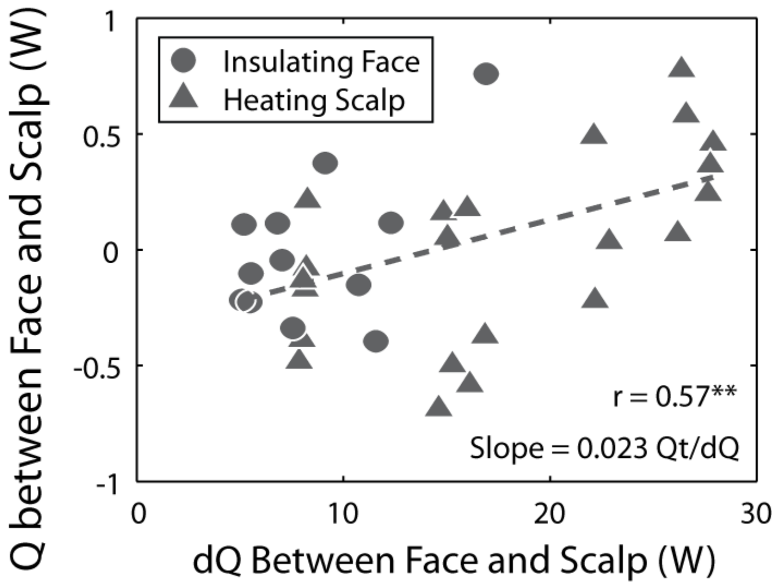

*Figure 2.4: Heat transfer between the scalp and face sections at a range of differences in heat production between both sections; ** $p < 0.01$. The results were obtained keeping all conditions constant, while applying textile insulation to only the face section, or by applying external radiant heat only to the scalp section.*

Heat loss measured with this headform reasonably relates to heat loss from a human head. For instance, at T_a of 25 ºC, $\dot{Q}$ from this headform equals 10.6 W (Brühwiler, 2003) if no sweating is applied. $\dot{Q}$ from the human heads under similar conditions are reported to be 14 W (Froese & Burton, 1957) and 12 W (Rasch et al., 1991) after compensation of heat loss from sweat evaporation. However, it must be realized the combined $\dot{Q}$ does not include the neck, which is (at least in part) the case for the human subject studies. Furthermore, results from the headform were found to relate to perception (Brühwiler et al., 2004). It can therefore be concluded that the headform approximates the total heat loss from a human head, and that its results can relate to perception.

During this thesis work, reference measurements were carried out with the headform, under the same conditions with v_w of 14.4 km·h^{-1}, and T_a of 22.0 ºC (Bogerd et al., 2008). These reference measurements allow the visualization of the stability of the headform over time (Figure 2.5). Both sections show a different time-development, indicating that the cause is not likely to be external (e.g., changing temperature regulation of the chamber). A linear regression fit to the data for the scalp section shows no significant changes over time. However, the linear regression for the face section is significant ($p < 0.001$) and shows a slope (or drift) of -0.41 $W \cdot year^{-1}$. This has to be taken into consideration if absolute results taken with an interval of several months (or longer) are compared. Since each study did not take longer than 6 months the theoretical drift is of the order of -0.2 W. However, the σ of the data-set for each helmet and condition is of the order of 0.5 W. It is therefore concluded that this drift did not affect the results. The cause of this drift is unclear. A possible explanation could be oxidation of electronics in the face section. The oxidation could be facilitated by a fraction of the 'sweat' that leaks into the inner side of the headform. Water accumulation is more likely on the face section because it is located below the scalp section. Finding the source of this drift and recalibration are recommended for future work with this manikin.

Formula 2.1 gives the relationship between v_w and T_w. Chapter 4 of this thesis investigates the effect of $\dot{Q}$ with respect to a range of v_w from ~0 $km \cdot h^{-1}$ to ~80 $km \cdot h^{-1}$. Thus, in order to make meaningful comparisons $\dot{Q}$ had to be corrected. Since, in this case, $\dot{Q}$ is only driven by forced convection, and thus by the temperature gradient between the surface of the headform ($T_{headform}$) and T_w, it can be described by formula 2.2 (Incropera & DeWitt, 2002).

$$\dot{Q} = h_c \cdot (T_{headform} - T_w) \tag{2.2}$$

Here h_c is the convective heat transfer coefficient ($W \cdot {}^{\circ}C^{-1}$), and $T_{headform}$ was for this comparison set to 35.0 ºC. Rewriting for h_c yields:

$$h_c = \frac{\dot{Q}}{(T_{headform} - T_w)} \tag{2.3}$$

Since h_c is independent of small temperature fluctuations of the order of 2 ºC, $\dot{Q}$ can be corrected as follows:

$$\dot{Q}_{cor} = \frac{\dot{Q}}{(T_{headform} - T_w)} \cdot (T_{headform} - T_a) \tag{2.4}$$

Here T_a represents the desired temperature (22.0 ºC).

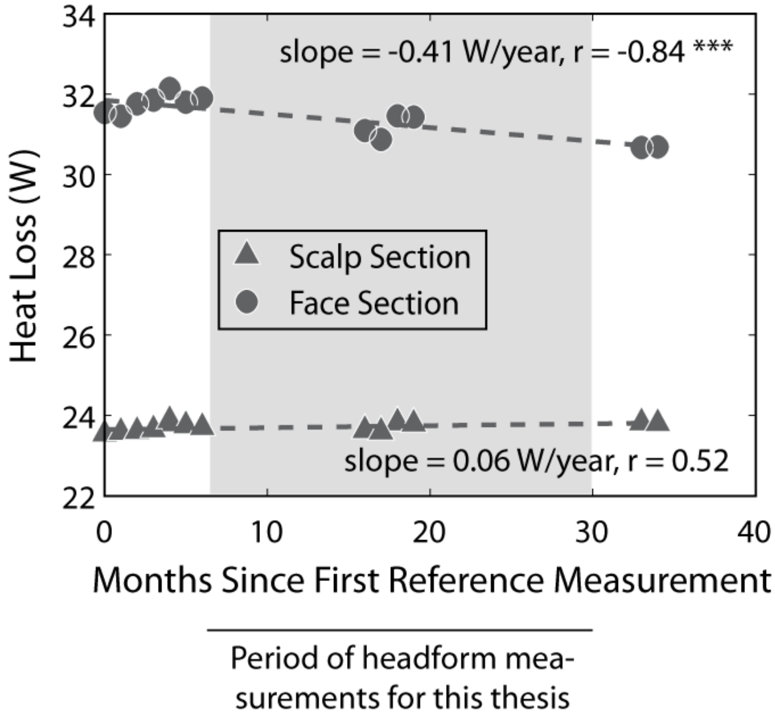

*Figure 2.5: Heat loss under similar conditions from scalp and face sections as indicated. These results indicate the stability of the thermal manikin headform employed in this thesis. The dashed lines indicate the linear regressions through the data-sets; significance is indicated as: *** $p < 0.001$. The gray area indicates the period during which headform measurements were carried out for this thesis. The first measurement was carried out in December 2005.*

2.3. Sensors general

All sensors were calibrated at intervals as indicated by the manufacturer or dealer, or if the readings given by the sensor were suspicious. The employed thermistors (DS18B20 – T3, Prospective Concepts, Glattbrugg, Switzerland) and combined thermistors and relative humidity sensors (SHT15, Prospective Concepts, Glattbrugg, Switzerland) were calibrated at least once before the start of a study and/or after finishing a study. As reference an externally calibrated mini climate chamber was used, equipped with a dew point sensor accurate at 2% and a temperature sensor with an accuracy of 0.1 ºC (Opti-Cal, Michell Instruments, Cambridgeshire, UK). A temperature range from 20 ºC to 40 ºC with steps of 5 ºC (at a RH of 50%) was used, and an RH range from 30% to 90% with steps of 10% (at a temperature of 35 ºC).

2.4. Statistics and data processing

Statistical significance was standardly taken to be reached at $p < 0.05$. Most statistics were carried out with SPSS version 13 through 16 for Windows. In some occasions another program (i.e. Matlab) was used for statistical analysis; in such cases, Matlab was verified to give the same results as SPSS. Furthermore, most data was analyzed with parametric statistics, and reported as average ± σ. However, where non-parametric statistics is used for data analysis the results are given as median (25^{th} percentile; 75^{th} percentile). Finally, in all figures symbolic representation of the significance level is given as follows: * is $p < 0.05$, ** is $p < 0.01$, and *** is $p < 0.001$. All data processing was carried out through programmed routines, using Matworks Matlab R2006b or R2007a for Windows.

3. Heat loss variations of full-face motorcycle helmets

Bogerd CP & Brühwiler PA.

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3.1. Introduction

Approximately 7000 powered two-wheeler (PTW) fatalities occur annually throughout Europe, accounting for 14% of the total traffic fatalities (ETSC, 2006). However, per traveled kilometer PTW drivers are 20 times higher at risk for a fatal accident than car drivers (Koornstra et al., 2003). Horswill and Helman (2003) studied traffic behavior of motorcyclists and car drivers and concluded that the influence of motorcyclist behavior on their accident risk may be surprisingly small. However, factors that might (partially) explain the higher PTW traffic accident risk are reduced conspicuity (ACEM, 2004; Wells et al., 2004) and higher vulnerability of the PTW drivers (ACEM, 2004). Furthermore, it has also been suggested that wearing a motorcycle helmet could influence cognitive performance of the wearer (Chinn et al., 2003).

Motorcycle helmets can cause disturbances to the wearer by factors such as noise (Iho et al., 1980; McCombe et al., 1994) and altered CO_2 and O_2 concentrations (Iho et al., 1980; Brühwiler et al., 2005). Thermal discomfort has been shown to be an issue with bicycle helmets (Gisolfi et al., 1988) and industrial helmets (Liu et al., 1999), and the same can be expected for motorcycle helmets (Patel & Mohan, 1993; Buyan et al., 2006). Airflow influences all three of these factors, indicating that heat loss, and in particular forced convection, are important for the level of comfort experienced.

Several studies have considered natural convection of industrial helmets, generally showing large variations among the helmets and a significant effect of the vents, particularly if positioned on the top (Abeysekera & Shahnavaz, 1988; Abeysekera et al., 1991; Holland et al., 2002). In the presence of wind, forced convection must be considered. For bicycle helmets relatively large variations in heat loss were found (Reid & Wang, 2000; Brühwiler et al., 2006). Some of the above-mentioned studies have been used in optimizing protective headgear for heat loss. One study addressed heat loss of motorcycle helmets in wind, and found that the heat loss from the scalp section of a thermal manikin headform was very low for the two measured helmets, whereas a 20% variation was observed for the face (Brühwiler, 2003). This already suggests that investigating the heat loss of motorcycle helmets should enable one to optimize these helmets for forced convection and, thereby, comfort and possibly safety.

We studied heat loss of 27 modern full-face motorcycle helmets to investigate the state-of-the-art of helmet ventilation, including the effectiveness of the vents provided on these helmets. The helmets were assessed on a thermal manikin headform.

3.2. Methods

A total of 27 modern full-face motorcycle helmets (9 flip-up and 18 integral models) from 13 manufacturers were examined on an electrically heated thermal manikin headform. The headform and its setup are described in Chapter 2 and shown in Figure 3.1. The wind tunnel was set to produce a wind speed of 50.4 ± 1.1 $km \cdot h^{-1}$ (14.0 ± 0.3 $m \cdot s^{-1}$). The climate was maintained at 22.90 ± 0.05 °C and 50 ± 1% relative humidity. All helmets except for the helmet designated by number 161 were equipped with at least one operable vent in the face section, and all with at least one in the scalp section. The visor remained closed throughout the entire experiment.

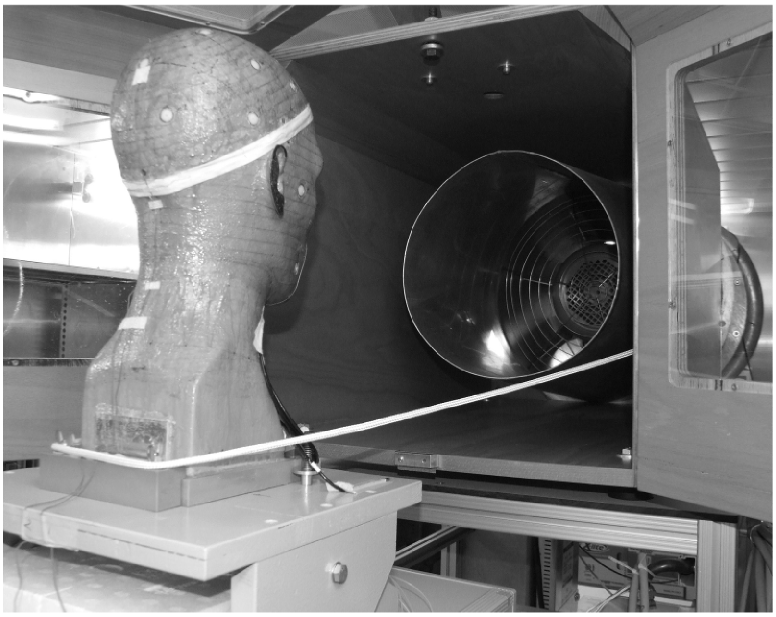

Figure 3.1: The headform positioned at the exit of the wind tunnel in the climate chamber. The headform has been displaced towards the observer and to the left to make details of the setup more accessible to view.

Two datasets were obtained i) absolute heat loss ($\dot{Q}$) from a section with a given vent configuration, and ii) relative heat loss that indicating the effect of opening the vents for a given section ($\Delta\dot{Q}$). For the absolute dataset both vent configurations were compared per helmet, using ANOVA, with a Tukey test for post hoc comparisons. The same was done for the relative dataset, which was tested for difference from zero.

3.3. Results

The results are shown in Figure 3.2. Large variations in heat loss among the helmets were observed in both the scalp and face sections, ranging roughly from $0 < \dot{Q}_S < 4$ W (scalp) and $8 < \dot{Q}_F < 18$ W (face). Eighteen helmets in the scalp section showed a significant $\Delta\dot{Q}_S$ (not significant for helmets 120, 161, 180, 181, 193, 202, 212, and 251). For the face section nine helmets indicated a significant $\Delta\dot{Q}_F$ (significant for helmets 130, 131, 132, 140, 150, 181, 210, 250, and 260). These results can be put into perspective by observations that human subjects are sensitive to heat transfer fluctuations of at least 1 W – 2 W in the scalp (Brühwiler et al., 2004) and the face (Buyan et al., 2006) sections. In the scalp section four helmets showed a $\Delta\dot{Q}_S > 1$ W (two helmets for $\Delta\dot{Q}_S > 2$ W); for the face section six helmets showed a $\Delta\dot{Q}_F > 1$ W (one helmet for $\Delta\dot{Q}_F > 2$ W).

3.4. Discussion

The heat loss in the face section was approximately a factor seven larger than in the scalp section, as seen for two older helmets studied previously (Brühwiler, 2003). This is not surprising since the face sections of the helmets allow much more airflow, and thus forced convection, due to a relatively large opening under the chin and, in some cases, at the visor-helmet interface. In the scalp section the contact between liner and manikin is much tighter, and thus airflow over the scalp section is mostly facilitated by the vents and built-in air passages to this section.

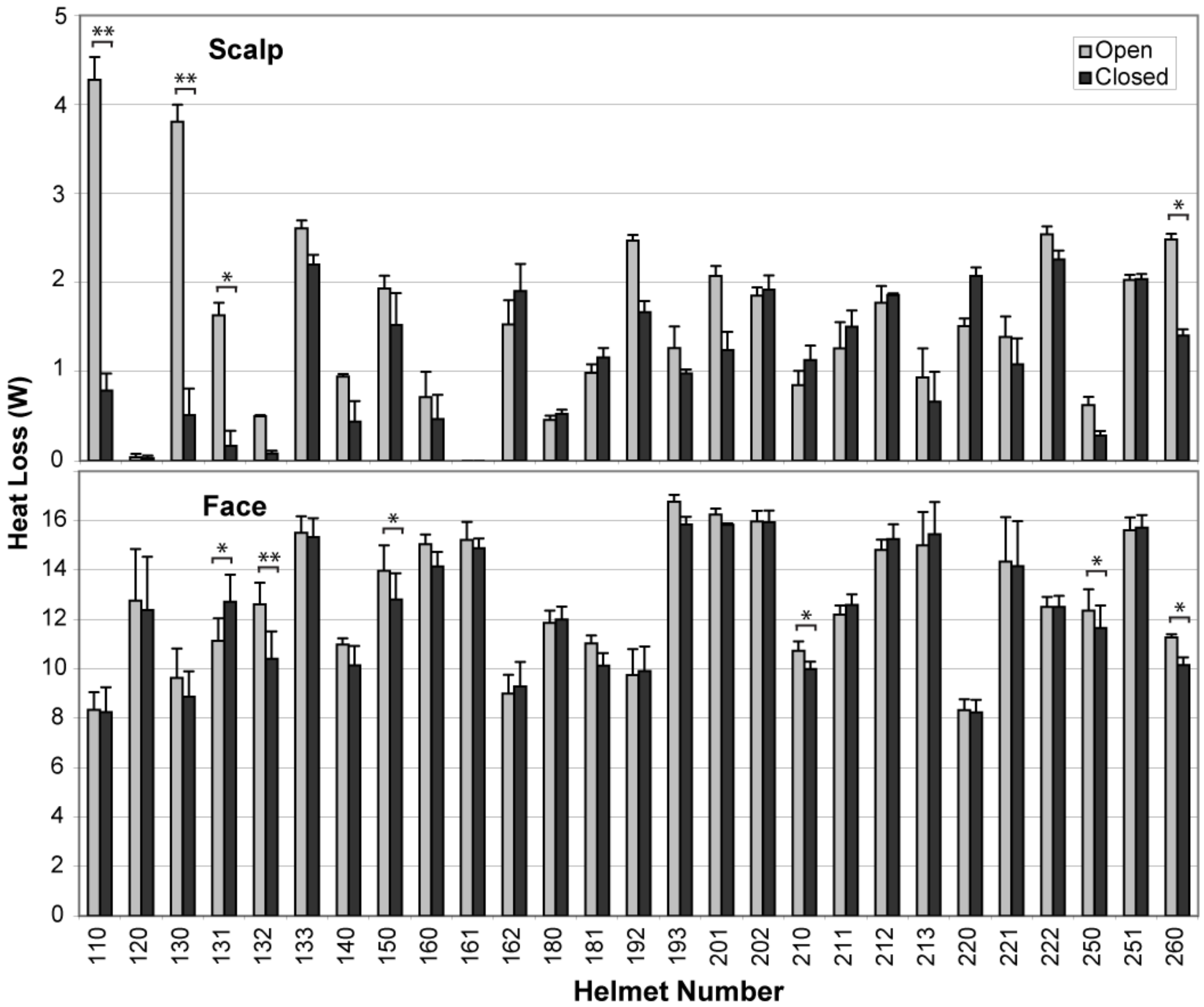

Figure 3.2: Heat loss of the helmets with the vent configuration as indicated. The error bars indicate one standard deviation; one asterisk indicates a effect of opening the vents larger than 1 W, two asterisks indicate a vent induced heat loss larger than 2 W.

Under the measured conditions the vents were usually ineffectual for changing the heat loss to an extent noticeable for human subjects. This together with the large variations among the helmets strongly suggests that this problem has not yet systematically been studied, as similarly found for bicycle helmets (Brühwiler et al., 2006). In order to gain insight into heat loss mechanisms for the present helmets, two intuitively important construction features were examined; i) the presence of a chin cover, and ii) the permeability of the liner (see Table 3.1). Pearson's correlation coefficient was calculated based on the numerically-expressed construction feature and the heat loss for the scalp and face sections separately. The results indicated a significant negative correlation between the presence of a chin cover and the heat loss in the face section ($r = -0.58$ and $p < 0.01$). Furthermore, a positive correlation was found between the permeability of the liner and the heat loss in the scalp section (r = 0.61 and p < 0.01). It appears reasonable that the existence of a chin cover, and a decreasing air permeability of the liner, should reduce heat loss from the face and scalp sections, respectively. The fact that these two construction features explain only ~35% of the heat loss variance in both sections indicates that there are additional unidentified factors determining the effectiveness of the vents.

Table 3.1: Helmet construction features found to be relevant to heat loss.

Construction feature	Description	Method	Scoring system
Chin cover	Fabric partly closing the relatively large opening underneath the chin.	Visual inspection	0 = no chin cover 1 = presence of chin cover (impossible to see the front of the chin if observed from the bottom)
Liner permeability	Resistance of the liner to air diffusion.	Tactile, breath resistance	0 = impermeable (<150 $l \cdot m^{-2} \cdot s^{-1}$) 1 = moderately permeable (550 – 650 $l \cdot m^{-2} \cdot s^{-1}$) 2 = permeable (>3000 $l \cdot m^{-2} \cdot s^{-1}$)

*The majority of the liners were fixed to the inner shell, so that the liners had to be examined subjectively. This method was validated on seven randomly-chosen liners from all categories, giving the corresponding permeabilities shown above. This validation was carried out in accordance with (ISO9237, 1995).

3.5. Conclusions and outlook

In this study we found large variations in heat loss among a large sample of modern full-face motorcycle helmets. Furthermore, four out of 27 helmets showed a change in the heat loss upon opening the vents of the order that is sensitive to humans, with six helmets showing a similar effect in the face section. Helmet construction features such as a chin cover and the permeability of the liner appear important for the heat loss, explaining ~35% of the variability in the vent induced heat loss.

The present results suggest that the general understanding of motorcycle helmet ventilation is still in its infancy. This study must be considered as a first examination of some aspects of motorcycle helmet heat loss. One could imagine that, for helmets with several vents, for instance, particular combinations of open and closed vents yields better heat loss than found here. Furthermore, it should be noted that helmets with a large heat loss are not necessarily optimal. In cool environments for instance, a helmet with a low heat loss might be advantageous. It therefore seems obvious that effective vents, which put the wearer in control of the micro-climate inside the helmet, are to be the focus of future studies in this area. In addition, the relation between helmet heat transfer and other aspects such as, e.g., wind speed, head angle, and the effect of hair (Brühwiler et al., 2006; Bogerd et al., 2008), remain unclear.

4. The role of head tilt, hair and wind speed on forced convective heat loss through full-face motorcycle helmets: A thermal manikin study

Bogerd, CP & Brühwiler, PA

Published in: International Journal of Industrial Ergonomics (2008), 38; 346 – 353.

4.1. Introduction

It has been proposed that helmet comfort is of decisive importance to riders of powered two-wheelers (PTW) in a warm climate (Patel & Mohan, 1993). A large study of PTW accidents found that ~10% of all riders studied did not wear a helmet while riding in traffic (ACEM, 2004). Furthermore, the self-reported helmet usage among teenaged PTW drivers in southeastern Italy in the summer was only ~35% (Bianco et al., 2005). These studies suggest that thermal discomfort can be important enough to PTW riders to prefer greater safety risk to wearing a helmet. This conclusion was drawn for protective headgear in general by Hickling (1986), who found that thermal discomfort reduces the willingness to wear such headgear.

Several studies showed increased levels of thermal discomfort caused by protective headgear in warm environments (Liu et al., 1999; Hsu et al., 2000). This is not surprising, since the head is among the most important body parts for determining whole body thermal comfort (Cotter & Taylor, 2005). The apparent connection between thermal comfort and heat transfer (Brühwiler et al., 2004) has motivated numerous studies focused on heat transfer characteristics of industrial helmets (Reischl, 1986; Abeysekera et al., 1991; Liu, 1997; Hsu et al., 2000) and sports headgear (Reid & Wang, 2000; Brühwiler et al., 2004; Brühwiler et al., 2006; Bogerd et al., 2008). Some studies have used heat transfer as a basis to optimize protective headgear for thermal comfort and/or temperature sensation (Abeysekera & Shahnavaz, 1988; Holland et al., 2002).

The heat transfer through motorcycle helmets will mostly be facilitated by forced airflow. Therefore, we have previously investigated variations of forced convective heat loss for 27 motorcycle helmets (Chapter 3), finding large inter-helmet variations in heat transfer at a wind speed of 50 $km \cdot h^{-1}$. In the present study, a smaller set of full-face motorcycle helmets were subjected to the following three detailed interventions, in order to more fully understand the current state-of-the-art: i) a head tilt angle of 30º, ii) headform-wig-helmet combinations to simulate hair, and iii) ten different wind speeds (range 0 – 80 $km \cdot h^{-1}$). We found strong linear behavior with respect to the wind speed, and a reduction of a factor ~2 caused by the wig. The effect of tilt angle varied among the helmets studied.

4.2. Methods

Six modern full-face motorcycle helmets were examined on a thermal manikin headform (Figure 4.1). More information on the headform and the setup are given in Chapter 2. The helmets included in this study were selected from among the helmets evaluated in Chapter 3; the helmet coding is left unchanged. The present helmets were chosen as high and low extremes of $\dot{Q}_S$, $\dot{Q}_F$, and/or of the difference in $\dot{Q}$ between the two vent configurations in the scalp section ($\Delta\dot{Q}_S$).

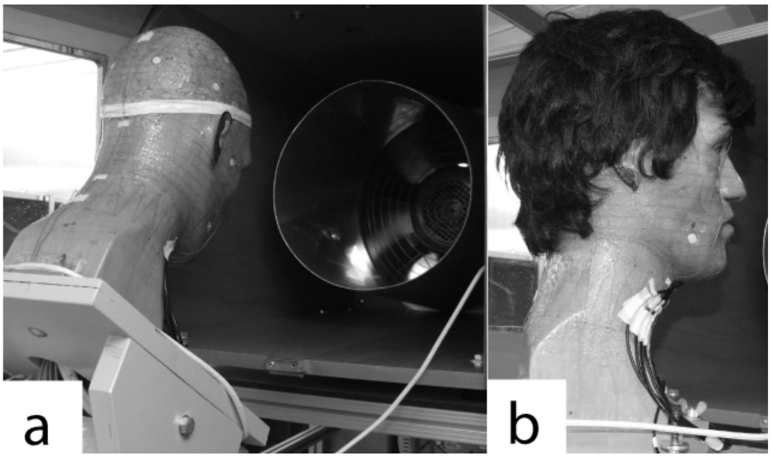

Figure 4.1: The thermal manikin headform (a) positioned at the exit of a wind tunnel with a 30º tilt and (b) equipped with a wig at a 0º tilt.

4.2.1. Interventions

This study consisted of the following three interventions: a 30° forward tilt (TILT), the wearing of a wig (WIG), and a variation of wind speed (SPEED) (Table 4.1). One measurement session consisted of assessing a given helmet with all vents open and consecutively all vents closed, or vice versa, in random order. Fresh placements were made between sessions. The nose of the headform was at approximately the same position with respect to the wind tunnel at both head tilt settings. In intervention WIG a 100% modacrylic wig (Gisela Mayer, Memmingen, Germany) was fitted to the headform before placing the helmet (Figure 4.1). Helmets 110, 131, and 201 were included in intervention SPEED, for which ten different applied wind speeds (v_w) were studied (Table 4.2). The results for these helmets at $v_w = 50.0 \pm 1.0$ km·h^{-1} were obtained from the results reported in Chapter 3.

Table 4.1: Interventions undertaken, characterized by the specified conditions.

Intervention	Head Tilt (º)	Wig Usage	Wind Speed (average ± σ) (km·h-1)	Number of Helmets	Number of Repetitions
TILT	30	No	50.0 ± 1.0	6	3
WIG	0	Yes	50.0 ± 1.0	6	3
SPEED	0	No	Variable (Table 4.2)	3	1

Table 4.2: The wind speeds (v_w) studied.

v_w (average ± σ)					
$km{\cdot}h^{-1}$	0.0 ± 0.0	4.7 ± 0.4	10.1 ± 0.4	20.9 ± 0.4	30.6 ± 0.4
$m{\cdot}s^{-1}$	0.0 ± 0.0	1.3 ± 0.1	2.8 ± 0.1	5.8 ± 0.1	8.5 ± 0.1
$km{\cdot}h^{-1}$	41.4 ± 0.4	50.0 ± 1.0	58.8 ± 0.8	70.4 ± 1.0	79.8 ± 0.8
$m{\cdot}s^{-1}$	11.5 ± 0.1	14.0 ± 0.3	16.3 ± 0.2	19.5 ± 0.3	22.2 ± 0.2

4.2.2. Data processing and statistics

The results from TILT and WIG were compared to those obtained in Chapter 3.2, carried out in a similar way at v_w = 50.0 $km{\cdot}h^{-1}$ and 0º tilt (REF). ANOVA was performed, with a Tukey test for post-hoc comparisons if a significant difference was found. TILT vs. REF and WIG vs. REF were analyzed separately. Pearson's correlation coefficients (r) between $\dot{Q}$ and v_w, and the slope of the linear regression lines through these datasets were calculated.

4.3. Results

The results for REF, TILT, and WIG are collected in Figure 4.2. From this figure it can be observed that the heat loss ($\dot{Q}$), is much larger in the face section compared to the scalp section, indicating the higher thermal insulation of the helmets in the scalp section. Furthermore, it can be observed that the wig substantially decreases $\dot{Q}$ in both sections. A more detailed analysis is given below.

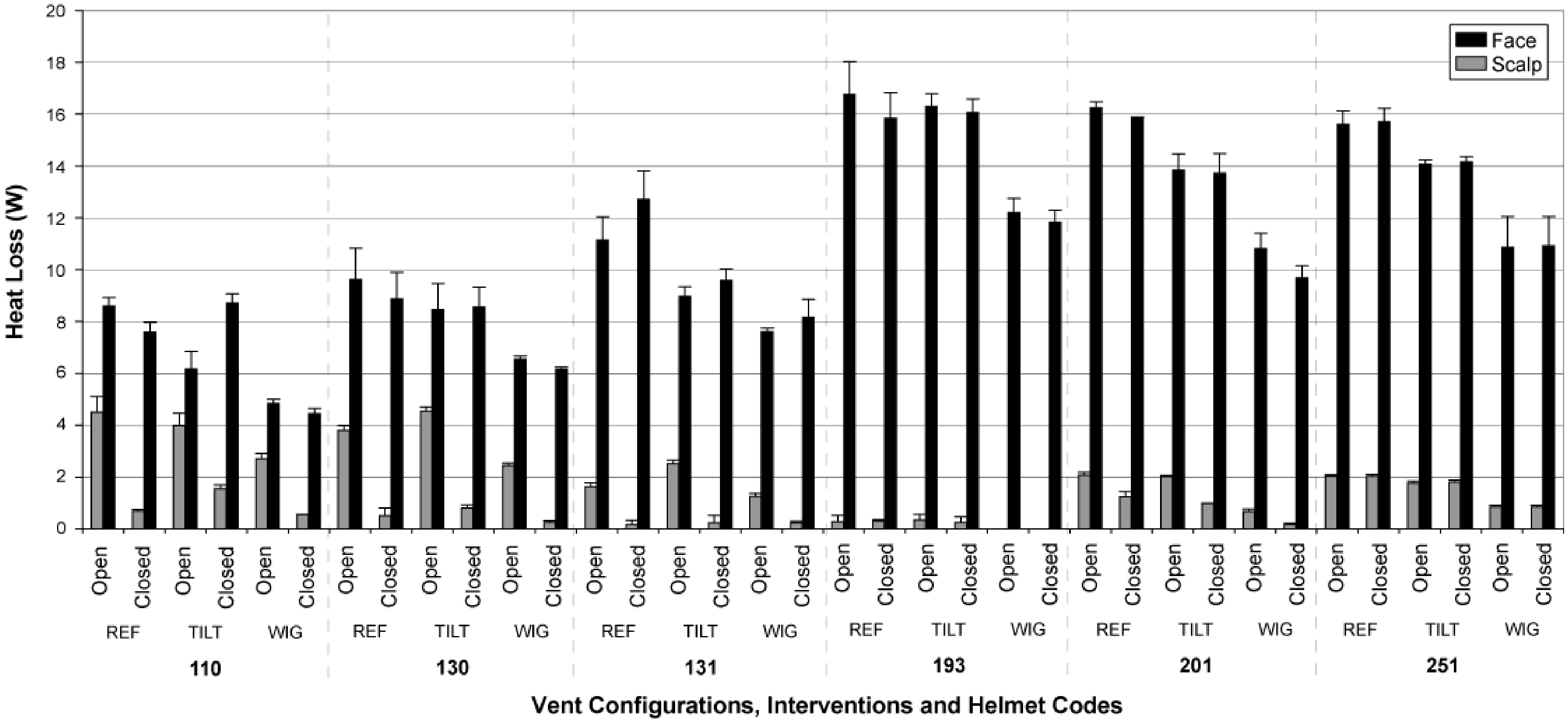

Figure 4.2: The results for the indicated interventions, with helmet, vent configuration, and manikin sections indicated. The error bars show one standard deviation.

4.3.1. *Head tilt*

We examine the effect of TILT in two manners, by a direct comparison as shown in Figure 4.3, and by studying the effect of changing the vent configuration in REF and TILT (Figure 4.4). REF and TILT are compared in Figure 4.3 for both vent configurations in the scalp and face sections. Only helmets 110, 130, and 131 show changes (increases, in this case) in $\dot{Q}_S$ for TILT ($p < 0.05$) for one of their vent configurations. All five configurations with significant changes in the face section (helmets 110, 131, and 201) show a decrease in $\dot{Q}_F$ for TILT ($p < 0.05$).

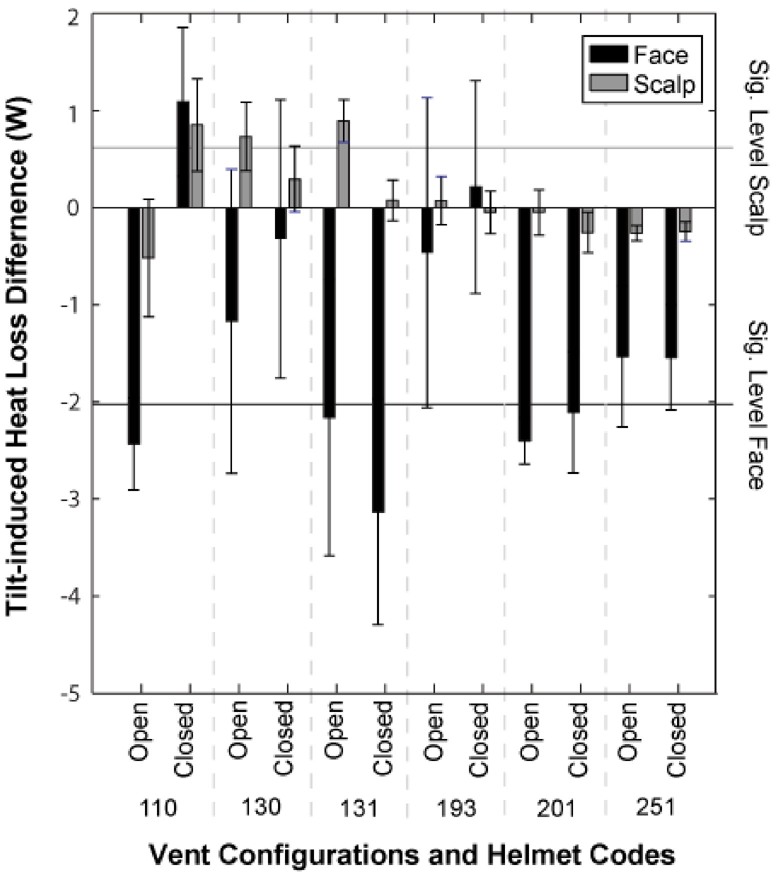

Figure 4.3: Difference between REF and TILT for the indicated helmets, vent configurations, and sections. Positive values indicated higher heat loss for TILT compared to REF. The significance levels ($p \approx 0.05$) are indicated, and the error bars indicate one standard deviation.

The difference in heat loss between vent configurations ($\Delta\dot{Q}$) is displayed in Figure 4.4; although WIG is also shown, we focus first on the comparison between REF and TILT. In the scalp section, $\Delta\dot{Q}_S$ was significant for all helmets ($p < 0.05$) except 193 and 251. Significant $\Delta\dot{Q}$ indicates that there was a difference measured between open and closed vents, and we therefore refer to such cases as functional vents. One helmet (110) showed a decrease in $\Delta\dot{Q}_S$ in TILT, whereas an increase was found for another helmet (131) ($p < 0.01$). In the face section helmets 110 and 131 have functional vents for both REF and TILT. Uniquely to helmet 110, $\Delta\dot{Q}_F$ is positive in REF, but negative in TILT ($p < 0.001$), indicating a qualitatively different functioning of the face vents at a tilt of 30°. In general, both increases and decreases in $\Delta\dot{Q}_F$ are found, spread over both interventions (REF and TILT), indicating that this behavior is helmet-dependent.

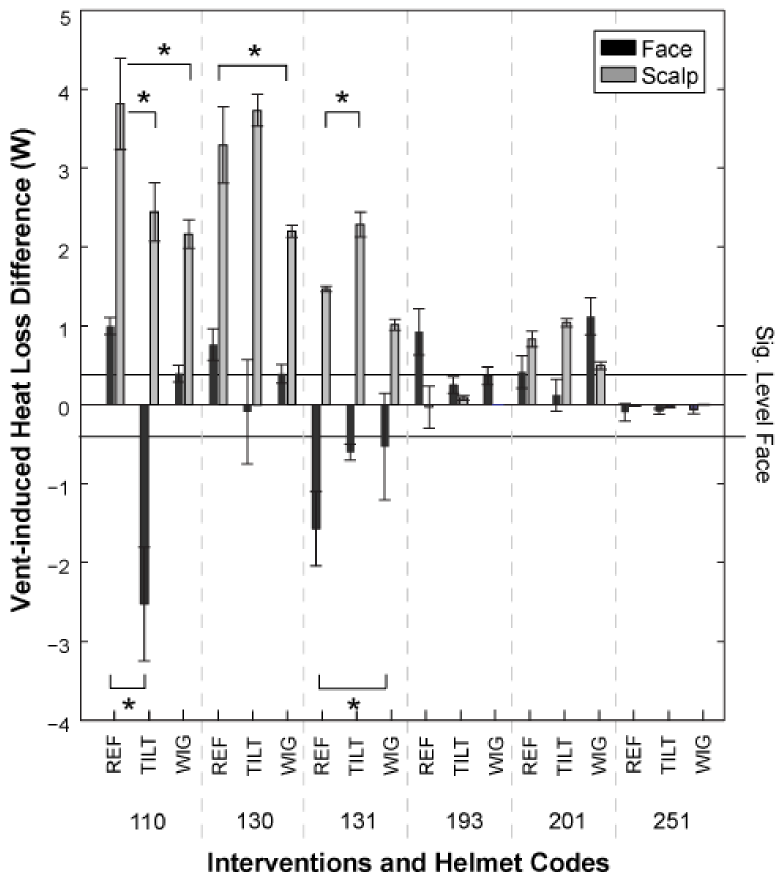

Figure 4.4: Effect of opening the vents for the indicated helmets and interventions. The significance level (p ≈ 0.05) is shown for the face section; for the scalp section it is too close to 0 to visualize. The error bars indicate one standard deviation. Significant differences (p < 0.05) between REF and the other two interventions are indicated with an asterisk (*).

4.3.2. Wig

The wig reduced $\dot{Q}$ significantly for all helmets in the face section (p < 0.01) and for half in the scalp section (p < 0.001), as shown in Figure 4.5. Moreover, for all helmets $\dot{Q}_F$ showed a consistent reduction with a factor of 1.5 ± 0.1 relative to REF, and with a factor of 2.3 ± 1.8 for $\dot{Q}_S$. Focusing on $\Delta\dot{Q}_S$ (Figure 4.4), reveals that the same helmets in REF and WIG have functional vents. However, two helmets (110 and 130) showed in WIG a significantly smaller $\Delta\dot{Q}_S$ compared to REF (p < 0.05). For the face section, functional vents are found for the same helmets as in REF; only helmet 193 lacks this in WIG. Furthermore, helmet 131 shows a significantly smaller $\Delta\dot{Q}_F$ in WIG compared to REF.

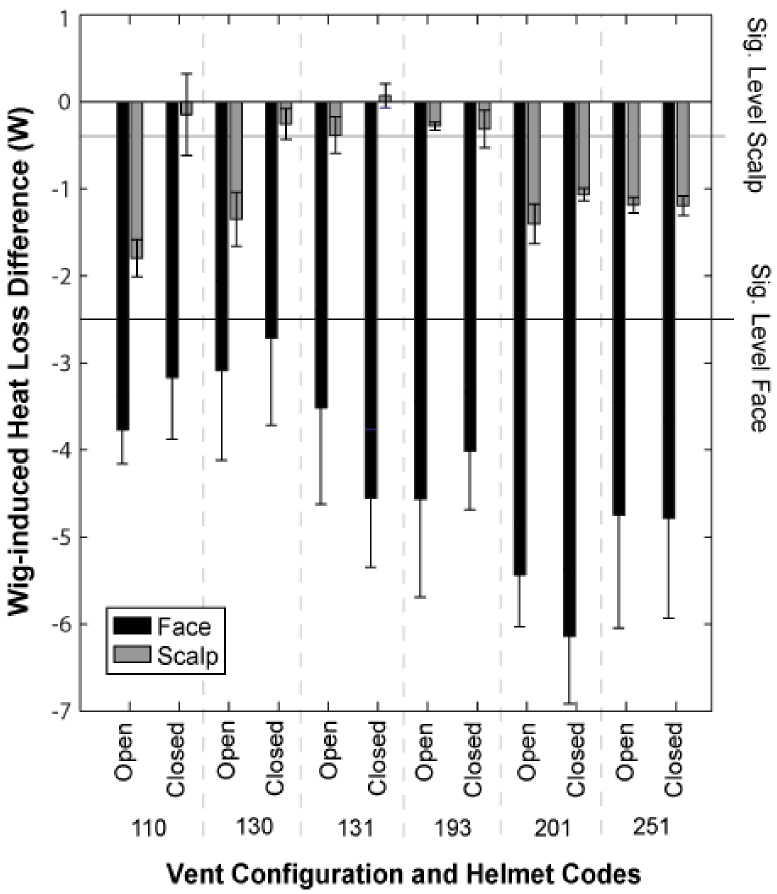

Figure 4.5: Difference between REF to WIG for the indicated helmets and vent configurations. Negative values indicated lower heat loss for WIG compared to REF. The significance levels (p ≈ 0.05) are indicated; the error bars indicate one standard deviation.

4.3.3. Wind speed

Figure 4.6 shows the variation of heat loss in the face section with respect to v_w. $\dot{Q}$ was corrected for warming of the air by the fan of the wind tunnel to allow comparison over the range of v_w, as explained in Section 2.2. For the face section strong linear correlations are found for $\dot{Q}_F$ in both vent configurations, as well as for ΔQ_F; an average correlation r = 0.96 ± 0.11 was found ($p < 0.01$). Interestingly, helmet 131 shows a negative correlation for ΔQ_F.

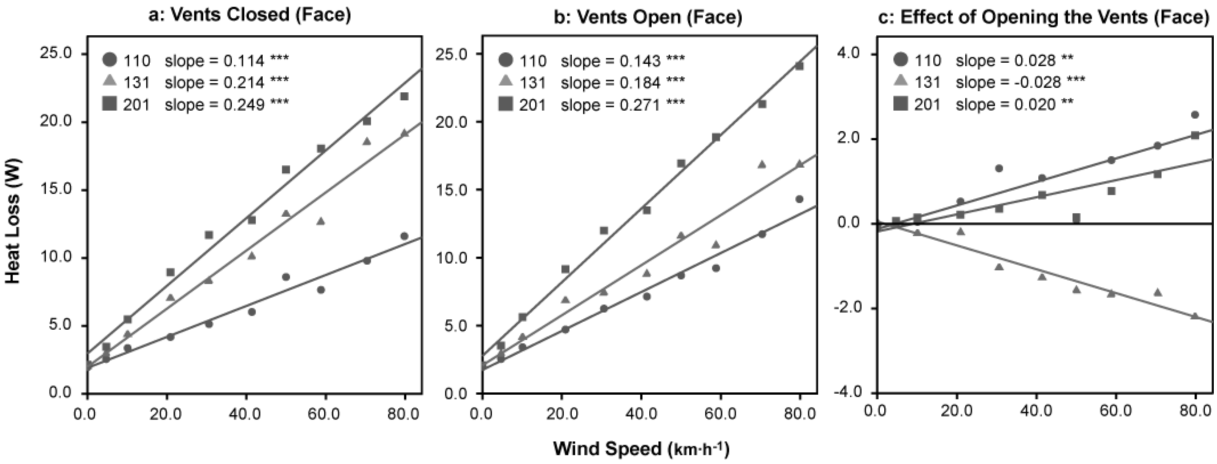

*Figure 4.6: Heat loss in the face section as a function of the wind speed (a, b) for the indicated vent configuration and (c) the difference (b) – (a). The slopes ($W\cdot(km\cdot h^{-1})^{-1}$) of the regression lines are indicated, as well as the p value of the regressions; ** $p < 0.01$; *** $p < 0.001$.*

Figure 4.7 displays the corresponding heat loss variations in the scalp section. Here, as well, strong linear correlations were found, with an average coefficient r = 0.92 ± 0.13 ($p < 0.01$). The changes were relatively small for helmet 131 with the vents closed, as was $\Delta\dot{Q}_S$ for helmet 201. Interestingly, $\dot{Q}_S$ is approximately constant with closed vents at or below 20 and 30 $km\cdot h^{-1}$ for helmets 201 and 110, respectively.

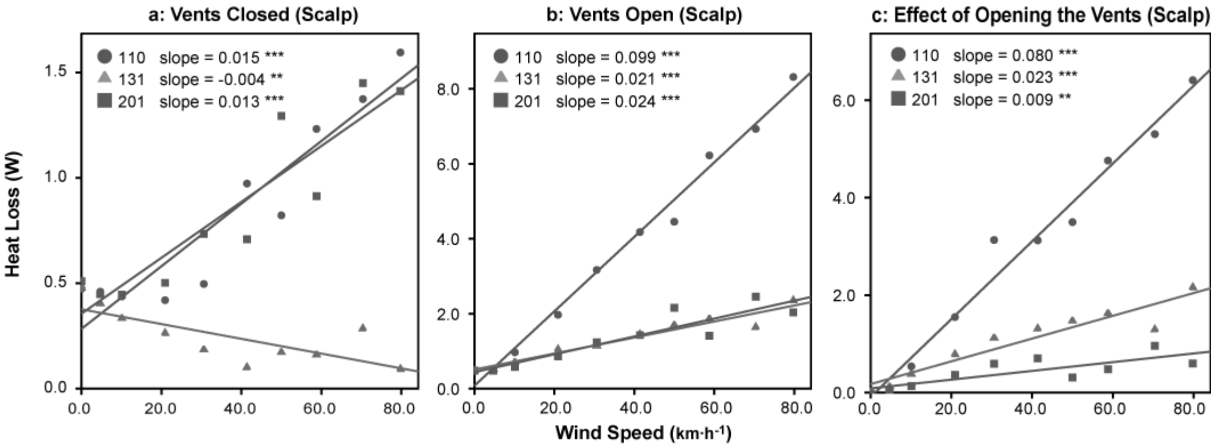

Figure 4.7: Heat loss in the scalp section corresponding to the face section results in Figure 4.6.

4.4. Discussion

4.4.1. Effects of tilt

Three cases show significantly higher heat loss in the scalp section for TILT compared to REF (Figure 4.3). The opposite can be observed in the face section, based on five significant cases (Figure 4.3). The observed behavior in the scalp section is difficult to interpret. In general, it suggests a change in the pressure distribution around the helmet, the characterization of which is beyond the scope of the present study. Since changes in heat loss smaller than 1 W on the human head are probably not noticeable (Brühwiler et al., 2004; Buyan et al., 2006), the observed small changes are likely irrelevant, though they could indicate relevant effects at other conditions, e.g., lower environmental temperatures. Interestingly, a significant reduction in $\Delta\dot{Q}_F$ was found for helmet 110. These results indicate that helmet characteristics, such as vent orientation and shape, as well as helmet surface shape, are important, since these are factors which vary among helmets. Previous work also found effects of head tilt on forced convective heat loss through bicycle helmets (Brühwiler et al., 2004; Brühwiler et al., 2006), confirming the general importance of geometric effects, e.g. vent placement and orientation, on forced convection through headgear.

4.4.2. Wig

Several studies have investigated the effect of placing a wig on a thermal manikin headform, in combination with headgear, in order to simulate hair

(Abeysekera et al., 1991; Ellis, 2003; Brühwiler et al., 2006; Bogerd et al., 2008). As expected, all these studies indicated a reduction in forced convective heat loss, ranging from 75% to 50% for the entire headform. In the present study a reduction due to the wig of 65% was found (43% and 66%, respectively for the scalp and face sections). Therefore, the reduction is in line with previous studies. The air channels and comfort liner vary strongly from helmet to helmet, and so likely explain the variations in the reduction due to the wig in the scalp section.

It is unclear to what extent the headform in combination with the wig represents the hairy skin of the scalp of (most) people. One important difference between real hair and a wig is that a wig is constructed from hairs attached to a somewhat elastic base, which makes the actual contact with the head. There will generally be some space between this base and the head, creating a layer of still air. This air and the base itself likely constitute an unrealistically large insulation relative to real hair. Therefore, the effect of the wig base was estimated with additional measurements, as previously described (Bogerd et al., 2008). For this purpose the hairs from a new wig (100% modacrylic, Gisela Mayer, Memmingen, Germany) were removed so that only the base remained. Measurements were carried out with this base, as for WIG, for helmets 110, 130, and 201. Two data-sets were obtained; i) helmets without a wig, and ii) helmets with only the base of the wig. The difference between these yields an estimate of the base-induced reduction (Table 3.3). In Table 3.3 these reductions are added to the results for WIG carried out with the original wig as displayed in Figure 4.2.

Table 3.3: Reduction in heat loss measured for the base of a wig (excluding the hairs), for the given helmets and sections. Also shown is an estimate of the heat loss without the contribution of the base.

		Vents Open		Vents Closed	
Helmet code	Section	Base induced reduction* (W)	Estimated corrected heat loss* (W)	Base induced reduction* (W)	Estimated corrected heat loss* (W)
110	Scalp	0.3 ± 0.3	3.0 ± 0.3	0.5 ± 0.2	1.1 ± 0.2
	Face	1.3 ± 0.8	6.1 ± 0.8	0.8 ± 0.3	5.2 ± 0.4
130	Scalp	0.5 ± 0.2	3.0 ± 0.2	0.4 ± 0.2	0.7 ± 0.2
	Face	1.4 ± 0.8	8.0 ± 0.8	1.2 ± 0.9	7.4 ± 0.9
201	Scalp	0.6 ± 0.3	1.2 ± 0.3	0.4 ± 0.2	0.6 ± 0.2
	Face	1.2 ± 0.6	12.0 ± 0.8	1.0 ± 0.7	10.7 ± 0.8

More information is given in the text.

* Average ± one standard deviation

These results roughly indicate the extent to which the insulation of the base of a wig diminishes the forced convective heat loss in these measurements (Table 3.3). The correlation between the base- and wig-induced reductions is $r = 0.72$ ($p < 0.01$) for the face section. Thus, the wig-induced reduction is for ~50% explained by that of the base. The corresponding correlation for the scalp section ($r = 0.62$, $p < 0.01$) indicates a contribution of the base of ~40% to the wig-induced reduction. We emphasize that minor differences existed between the base of the new wig and that of the original; the latter consisted of a somewhat thicker material in the front part (~20% of the surface area of the base), and the surface area covered by it was slightly smaller (~5%). Therefore, the corrected heat transfer should be taken as a rough estimate. A further consideration in practice is the great variety of hair types and styles, suggesting that the modification of forced convective heat loss by hair to be expected in practice will vary.

4.4.3. Wind speed

Strong linear correlation of heat loss with v_w was found over a range of speeds for all three measured helmets and in both sections. Such a linear relationship is consistent with simple models of forced convective heat loss, which show relatively linear behavior for wind speeds larger than 10 $km{\cdot}h^{-1}$ (Brühwiler, 2003; Brühwiler et al., 2006). Exceptions to this are helmets 110 and 201 in the scalp section with the vents closed; wind speeds lower than 30 or 20 $km{\cdot}h^{-1}$, respectively, induce no change in heat loss. The reasons for this threshold effect are unclear, but could be explained in principle by the need to overcome a blockage inside the helmet, or perhaps by a qualitative change in the airflow pattern around these observed wind speeds.

Helmet 131 showed a reduction in $\Delta\dot{Q}_F$ with increasing wind speed. This indicates an inverse function of the face vent, for which opening results in a reduced heat loss, as also observed when tilting the headform with this helmet. Since this must be an effect of the overall helmet and vent geometry in the face region, structural modifications to the helmet would be needed to study it experimentally, which is beyond the scope of the present study.

4.5. Conclusions and outlook

The detailed characteristics of heat loss through motorcycle helmets under windy conditions are relatively complex. However, we can conclude that for many helmets a reduction in heat loss in the face section is found when tilting the head forward. Adding a wig reduces the heat loss by a factor of ~2 under the present conditions, of which about 45% is caused by the base of the wig. Finally, strong linear relationships exist between heat loss and wind speed (0 $km \cdot h^{-1}$ – 80 $km \cdot h^{-1}$), in principle enabling prediction of heat loss in many cases based on a limited number of measurements.

On the technical side, measurements and simulations from a fluid dynamics perspective would be interesting, in order to better understand flow patterns and pressure fields, and their relation to heat loss, while taking helmet construction features into account. The relation of the heat loss characteristics to human perception, e.g., comfort is another important area which remains to be explored, and which would help guide modifications, which could improve the acceptability of such helmets in warm climates.

5. Thermal perception of ventilation systems of full-face motorcycle helmets: Subject and manikin study

5.1. Introduction

Given the rising number of motorcycles and scooters in traffic, and the contribution that they can make towards reducing congestion, there has been a concomitant interest in understanding and improving the safety of such powered two-wheelers (PTW) (Clarke et al., 2007; Shinar, 2007; Crundall et al., 2008a; Crundall et al., 2008b; Majdzadeh et al., 2008; Pai et al., 2009). It is well established that the use of a motorcycle helmet increases the likelihood of surviving a motorcycle or moped traffic accident (Deutermann, 2004; Keng, 2005; Ouellet & Kasantikul, 2006; Houston & Richardson, 2008), motivating efforts to study their function (Buyan et al., 2006; Tan & Fok, 2006; Comelli et al., 2008; Lai & Huang, 2008; Pinnoji et al., 2008; Mills et al., 2009) and use (Oginni et al., 2007; Houston & Richardson, 2008; Li et al., 2008a). However, a substantial fraction of riders in traffic do not wear a helmet, ranging, e.g., from 7.7% (ACEM, 2004) between 1999 and 2000 for European countries, 40 ± 8% for the USA from 1994 to 2007 (Glassbrenner & Ye, 2007), and 25% in Taiwan between 1999 and 2001 (Keng, 2005). Unfavorable temperature perception or thermal discomfort are frequently given arguments for not wearing a motorcycle helmet (Patel & Mohan, 1993; Skalkidou et al., 1999; Li et al., 2008b), which is also supported by field observations (Gkritza, 2009). This implies that understanding the effect of motorcycle helmets on temperature perception and thermal comfort of the wearer is a relevant safety and ergonomics topic, which has for instance motivated the development of a motorcycle helmet equipped with phase change material (Tan & Fok, 2006).

Temperature perception and thermal comfort of headgear have most often been studied with thermal manikin headforms (Fonseca, 1974; Reischl, 1986; Spaul et al., 1987; Abeysekera et al., 1991; Liu & Holmer, 1995; Osczevski, 1995; Liu et al., 1999; Reid & Wang, 2000; Holland et al., 2002; Brühwiler, 2003; Brühwiler et al., 2004; Buyan et al., 2006; Bogerd et al., 2008). These authors generally assumed an intuitive relationship between thermal perception of subjects and a measure obtained from such headforms (e.g. heat loss, temperature, heat flux, or airflow). Several studies found that in warm environments the categorization of headgear based on manikin headform measurements is comparable to the categorization based on temperature perception or thermal comfort by human subjects (Liu et al., 1999; Holland et al., 2002; Brühwiler et al., 2004; Buyan et al., 2006), supporting this assumption. However, the most detailed study equipped subjects with bicycle helmets and let them determine which of two head angles ‘provided better cooling to the scalp' (Brühwiler et al., 2004). Comparing to thermal manikin headform measurements, wearing of helmets with a near-zero heat loss difference between both angles did not induce a consistent response among subjects, contrary to helmets with measurable angle-induced effects. These studies indicate that headform measurements are relevant to temperature perception or thermal comfort. However, it is unclear how vent-induced effects of motorcycle helmets relate to human perception.

In Chapter 3 and 4, two manikin studies are reported on the effect of full-face motorcycle helmets on heat loss ($\dot{Q}$) under a wide range of conditions. An important observation is that from the scalp section is reduced relative to comfortable conditions for the nude head. This, and the observation that vent-induced heat loss ($\Delta\dot{Q}$) in the scalp section is, on average, much larger than for the face section, motivate us to focus on the scalp section in this work. Therefore, we investigated the relationships between headform measurements and perception of subjects for vent-induced effects of full-face motorcycle helmets. A wider range of parameters was queried compared to previous studies in order to extend the understanding of temperature perception and thermal comfort of headgear, and the influence of the ventilation systems of these helmets. Finally, we examined parameters such as noise and airflow which are not necessarily directly connected to temperature perception and/or thermal comfort, but might relate to general comfort associated with wearing a motorcycle helmet in windy conditions.

5.2. Methods

5.2.1. Subjects

Eight healthy male subjects participated in this study, aged 28.0 ± 5.4 years. The head circumference, measured according to ISO 8559 (1989), was 57.5 ± 0.5 cm, corresponding to helmet size medium for all helmets. Each subject visited the laboratory three times, once for a familiarization trial and twice for the experimental trials. All trials were carried out at the same time of day for a given subject, and the time between the first (familiarization) and the last trials was not more than two weeks. The subjects were dressed comfortably with respect to the thermal environment, including a scarf protecting the neck from large values of forced convective heat loss. Finally, during the trials a subject had the choice to start or stop wearing a thin windstopper fleece jacket in addition to his clothing, allowing some regulation of overall thermal comfort.

The study was approved by the Cantonal Ethical Committee of St. Gallen (Switzerland). All subjects signed a consent form, after being fully informed about the study. Each attested to have refrained from consuming alcohol, nicotine, and caffeine during the 12 hours preceding each trial, and did not conduct any panting-inducing exercise between waking and the start of the trial.

5.2.2. Thermal environment

All measurements were conducted in a climate chamber at ambient temperatures (T_a) (average ± one standard deviation (σ)) of 23.7 ± 0.4 ºC and 27.5 ± 0.3 ºC, referred to as neutral and warm, respectively. T_a was measured at the following two locations: i) in the wind stream ~56 cm in front of the head of a subject (Figure 5.1), and ii) at the ceiling of the climate chamber (PT100, Roth+CO, Oberuzwil, Switzerland). The warm climate represents the upper ambient temperature in which the headform achieves the necessary sensitivity for evaluating full-face motorcycle helmets at the wind speeds (v_w) employed in this study. At both ambient temperatures two different v_w were applied, labeled moderate (39.2 ± 1.9 km/h) and high (59.3 ± 1.4 km/h); v_w was measured beside the head as described elsewhere (Brühwiler 2003). The relative humidity (RH) was kept at 50 ± 2%, and measured at the same location as the temperature in the wind stream (145W, MSR, Henggart, Switzerland).

5.2.3. Setup

A schematic representation of the setup is depicted in Figure 5.1. The subjects sat at the exit of the wind tunnel, which projected the air stream on the upper torso, neck and head. A 19’ LCD screen was positioned under the Plexiglas bottom of the wind tunnel, which allowed the subject to see the screen clearly. A keyboard and mouse were positioned in front of the screen. The wind tunnel’s inner cross-sectional dimensions were 50 x 50 cm^2. The distance of a subject’s head to the top of the wind tunnel ‘a’, and the position of the subject’s head on the longitudinal axes of the wind tunnel ‘b’ were 5 ± 1 cm and 8 ± 6 cm, respectively. Both distances were quantified by photographs taken from the side of the setup, which were then calibrated against an object of known dimensions. The head angle was obtained in a similar manner by evaluating the orientation of specific helmet features, and resulted in an average head angle of ~20º.

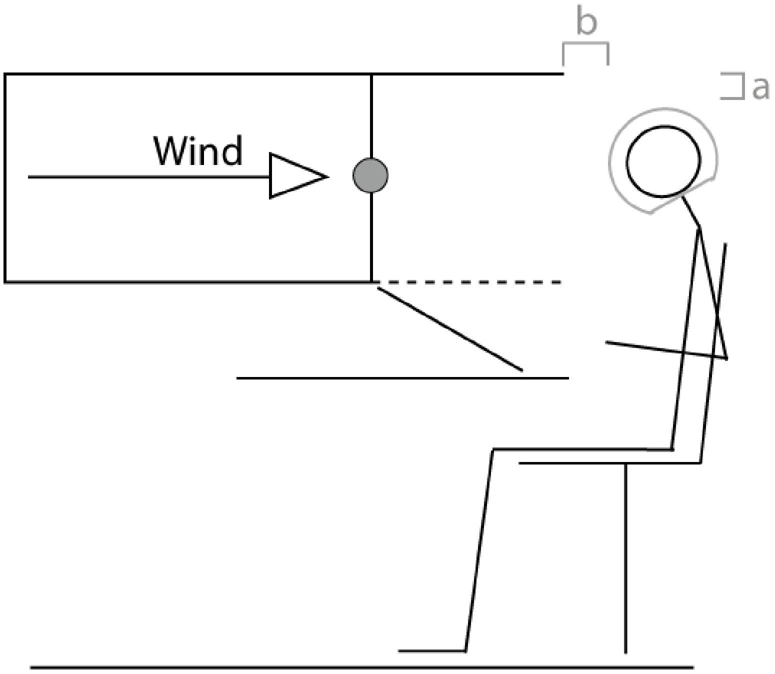

Figure 5.1: The measurement setup. The head of the subject or the headform was positioned at the exit of the wind tunnel at an angle of about 20º; allowing viewing of the computer screen. Distances 'a' and 'b' were measured to be 5 ± 1 cm, and 8 ± 6 cm, respectively. The dashed line indicates the Plexiglas bottom of the wind tunnel. The location of the temperature and relative humidity sensors is indicated (●), temperature was in addition measured on the ceiling of the climate chamber as explained in the text.

5.2.4. *Protocol and interventions*

Figure 5.2 illustrates the protocol for the experimental trials. For each subject, the two trials differed from each other in ambient temperature, either neutral or warm; this sequence was balanced over the subjects. The trials consisted of the following four consecutive phases, during which the subject sat still at the exit of the wind tunnel: i) 30 min acclimation, ii) 30 min steady state, iii) perception examination 1 (~20 min), and iv) perception examination 2 (~20 min). Four subjects wore helmet 110 during the acclimation and steady state phases during both visits, and other four subjects wore helmet 130. The other two helmets were not included in this phase to allow the collection of sufficient cases for statistical analysis. The initial vent configuration for the vents in the scalp and face sections was either open or closed, and randomly chosen. During the acclimation phase no wind was applied and the subject was allowed to read or carry out computer work. In the steady state phase the moderate wind speed was applied. Midway through the steady state period the vent configuration was changed, always first for the scalp section followed by the face section; this was not randomized so as to make the protocol unambiguous to the subjects.

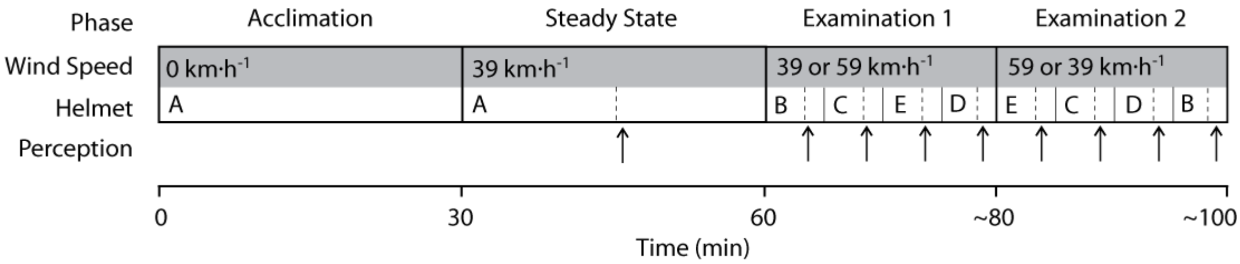

Figure 5.2: Schematic of the protocol and interventions during an experimental trial. A dashed gray line (¦) indicates a change of the vent configuration, whereas a solid gray line (|) indicates a change of helmet (during this short period no wind was applied). Perception assessments are indicated with arrows. Wind speed during the examination periods was offered in a balanced order over all subjects. The helmet used during the acclimation and steady state phase (A) was kept constant per subject and was either helmet 110 or 130. During each examination phase all four helmets were evaluated in random order.

Both examination phases differed in v_w, determined in a balanced order. During each examination all four helmets (in random order) were examined in the following manner: i) the helmet worn by the subject was removed and the subject was fitted with another helmet, during which no wind was applied; ii) wind was applied while the subject sat still at the exit of the wind tunnel in order to regain values close to thermal steady state, for which 3 min was taken; iii) the experimenter manually changed the vent configuration, always first in the scalp section followed by the face section. After each change in vent configuration the subject was asked to assess his perception in a manner described below. The examination of one helmet took approximately 5 min. To minimize the effect of helmet exchange on skin and microclimate temperatures, each helmet was pre-heated to 35 ºC for at least 5 min on the thermal manikin headform prior to being worn.

5.2.5. Perception assessment

Directly after a change in vent configuration, the subject filled out a questionnaire (Table 5.1). Question 1 served to determine if any changes were perceived. If so, questions two through five were filled out, assessing perceptual effects of local temperature, airflow, noise and thermal comfort. These parameters were assessed in a fixed order, in an attempt to make the questionnaire as unambiguous as possible. All perception questionnaires were presented as userfriendly Excel sheets (Office Excel 2003 SP3), in which the scalp and face sections were visualized.

Table 5.1: Subjective perception assessment questionnaire

Number	Question	Possible Responses		
1	Do you notice a difference from the situation before the change in the section?	yes	no	
2	Is the temperature of the skin of the section different?	warmer	indifferent	cooler
3	Is the airflow over the section different?	increased airflow	indifferent	decreased airflow
4	Is the noise level different?	increased noise	indifferent	decreased noise
5	How do you perceive the temperature in the section?	more comfortable	indifferent	less comfortable

5.2.6. Skin temperature

Before each experimental trial the subject was instrumented with three thermistors (DS18B20 – T3, MSR, Henggart, Switzerland) on the face at the following locations: i) the middle of the chin (mental protuberance), ii) the middle of the forehead 1 cm above the eyebrows, iii) 3 cm in front of the ear at the level of the ear channel. The skin temperature sensors were read out every 10 s to a data-logger (MSR 12, MSR, Henggart, Switzerland).

5.2.7. Familiarization trial

All subjects participated in a familiarization trial, the goal of which was to train the subjects in filling out the questionnaires, and optimizing the exchange of helmets during the examination phases. First the protocol was explained in detail and the subjects were instructed on the use and meaning of each question in the questionnaires. Secondly, they experienced one examination phase, as described above.

5.2.8. Helmets and sensor integration

Four full-face motorcycle helmets were employed in this study (helmets 110, 130, 201, and 210). Each had at least one operable vent in the scalp section and at least one in the face section. Helmets 110 and 130 were found to facilitate the largest vent-induced heat loss in the scalp section ($\Delta\dot{Q}_S$) from a sample of 27 state-of-the-art motorcycle helmets (Chapter 3). $\Delta\dot{Q}_S$ was measured on a thermal manikin headform, and quantifies the change between all vents opened and all vents closed; positive values were associated with opening the vents, and negative values with closing them. The ventilation system of helmet 210 was closed from the inside, so that $\Delta\dot{Q}_S$ was approximately zero. Helmet 201 exhibited a value of $\Delta\dot{Q}_S$ of approximately half the maximum. Thus, the chosen helmets represented a broad distribution of $\Delta\dot{Q}_S$ values.

The ventilation system of the helmet was used to provide the intervention for the scalp section. These vents seemed to facilitate guidance for airflow towards the front of the scalp inside the helmet. However, the vents were unique for each helmet model. For the face section, helmets 110 and 130 had an option of slightly opening the visor, creating a gap of some millimeters between it and the interface of the helmet. In an attempt to gain a larger range of vent-induced heat loss in the face section ($\Delta\dot{Q}_F$), the visor ventilation option of helmets 110 and 130 was used, instead of the vents in the face section. For helmets 201 and 210 the vents in the face section were operated, and seemed to guide airflow onto the visor's inside and onto the face at the level of the nose. In what follows, the visors of helmets 110 and 130 will also be referred to as vents.

Helmets 110, 130, and 201 were instrumented with six thermistors per helmet (DS18B20 – T3, MSR, Henggart, Switzerland) in the scalp (Figure 5.3). In addition, two combined RH and temperature sensors (SHT15, MSR, Henggart, Switzerland), were installed in the scalp sections. These sensors were integrated in two rows, each with four evenly-spaced sensors starting at the top of the ear; a vertical row (spacing ~4 cm), and a horizontal row (spacing ~3.5 cm). In order to ensure a consistent placement of sensors among the three helmets, a dummy head was modified with holes drilled on the sensor locations. The helmets were placed on the dummy to achieve a distance from the visor opening to the bridge of the nose defined by a broadly-used impact test standard (ECE324, 2002), and the sensor locations marked. All sensors were sewn into the helmets. The face section was equipped with two combined RH and temperature sensors in the upper and lower left corners of the facial opening. Furthermore, all sensors were placed on the left side, as symmetry was assumed. The sensors were read out every 10 s to a data-logger (MSR 12, MSR, Henggart, Switzerland).

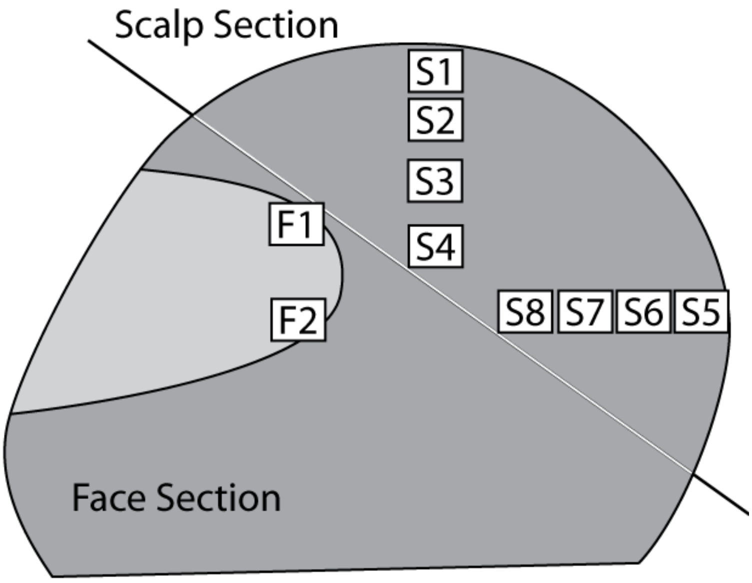

Figure 5.3: The temperature sensor locations for helmets 110, 130, and 201. Relative humidity was measured by the same sensor at locations S1, S5, F1, and F2. The area above the solid line indicates the scalp section; the rest of the head down to the top of the neck was defined as the face section, consistent with the manikin employed in the present study

5.2.9. Thermal manikin headform measurements

To get accurate estimates of the steady state heat loss experienced by the subjects, headform measurements were carried out under conditions closely simulating the situation during subject examinations, as described below. The specifications of the headform are given elsewhere (Brühwiler, 2003), and details on the protocol for assessing helmets on the headform was identical to that reported in Chapters 3 and 4. Finally, the position and orientation of the headform was based on subject examinations as given under Section 5.2.3.

Since the difference between the skin surface temperature and the microclimate temperature is the driving parameter for steady state heat loss, it is a priori unclear whether the previous manikin measurements took place under conditions realistic enough to accurately assess the heat loss experienced by the subjects. For this reason, we chose to carry out new manikin measurements. This was carried out in two stages, with the goal of the first stage being a determination of the manikin surface temperature necessary to reproduce the microclimate measured with the subjects. This was obtained from at least 20 measurements per thermal environment for helmets 110 and 130, with the vents open and closed, at different surface temperatures and at moderate v_w. The average microclimate temperature from the subject trials was obtained from the steady state phase for each section from a 3 min steady state period for each vent configuration, just before the change in vent configuration, and at the end of the steady state phase. The resulting surface temperatures for the manikin simulations were for the neutral climate 38.6 ºC and 40.0 ºC, respectively, for the scalp and face sections; and for the warm climate 36.8 ºC and 38.1 ºC. Only helmets 110 and 130 were included here, since only they were used in the steady state phase of the subject trials at moderate wind speed. For the face section breathing was not taken into consideration. Therefore, the reported heat loss for this section is likely overestimated.

5.2.10. Statistics

SPSS 14.0.1 for Windows was used for statistical analysis, for which $\alpha < 0.05$ was the significance threshold. Several statistical tests were employed. The description of the statistics is therefore given in the results section. The exception is the logistic regression analysis, which is relatively complex and will therefore be explained here.

Logistic regression enables one to model categorical responses, such as given by the subjects to the survey questions. Such a model gives the probability (P) for the response category, the general formula of such a model is $P = 1 / (1 + \exp(-\text{logit}))$, where the logit is linear, and given by $\text{logit} = \gamma + \delta_1 \cdot X_1 + \delta_2 \cdot X_2 + \ldots + \delta_k \cdot X_k$. In the logit, γ is an overall constant (referred to as the intercept), the X_k are variables, and the δ_k are their associated constants. We used a forward step-by-step procedure, in which each given parameter is considered. At each step a parameter is added which makes the model perform significantly better. If more than two parameters improve the model, then the parameter yielding the smallest p-value is added to the mode, using the likelihood ratio test as the selection criterion. The modeling procedure is terminated at the step at which the model does not improve significantly. Thus, the result of the procedure is a model which yields the probability for a response as a function of the included parameters (which can be continuous or categorical), in which the letter are statistically related to the response behavior of the subjects. The goal of this modeling procedure as applied here was to indicate which of the measured parameters is important in describing the response behavior of the subjects, for questions two through five. More information on logistic regression is given, e.g., by Menard (2002).

For the generation of these models the following parameters were considered: $\Delta\dot{Q}$, subject, helmet, ambient air temperature (neutral or warm), applied wind speed (moderate or high), the vent configuration in the other section, and facial skin temperature. Furthermore, two procedures were carried out per question, either including or not including the thermal microclimate parameters (Figure 5.3). This distinction was considered necessary since one helmet was not equipped with sensors. In order to keep the models as simple as possible and reduce ambiguity caused by correlated parameters, all continuous parameters, i.e., microclimate parameters, were included only if the corresponding Pearson's r^2 between the parameter and $\Delta\dot{Q}$ was smaller than 0.5. In total, sixteen models were generated in this manner, addressing the four questions considered by the subjects, the two sections, and the two model types (with or without microclimate parameters). To estimate the effect of the vent on the microclimate parameters, the corresponding thermal data was represented by the slope of the data over a period of 50 s following the change in vent configuration.

The primary criterion for evaluating the performance of the models is the percentage of correctly predicted responses, and the McFadden r^2; the latter is analogous to Pearson's r^2 for linear regression analysis (Menard, 2000). Below, models will be referred to as 'highly-performing' if correctly predicting at least 80% of the responses and having a McFadden r^2 greater than 0.50. Finally, in order to test the importance of the parameters for the response behavior, each parameter included in a model was separately omitted after which a likelihood ratio test was employed to quantify the reduction of the performance of the model.

5.3. Results

5.3.1. Manikin measurements

The largest change between open and closed vents was 6.1 W. Therefore, $\Delta\dot{Q}_S$ ranged from -6.1 W to 6.1 W (Figure 5.4a), for which negative values indicate closing of the vents, and positive values indicate opening of the vents. Values within this range occur with similar frequencies, with the exception of values near zero. In Figure 5.4b the total value of $\dot{Q}$ for each helmet is indicated for the vents open and closed, for the neutral temperature at high v_w; the difference between the vent configurations is $\Delta\dot{Q}$. It can be observed that helmets 110 and 130 result in very similar $\Delta\dot{Q}_S$, helmet 210 results in the smallest value, and helmet 201 is intermediate. As expected the results for helmets 110, 130, and 201 are consistent with the studies reported in Chapters 3 and 4; helmet 210 was not consistent since it was modified for the present study. The results for the other three conditions are qualitatively similar for the other thermal environment.

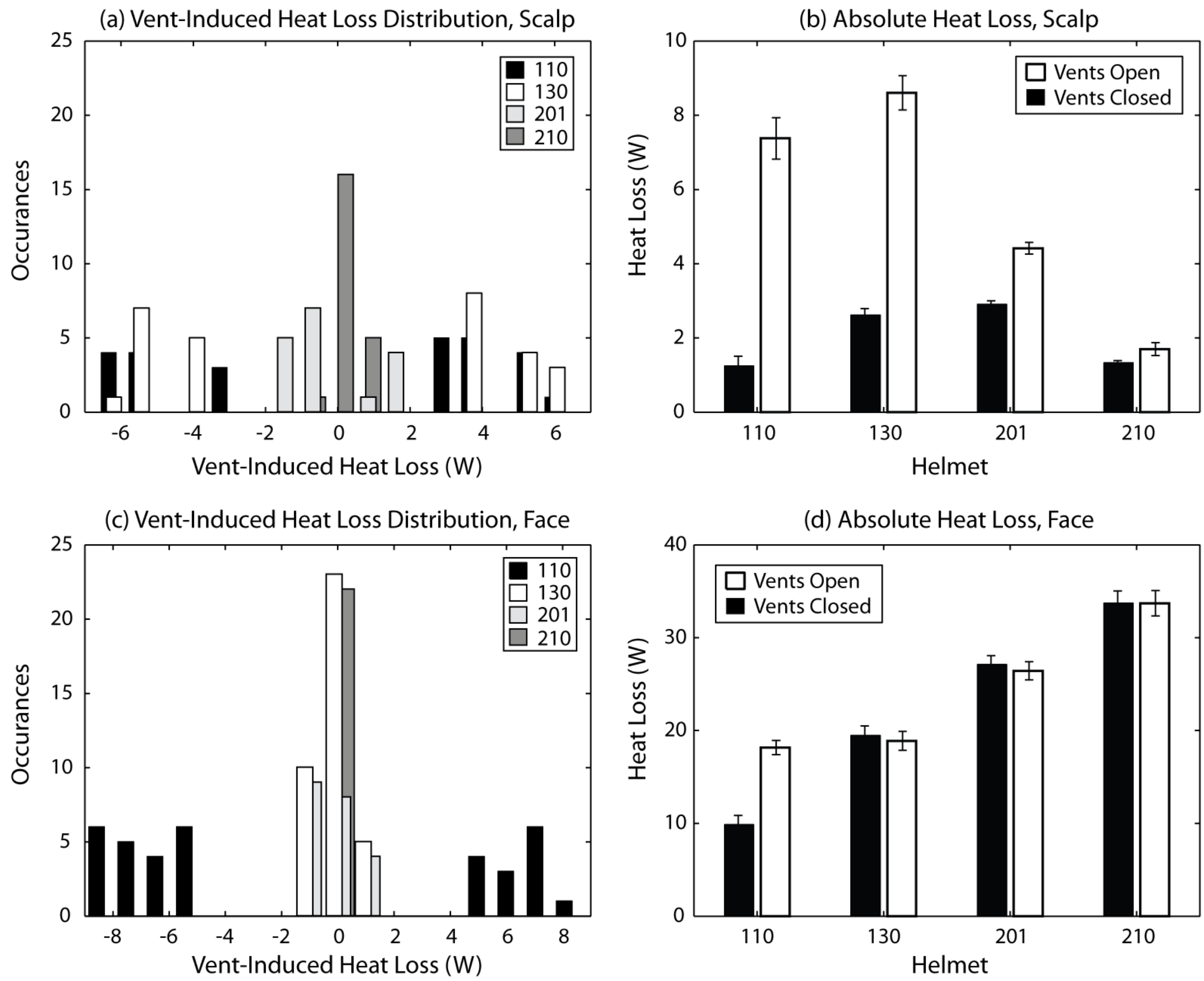

Figure 5.4: Histogram of vent-induced heat loss for the scalp (a) and face (c) sections, and absolute heat loss measured from the scalp (b) and face (d) sections with the neutral temperature at wind speed high, for the indicated vent configurations and helmets. The vent-induced heat loss indicated by the bars in (a) and (c) do not exactly correspond to the true values, since the bars are wide and show an offset with respect to each other, allowing a visual differentiation among the helmets.

For the face section, $\Delta\dot{Q}_F$ for helmets 130, 201, and 210 does not exceed ±0.9 W (Figure 5.4c). However, opening the visor for helmet 110 resulted in a substantially larger $\Delta\dot{Q}_F$ of minimally ±4.6 W (Figure 5.4d). As a consequence, $\Delta\dot{Q}_F$ is less evenly distributed over the studied range than $\Delta\dot{Q}_S$. Among the different thermal environments, $\Delta\dot{Q}_F$ was qualitatively similar. For both the scalp and face sections the frequency of the direction of opening or closing the vents was statistically unbiased, based on a non-parametric test for frequency of occurrence for categories in dichotomous data (binomial test).

5.3.2. Subject examinations

The values of all thermal parameters at the end of the acclimation phase and during the steady state phase are given in Table 5.2. The highest values are observed during the acclimation phase, as expected, since no wind was applied. The scalp section microclimate temperature reached values close to the upper limit, hypothetically defined by the core temperature under these conditions.

Table 5.2: Average steady state results for skin and microclimate temperature and relative humidity at the end of the acclimation and the steady state phases.

		Acclimation Phase			Steady State Neutral			Steady State Warm		
		Temperature (ºC)			Temperature (ºC)			Temperature (ºC)		
Section		Neutral	Warm		Closed	Open		Closed	Open	
Face	Skin	34.8 ± 0.5	35.2 ± 0.3		33.0 ± 1.1	32.6 ± 1.4		34.1 ± 0.6	34.0 ± 0.7	
Face	Microclimate	28.6 ± 0.7	30.8 ± 0.7	***	26.3 ± 1.8	24.8 ± 0.7		28.7 ± 1.0	28.5 ± 0.5	
Scalp	Microclimate	36.1 ± 0.8	36.8 ± 0.8	*	34.3 ± 0.6	33.3 ± 0.7	*	35.3 ± 0.4	34.0 ± 0.8	***
		Relative Humidity (%)			Relative Humidity (%)			Relative Humidity (%)		
Section		Neutral	Warm		Closed	Open		Closed	Open	
Face	Microclimate	42.2 ± 3.7	47.6 ± 5.2	*	46.5 ± 1.5	47.4 ± 1.7	*	49.0 ± 1.1	48.4 ± 1.6	
Scalp	Microclimate	53.7 ± 7.3	60.1 ± 11.0		47.9 ± 9.1	42.7 ± 6.5	*	55.7 ± 15.8	50.4 ± 11.2	

One standard deviation is given for each average; one or more asterisks indicates a significant difference according to a paired t-test between the two data-sets represented by the two preceding averages in the same row (* $p < 0.05$, and *** $p < 0.001$).

We modeled the temperature development in the helmet during the acclimation period with an exponential function, enabling us to quantify how much time was required to reach steady state. Since some data-sets contained noise exceeding the amplitude of the exponential trend, models were selected for further evaluation if they exhibited a significant Pearson's $r > 0.90$. These models were then used to calculate the acclimation time, defined as the time elapsed when 95% of the maximum was reached, as visualized in Figure 5.5. For the scalp section in the neutral and warm environments, the estimated acclimation time for all temperature sensors was 19:27 ± 4:15 min and 19:38 ± 4:59 min, respectively, over a temperature range of 2.7 ± 0.4 ºC and 5.7 ± 2.1 ºC. The microclimate temperature for the facial area was too scattered to meet the evaluation requirements. However, the face skin temperature showed acclimation times of 17:57 ± 5:13 min and 15:03 ± 2:41 min for the neutral and warm environments respectively, over a temperature interval of 1.2 ± 0.3 ºC, and 1.8 ± 0.3 ºC, respectively. Importantly, all acclimation times are well below the 30 min duration of the acclimation phase.

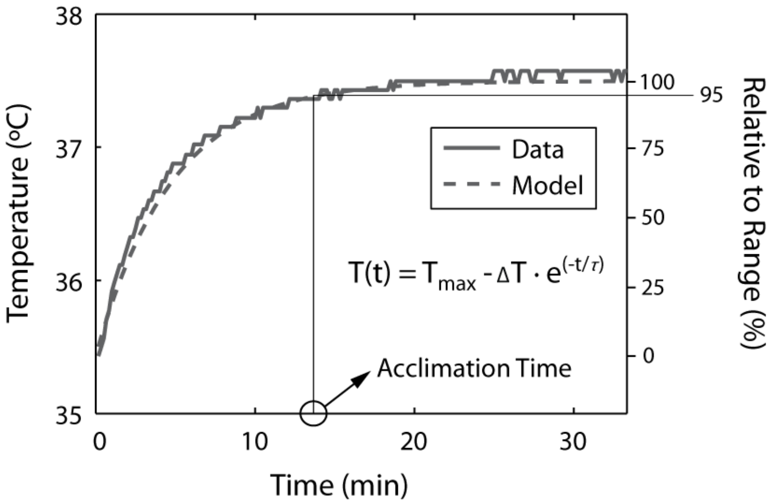

Figure 5.5: The temperature in the scalp section between the helmet and the skin during an acclimation period for one case. In order to obtain the acclimation time, the data was modeled with an exponential function as given. The acclimation time was calculated as the point at which 95% of the maximum temperature was reached, as indicated. More information is given in the text.

RH was often well-represented by a linear function, with a corresponding Pearson's r^2 of 0.54 ± 0.43 ($p < 0.05$). The increase was 28 ± 19 %/h, and -2 ± 13 %/h for the scalp section in the neutral and warm climates, respectively. The face section exhibited comparable rates, with 30 ± 46 %/h and 14 ± 19 %/h, respectively. The RH slopes in the neutral environments were significantly different from zero, and therefore tend to indicate that steady state was not reached under these conditions.

During the steady state phase the microclimate temperature and RH showed significant reductions from the plateau levels reached in the acclimation phase. However, at 0.06 ± 0.26 ºC and 0.42 ± 1.83% over 15 min, respectively, these reductions were negligible with respect to human perception thresholds (Essick et al. 2004). Between the steady state and examination phases most parameters were indistinguishable, with the exception of RH in the scalp section in the neutral and warm thermal environments, which according to comparison by paired t-tests was lower in the examination period by 7.9 ± 7.9% ($p = 0.026$), and 9.2 ± 9.2% ($p = 0.025$), respectively. However, these changes in RH did not result in perceptible differences, according to the non-parametric McNemar test.

A total of 93 responses were collected to each of questions two through five for the scalp section, and are visualized in Figure 5.6. There it can be observed that the response 'indifferent' was most often given. The value of $\Delta\dot{Q}_S$ corresponding to the mean response (M) is also indicated for each response category of every question. M is helpful for quantifying the differences in distribution of the responses. Comparison of the results for the different questions reveals that for the response category 'indifferent', M is close to zero with -0.57 ± 0.52 W. Since opening the vents results in $\Delta\dot{Q}_S > 0$ W, it follows that, if M > 0, then these response categories occur most often upon opening the vents. If this criterion is used to select the response category for each question related to opening the vents, then an average M of 2.19 ± 0.36 W is found. Thus, opening the vent is related to perceptions of 'cooler', 'more airflow', 'more noise', and 'less comfortable'. The same approach can be used to associate the response categories with closing the vents (M is -2.72 ± 1.92 W), i.e., 'warmer', 'less airflow' and 'less noise'. However, comfort was not very well related to closing the vents as displayed by an M of 0.01 W for response category 'more comfortable'. Since more responses are given for perceiving an effect associated with opening the vents compared to closing the vents, M for 'indifferent' is negative for most questions.

107 responses were collected for each of questions two through five for the face section. Compared to the scalp section the distribution of the responses for the face section are qualitatively similar. However, this distribution is mainly due to helmet 110 since it was the only helmet resulting in $\Delta\dot{Q}_F > 0.9$ W.

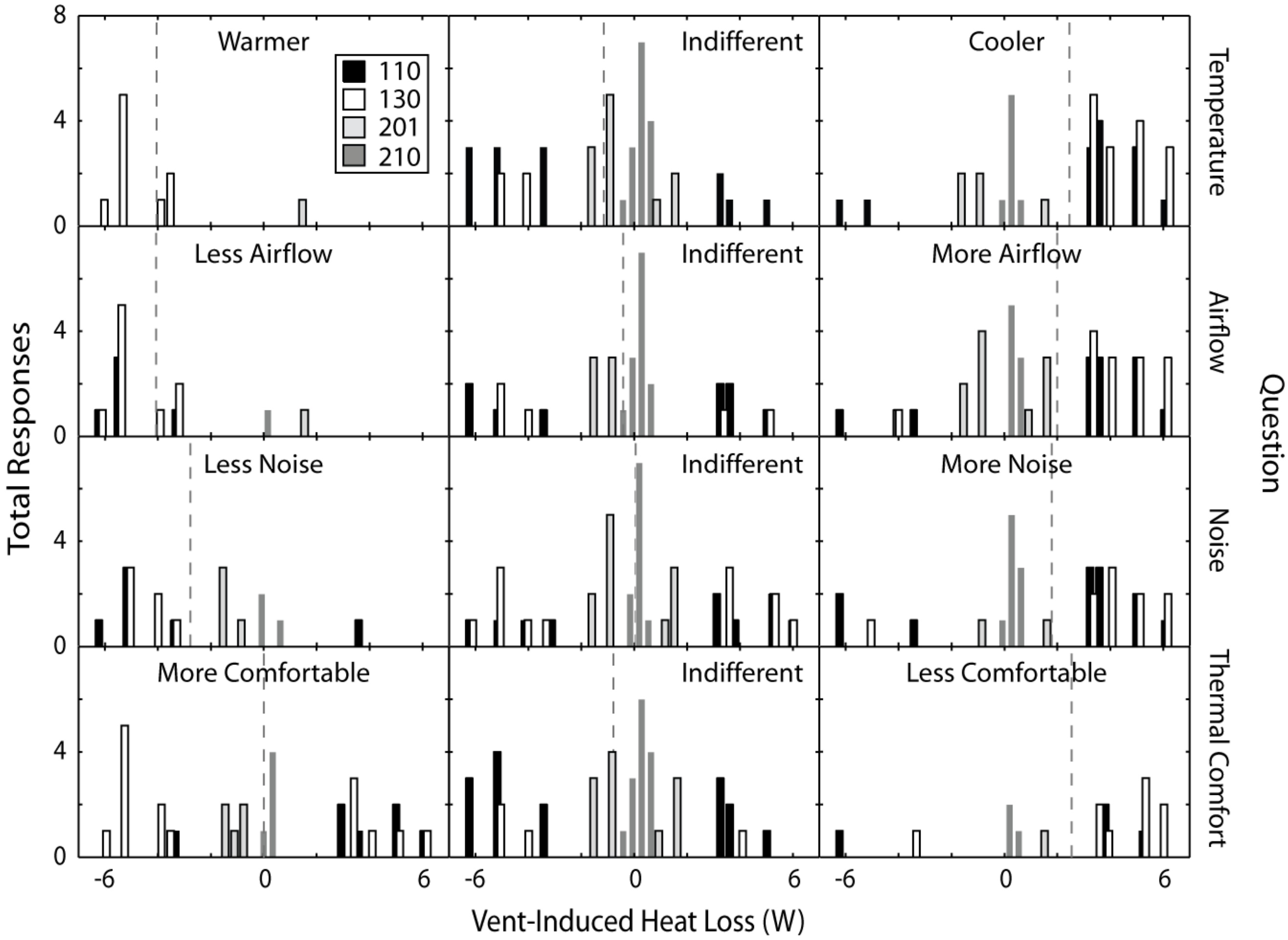

Figure 5.6: Number of responses for the scalp section with respect to vent-induced heat loss ($\Delta\dot{Q}$) for all questions and helmets as indicated. The dashed lines indicate the value of $\Delta\dot{Q}$ corresponding to the mean response for all helmets combined, for each response frequency.

5.3.3. Relationship among parameters

All continuous variables were compared to assess their mutual correlation, since only one of a given pair of strongly-correlated parameters should be included in a logistic model (Menard 2002). As measured during the examination phases, $\Delta\dot{Q}_S$ correlated strongly with T_{S5}, RH_{S1} and $\overline{RH}_s$, defined by a significant Pearson's $r^2 > 0.5$. It is notable that T_{S5} and RH_{S1} are located at the midline of the helmet (Figure 5.3). For the face section the relationships among all parameters were assessed in a similar fashion, with none identified.

5.3.4. Logistic regression - scalp section

All models for questions two through five for the scalp section were highly-performing as defined above under Statistics. Table 5.3 gives the performance of these models, and shows the parameters included. A smaller p-value of the likelihood ratio test of the reduced model indicates higher importance of the parameter for predicting the response behavior. The most frequently occurring parameters were, in order of decreasing importance, the following: $\Delta\dot{Q}_S$, subject, and helmet. These parameters will be put into context with the original responses below.

Table 5.3: The performance of the multinomial logistic regression models for the scalp section for questions two through five and the importance of the parameters in explaining the response behavior.

Scalp Section		Model Performance		p-Value of the likelihood ratio test of the full model reduced for the indicated parameter (smaller values indicate higher importance of the parameter for the overall model)*					
Question	MC	Correctly Predicted	McFadden r^2	ΔQ_S	Subject	Helmet	v_w	T_{s2}	T_{s8}
2 Temperature	no	85%	0.61	$<10^{-6}$	$<10^{-3}$	$<10^{-4}$			
	yes	86%	0.65	$<10^{-6}$	$<10^{-2}$	$<10^{-2}$			
3 Airflow	no	87%	0.56	$<10^{-6}$	$<10^{-2}$				
	yes	87%	0.67	$<10^{-6}$	$<10^{-6}$		$<10^{-4}$		$<10^{-4}$
4 Noise	no	80%	0.67	$<10^{-4}$	$<10^{-3}$		<0.05		
	yes	87%	0.79	$<10^{-4}$	$<10^{-4}$				
5 Thermal Comfort	no	81%	0.6	$<10^{-2}$	$<10^{-2}$	$<10^{-3}$			
	yes	80%	0.62	<0.05	$<10^{-2}$			<0.05	

Column MC indicates whether the thermal microclimate parameters are included in the parameter pool. In such cases, only three helmets are included, since one helmet was not equipped with sensors; otherwise all four are included. ΔQ_S indicates the vent-induced heat loss, v_w applied wind speed, and T_{s2} and T_{s8} microclimate temperatures measured on locations S2 and S8 (Figure 5.3). More information is provided in the text. *Blanks indicate that the corresponding parameter was not included in the model.

As noted under Subject Examination, effects of changing the vents are most often perceived at nonzero $\Delta\dot{Q}_S$, and responses for not perceiving an effect show a peak around zero $\Delta\dot{Q}_S$; these patterns suggest that the subjects were sensitive to the parameters being studied. Thermal comfort was an exceptional perceptional parameter, in that $\Delta\dot{Q}_S$ was not the first physical parameter included in the models; indeed, Figure 5.6 reveals that for all helmets taken together $\Delta\dot{Q}_S$ does not affect the response behavior for perceiving ‘more comfortable’.

One can also observe that $\Delta\dot{Q}_S$ alone does not completely determine the response behavior of the subjects, for all these questions. For instance, the response ‘warmer’ shows a dependence on $\Delta\dot{Q}_S$ only for helmet 130, and not helmet 110, even though $\Delta\dot{Q}_S$ is similar for both helmets. This indicates helmet-specific sensitivities, which is confirmed by the inclusion of the parameter 'helmet' in these models.

The importance of the predictor subject is consistent with the expectation that each subject has a unique sensitivity. However, a more detailed analysis of these two predictors will not be undertaken, since we examined a small pool of subjects and obvious subject-specific characteristics, e.g., hair style (not described in detail here), did not appear consistent with differences among subjects.

5.3.5. Logistic regression - Face section

Six parameters were identified in the face section by the modeling procedure for questions two through five (Table 5.4). The most frequently occurring were, in descending order of importance, helmet and $\Delta\dot{Q}_F$. However, only the two models for thermal comfort were highly-performing. The remaining models performed only slightly better than the corresponding intercept models, as expressed by the low values of McFadden r^2. It is interesting that, although the range of $\Delta\dot{Q}_F$ is close to zero for three out of four helmets (Figure 5.4c), it was included in all models. This indicates that $\Delta\dot{Q}_F$ was important for the response behavior for at least some cases for each question. Removing helmet 110, which showed much larger changes in $\Delta\dot{Q}_F$ compared to the other three, from consideration in the modeling did not result in exclusion of $\Delta\dot{Q}_F$ from the resulting models; neither did limiting the models to include only helmet 110. This indicates that $\Delta\dot{Q}_F$ was important for the response behavior of at least two of the helmets, including helmet 110. Notably, the final model for thermal comfort is characterized by the inclusion of many more physical parameters than the models for the other perception parameters.

Table 5.4: The performance of the multinomial logistic regression models for the face section for questions two through five and the importance of the parameters in explaining the response behavior.

Face Section		Model Performance		p-Value of the likelihood ratio test of the full model reduced for the indicated parameter (smaller values indicate higher importance of the parameter for the overall model)*					
Question	MC	Correctly Predicted	McFadden r^2	Helmet	ΔQ_F	Subject	$T_{sk\text{-}mean}$	T_{sk3}	RH_{f2}
2 Temperature	No	56%	0.34	$<10^{-5}$	$<10^{-4}$				
	yes	55%	0.35	$<10^{-5}$	$<10^{-2}$			<0.05	$<10^{-3}$
3 Airflow	No	57%	0.13		$<10^{-6}$				
	yes	62%	0.2	<0.05	$<10^{-4}$				
4 Noise	No	62%	0.28	$<10^{-6}$	$<10^{-3}$				
	yes	64%	0.18	$<10^{-2}$	$<10^{-3}$				
5 Thermal Comfort	No	82%	0.6	$<10^{-6}$	$<10^{-2}$	$<10^{-3}$			
	yes	91%	0.86	$<10^{-6}$	$<10^{-3}$	$<10^{-4}$	$<10^{-3}$	$<10^{-2}$	<0.05

Column MC indicates whether the thermal microclimate parameters were included in the parameter pool. If so, three helmets are included, since one helmet was not equipped with sensors, otherwise four helmets. ΔQ_F indicates the vent-induced heat loss, $T_{sk\text{-}mean}$ the average skin temperature of the face, T_{sk3} the skin temperature measured on the chin, and RH_{f2} the microclimate relative humidity measured in the face section (F2 in Figure 5.3). More information is provided in the text. *Blanks indicate that the corresponding parameter was not included in the model.

5.3.6. Measured effects of changing the vents on local temperature and RH

The effect of changing the vent configuration on the microclimate and skin temperature and RH was studied with the data obtained in the steady state period. Here responses to moderate and high values of v_w were combined in order to yield a more favorable false negative ratio (β) for helmets 110 and 130. The increased sample size (n = 8 vs. n = 4) outweighed the combination of slightly different results obtained in the two conditions, as indicated by β of 0.54 ± 0.35 for the combined data and 0.27 ± 0.22 for the uncombined data. The locations that reached a significant difference on a paired t-test between just before and 15 min after the change in vent configuration are visualized in Figure 5.7a. Both the temperature and RH sensors reacted to changing the vents during the examination phase. For helmet 110 only the sensor at the top of the scalp (S1) was affected, whereas for helmet 130 both RH sensors at the midline of the scalp (S1 and S5) registered significant changes. These results suggest that for helmet 110 the airflow is more concentrated around the midline, whereas the airflow for helmet 130 is most prominent between the midline and the ear.

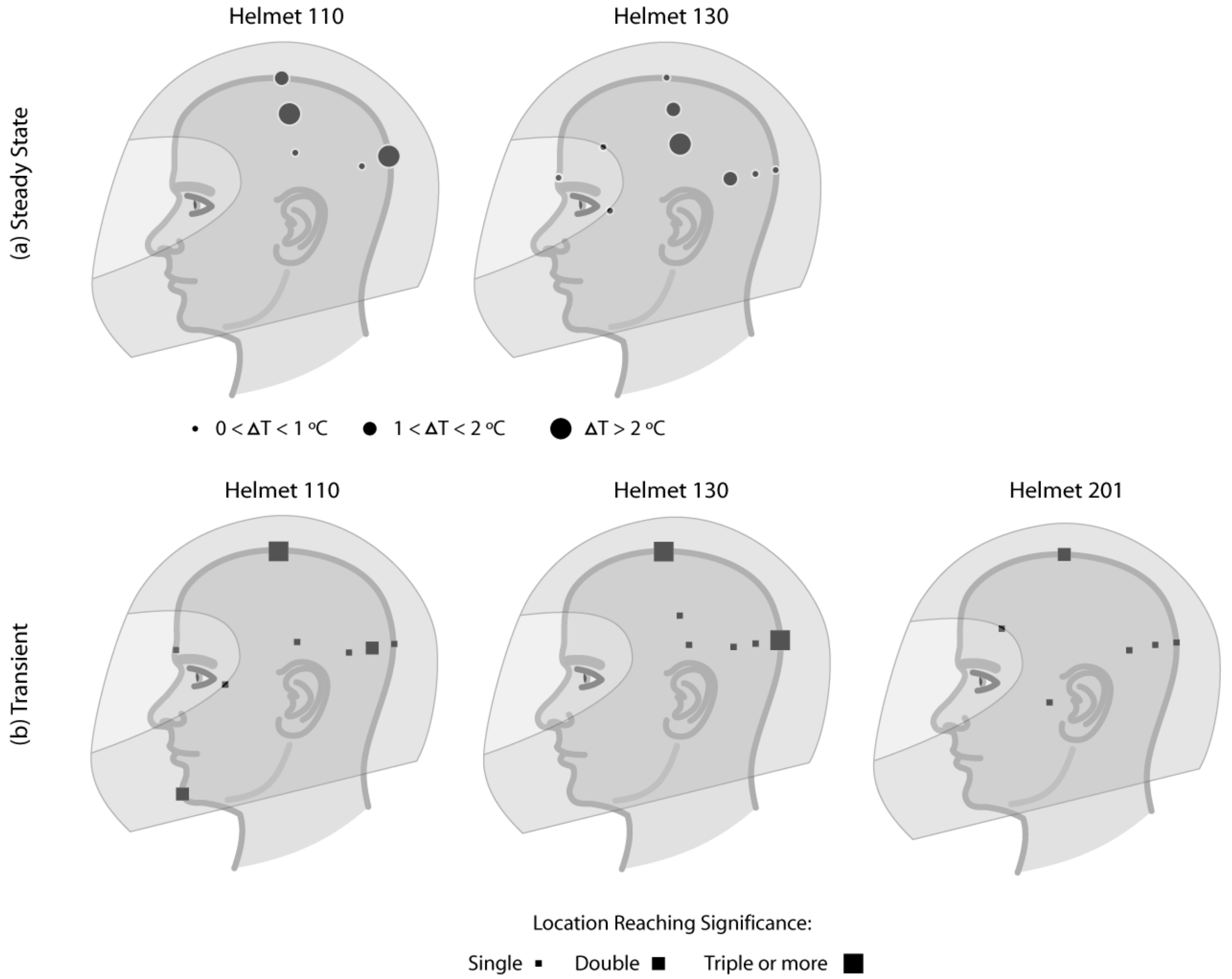

Figure 5.7: The effect of closing the vents on measured microclimate parameters in the indicated helmets, (a) as measured during steady state, given by the difference between just before the change and approximately 15 min after the change; (b) as obtained during the transient up to 50 s after closing the vents during the examination phases. Only sensors reaching a significant effect of changing the vents are visualized, with the frequency of reaching significance per sensor location given by the size of the symbol, as indicated. More information is given in the text.

A similar analysis was carried out during the examination phase for all helmets equipped with temperature and RH sensors, and for all conditions. Unfortunately, a given sensor in a helmet during the same condition measured on the eight subjects yielded thermal data with relatively large variations compared to the steady state phase. This variation is probably caused by the transient situation created by changing the vent configuration. Therefore, we report the number of times a significant effect is found for a particular sensor in the same helmet (Figure 5.7b). As is apparent there, the affected temperature sensors in the steady state phase are not exactly the same set as those affected just after a change in vent configuration.

For helmets 110 and 130 the RH sensor in the top position (S1) was affected by changing the vent configuration for each helmet in three conditions. For helmet 130, RH measured at the back of the scalp (S5) also reached significance twice. When closing the vents in the scalp section, the temperature (RH) of the significantly-affected sensors changed during the steady state phase with 1.2 ± 2.2 ºC (1.0 ± 0.1%), 0.3 ± 0.1 ºC (0.5 ± 0.3%), and 0.2 ± 0.4 ºC, for helmets 110, 130, and 201 respectively. For the face section this was 0.3 ± 0.1 ºC, and 0.1 ± 0.1 ºC, for helmets 110, and 201 respectively.

5.4. Discussion

This study collected 93 responses for four perception-related questions over a wide range of $\Delta\dot{Q}_S$ (-6.1 to 6.1 W). The subjects were able to systematically perceive effects caused by changing the vent configuration in the scalp section while wearing one of four different full-face motorcycle helmets under two different wind speeds (39.2 km/h and 59.3 km/h) applied at two different ambient temperatures (23.7 ºC and 27.5 ºC). Furthermore, $\Delta\dot{Q}_S$ was the most important determinant for the response behavior. As noted in the Introduction, many studies have been carried out with an implicit or explicit assumption of such a relationship with respect to headgear; we attempt here to investigate this relationship in greater detail.

The visual similarity of several of the distributions in Figure 5.6 strongly suggests the existence of relationships among the perception parameters, especially among temperature, airflow and noise. In order to investigate this quantitatively, four new full-factorial multinomial logistic regression models were generated as defined under Statistics. Each model predicted the responses of one of the questions two through five. The inputs to these models were the responses to the remaining three questions (Table 5.5). For the scalp section the models predicting the response behavior for temperature and airflow perform similarly, and each included the responses to the other as the most important predictor. This suggests that temperature perception and airflow perception are related in the present study, as also indicated by similar values of M (Figure 5.6); this may be due to the obvious connection under physical law, but may also signal an overlap in the way the questions were interpreted, i.e., that subjects tended to perceive the questions as being related, or perhaps a mixture of these influences. The models for noise and thermal comfort are poorly performing as indicated by the low values of McFadden r^2, indicating that these responses are not closely related to the responses to other questions. Thus, although the response behavior for noise has a similar distribution compared to temperature and airflow, the overall response of the subjects to this question is different, signified for example by the stronger non-indifferent responses when wearing helmet 201. It is more difficult to derive relationships among the questions for the face section, probably caused by the small range of $\Delta\dot{Q}_F$ for most helmets.

Table 5.5: The performance of the multinomial logistic regression models for questions two through five and the importance of the parameters, with the remaining questions as input.

		Model Performance		p-Value of likelihood ratio test of the model reduced for the indicated parameter (smaller values indicate higher importance of the parameter for the overall model)*			
				2	3	4	5
Question	Section	Correctly Predicted	McFadden r^2	Temperature	Airflow	Noise	Thermal Comfort
2 Temperature	Scalp	82%	0.53		$<10^{-6}$		$<10^{-6}$
	Face	86%	0.68		<0.05	<0.05	$<10^{-5}$
3 Airflow	Scalp	77%	0.46	$<10^{-6}$		$<10^{-5}$	
	Face	83%	0.69	<0.05		$<10^{-6}$	$<10^{-3}$
4 Noise	Scalp	56%	0.28		$<10^{-6}$		<0.05
	Face	78%	0.55	<0.05	$<10^{-6}$		
5 Thermal Comfort	Scalp	74%	0.39	$<10^{-6}$	$<10^{-2}$	<0.05	
	Face	71%	0.41	$<10^{-5}$	$<10^{-2}$	<0.05	

*Blanks indicate that the corresponding parameter was not included in the model.

Little is known about effects on thermal comfort associated with a local transient, such as in the present study. One group recently conducted extensive measurements on spatially and temporally skin distributions (e.g., Zhang, 2003; Zhang et al., 2004; Arens et al., 2006b). They found a similar response behavior for temperature perception and thermal comfort under application of a local temperature transient, in situations in which the subject's entire body was in a thermally neutral state. However, the present study did not find such a relationship between temperature perception and thermal comfort. This discrepancy might be explained by the following differences, relative to the present study: i) the skin area to which the intervention was applied was larger; ii) it is unclear how long after the application of the intervention thermal comfort of the corresponding body part was assessed and if this was controlled for; iii) it is unclear what the applied rate of change in temperature was. In any case, the current results indicate that thermal comfort does not follow temperature perception under conditions of whole body non-uniform skin temperature distribution combined with a local temperature transient on the scalp section, in a period from the onset of intervention up to 60 s.

The responses to each of questions two to four show a peak around zero $\Delta\dot{Q}_S$ for the category 'indifferent', and the responses for perceiving an effect are concentrated at large positive (opening vents) or large negative (closing vents) values of $\Delta\dot{Q}_S$ (Figure 5.6). Together with the observation that $\Delta\dot{Q}_S$ is for these questions the most important predictor, this suggests the basis of a definition for perception thresholds for these questions. To our knowledge, no previous studies have derived perception thresholds for fluctuations of heat transfer, so that there is no established methodology. As a first attempt, we expressed each response category as the corresponding likelihood relative to the total response for each given value of $\Delta\dot{Q}_S$. These likelihoods were calculated for each question and each helmet, e.g. for temperature perception in Figure 5.8. While starting at zero and evaluating the likelihood values at increasingly large (positive or negative) values of $\Delta\dot{Q}_S$, a perception threshold can then be defined as the value of $\Delta\dot{Q}_S$ at which the likelihood for perceiving an effect continually and consistently exceeds the combined likelihood for the other two responses. For instance, for helmet 110 temperature perception (Figure 5.8) indicates a higher likelihood for response 'cooler' compared to the other two responses for all positive values of $\Delta\dot{Q}_S$, indicating that the perception threshold for 'cooler' is probably at smaller values of $\Delta\dot{Q}_S$ as measured for that helmet. Interestingly, for the same helmet 'warmer' is never given as a response, suggestion that its perception threshold is at larger absolute values of $\Delta\dot{Q}_S$. On the contrary, for helmet 130 the same question shows a perception threshold for 'warmer' of the order of -5.1 W, whereas the perception threshold for 'cooler' must be less than the lowest $\Delta\dot{Q}_S$ measured for that helmet. Helmets 201 and 210 do not indicate a perception threshold, thereby suggesting that the threshold for those helmets, if it exists, lies beyond their measured range of $\Delta\dot{Q}_S$. The thresholds for questions two to five are given in Table 5.6. Temperature and airflow perceptions yielded the most reliable thresholds, since most fall within the measured range of $\Delta\dot{Q}_S$. Interestingly, the sensitivity of the subjects was greater for airflow compared to temperature, expressed by thresholds closer to zero for airflow. This tends to indicate that airflow is not only perceived through thermoreceptors. Furthermore, noise and thermal comfort perception did not allow the definition of a threshold range, e.g., because of the large differences between thresholds for 'more noise'. For 'more comfortable' a positive threshold was found for helmet 110, whereas helmet 130 indicated a negative threshold; this hints at a greater complexity of thermal comfort perception compared to temperature or airflow perceptions, as suggested above.

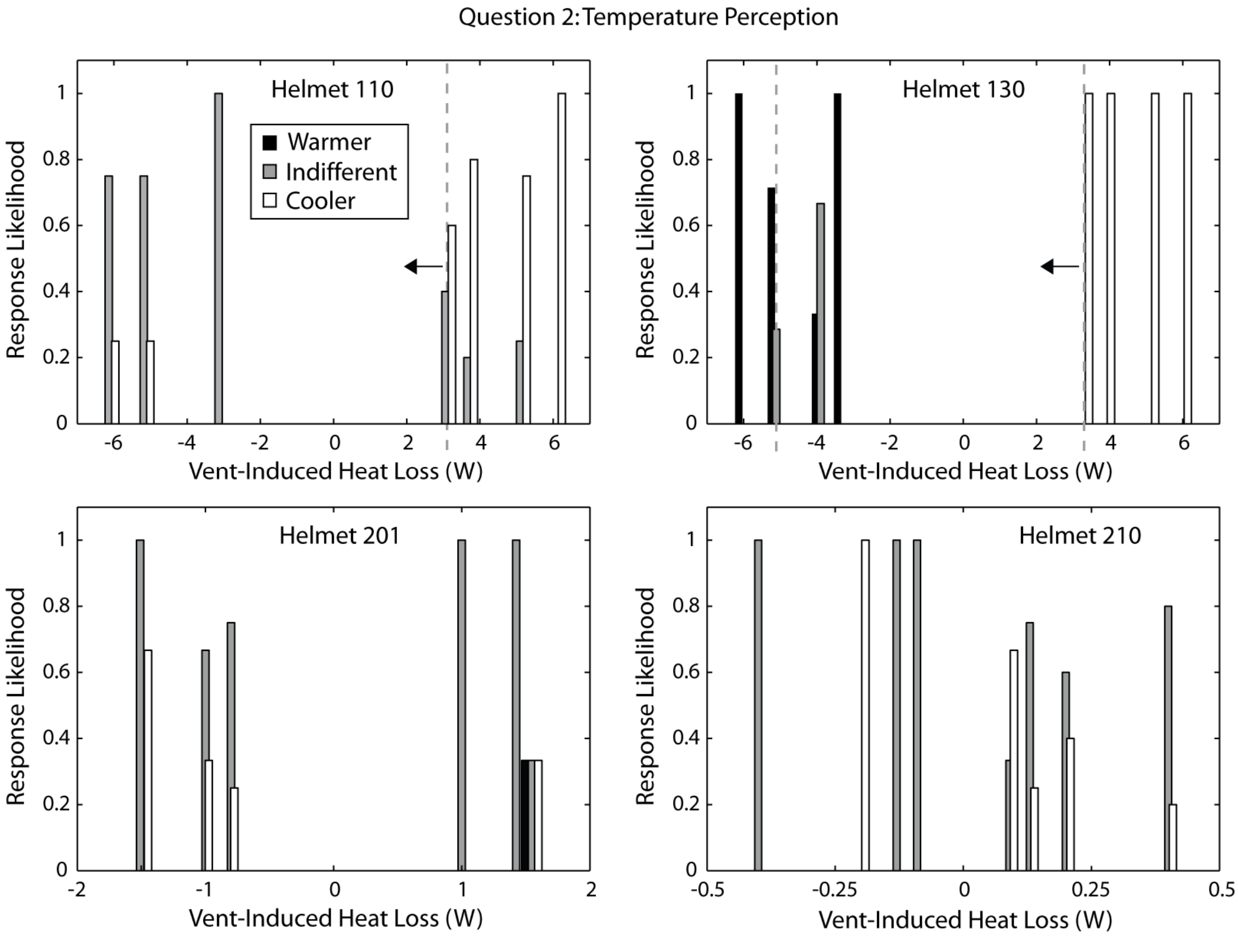

Figure 5.8: The response likelihood for temperature perception for each helmet and response category, as indicated. These likelihood values are obtained by dividing the number of responses given per vent-induced heat loss for a given response category, by the total number of responses. These results were used to derive the perception threshold as is roughly indicated, and explained in more detail in the text. Note the differences among the heat loss ranges shown between the different graphs.

Table 5.6: Perception thresholds for each question for the scalp section for all response categories, and for the indicated,

Question	Response Category	Perception Thresholds (W) Helmet 110	130	201	210	Summary All
2 Temperature	Warmer	< -6.1	≤ -5.1	< -1.5	< -0.4	≤ -5.1
	Cooler	< 3.1	< 3.3	> 1.5	> 0.4	[1.5; 3.1]
3 Airflow	Less	< -6.1	> -3.3	< -1.5	< -0.4	[-3.3; -1.5]
	More	< 3.1	< 3.3	< 1.0	0.4†	[0.4; 1.0]
4 Noise	Less	< -6.1	< -6.0	< -1.5	< -0.4	< -6.1
	More	6.1†	6.0†	> 1.5	0.4†	‡
5 Thermal Comfort§	Less	-	5.1	-	-	-
	More	5.1	-3.9	-	-	-

† The threshold is based on only one value, i.e. for the corresponding helmet there are no larger values of vent-induced heat loss present. ‡ Too many thresholds in this row are based on a single observation, the summary is therefore not given. § It is unclear which response is associated with increased heat loss and vice versa, as indicated by the opposing thresholds for 'more comfortable' for helmets 110 and 130. Therefore, the threshold is only given when falling in the range of the applied vent-induced heat loss.

A previous study derived an approximate perception threshold for $\Delta\dot{Q}_S$ (Brühwiler et al., 2004) of the order of 1.5 W for bicycle helmets. This is at the edge of the range consistent with present results, which must be located between 1.5 W and 3.1 W for perception of cooler temperatures. As will be discussed later, airflow patterns might be responsible for differences in sensitivity, thereby making a direct comparison difficult.

The present measurements were carried out on a bald headform and none of the subjects were bald. Since the presence of hair increases thermal insulation (Chapter 4), this suggests an overestimation of the thresholds derived from the present results. In previous work using a wig, we estimated a reduction of $\dot{Q}_S$ by approximately 26% (Chapter 4) under conditions similar to those studied here, but how individual subjects will be affected remains question for future work.

The thresholds for temperature and airflow perceptions nevertheless suggest an asymmetry, with larger thresholds for perception associated with closing the vents. Asymmetries are also found in studies investigating perception thresholds for temperature changes (Bartlett et al., 1998; Hagander et al., 2000; Golja et al., 2003; Essick et al., 2004). Only one of these works investigated the temperature threshold of the scalp for warming and cooling (Essick et al., 2004), finding larger thresholds for warming compared to cooling, consistent with the present results.

As indicated by the reported perception thresholds (Table 5.6), and the logistic models (Table 5.3), helmet-specific sensitivities exist, e.g., helmet 110 generally results in larger thresholds compared to helmet 130. Figure 5.7b indicates that more sensor locations are affected by changing the vent configuration for helmet 130 compared to helmet 110. Therefore, the difference in airflow patterns might be responsible for the difference in sensitivity between these two helmets. In addition, the difference between steady state and transient measurements for a given helmet suggests that skin blood flow could be modified by vent-induced effects. However, these helmet-specific sensitivities make it impossible to define more accurate perception thresholds from the present data set. Effective differences in airflow patterns might be a very general phenomenon and important in comparing different kinds of headgear.

The conditions created in the present study are reasonable simulations of motorcycle riding with respect to air exchange in the helmet. Previously we estimated that v_w reported here of 36 km/h and 62 km/h simulate higher speeds in traffic of 53 km/h and 80 km/h, respectively (Chapter 2), which are typical for many traffic situations. At the same time, there are factors which make it difficult to transfer the present observations to the field. For instance, motorcyclist protective clothing is thermally insulating, constituting a potentially large thermal burden in warm weather, which should be even greater under solar radiant heating. Finally, the noise experienced by the subjects was likely lower than often experienced in the field, where factors such as drafts created by the windscreen of a motorcycle intercepting the helmet can be important (Lower et al., 1994; McCombe et al., 1994). Thus, the present study must be considered a first attempt at examining the affects of wearing such helmets on the investigated perception parameters.

5.5. Conclusions and outlook

It was found that subjects are able to systematically perceive effects caused by changing the vent configuration of motorcycle helmets, especially in the scalp section, under simulated riding conditions. Furthermore, the main determinant of the response behavior of the scalp sections of the subjects was the vent-induced heat loss, particularly for the perception of temperature, airflow, and noise. Perception thresholds for temperature and airflow perception were obtained for changing the vent configuration in the scalp section, suggesting that subjects are more likely to perceive opening of the vents compared to closing. However, the relationship between vent-induced heat loss and response behavior varied among the helmets.

The observed differences in airflow patterns derived from temperatures between scalp and helmet suggest airflow pattern as a likely cause of this helmet-specific sensitivity. Finally, the perception of temperature and airflow were found to be related for both the scalp and face.

These results confirm that a thermal manikin headform is a useful tool for investigating and optimizing temperature and airflow perception of headgear. The important role suggested for airflow inside the helmet suggests that a local measure of airflow (Pinnoji et al., 2008; Van Brecht et al., 2008) could help to elucidate temperature and airflow perceptions when wearing such helmets. Since changes in heat loss are confirmed as a driving factor in such perception, local measures of heat loss on manikins and human subjects may be necessary for a full understanding. Future work could improve the present approach by access to a method to continuously vary one or more parameters of interest, i.e., with specially-designed helmets, avoiding secondary effects of the helmet construction. A further improvement could be objective registration of all subjective parameters under study, e.g., with in-the-ear microphones.

6. The effect of wearing a full-face motorcycle helmet on cognitive performance in a warm environment

6.1. Introduction

Riders of powered two-wheelers (PTW), such as motorcycles and mopeds, have a higher risk for a fatal traffic accident than for any other mode of transport. It has been estimated that 440 PTW-rider fatalities occur per 100 million person traveling hours, whereas for respectively a bicyclist or a car driver, 75 and 25 fatalities were found over the same period (Koornstra et al., 2003), respectively. Half of these accidents are caused by the other collision participant, 37% to 41% by the PTW rider, and the remaining are attributable to factors such as vehicle and road failures (Hurt et al., 1981; ACEM, 2004). Notably, cognitive failures on the part of the PTW rider were determined to cause 34% of these accidents (ACEM, 2004). However, it is difficult to address the cause of this impaired cognitive performance. Most PTW riders wear a motorcycle helmet (ACEM, 2004; Keng, 2005; Glassbrenner & Ye, 2007), the influence of which is known to affect their wearer, e.g. through temperature perception and thermal comfort (Chapter 5). Therefore, such helmets might contribute to impaired cognitive performance. It has been established that full-face motorcycle helmets induce microclimate temperatures much higher than for the uncovered head in temperate conditions (Chapter 5). Furthermore, the average microclimate carbon dioxide levels are of the order of 2%, under wind still conditions, much higher than the ambient concentration (Iho et al., 1980; Aldman et al., 1981; Brühwiler et al., 2005). Since the present interest is on physiological aspects of cognitive performance impairment, the literature relevant to cases of warm temperatures applied to the head and increased carbon dioxide concentrations will be reviewed.

Several studies have examined the effects of warming the head of resting subjects in thermally neutral environments, with and without manipulating the thermal state of the rest of the body (Holt & Brainard, 1976; Hancock & Dirkin, 1982; Hancock, 1983). These studies all used a helmet instrumented with electrical heaters on its inner surface, achieving an increased tympanic temperature of the order of 1 °C (Holt & Brainard, 1976). One study reported a shortening of reaction time by heating the head, at the $p < 0.1$ level (Holt & Brainard, 1976). Hancock and Dirkin (1982) found increased reaction times and a decrease in errors on a choice reaction test. In a follow-up study, subjects completed more mathematics problems in a given period while wearing the heated helmet (Hancock, 1983). These three studies also evaluated cognitive performance while wearing the helmet without the heating elements turned on. However, only one found an effect, in the form of an increased reaction time (Hancock & Dirkin, 1982). Others have focused on the effects of externally cooling the heads of subjects in neutral and warm environments (Konz & Gupta, 1969; Nunneley et al., 1982; Simmons et al., 2008). None of these studies found a significant effect on cognitive performance. Finally, one publication indicated an effect on cognitive performance of wearing standard cricket headgear during cricket practice (Neave et al., 2004). Thus, two studies found an effect of passive (non-heating) headgear on cognitive performance (Hancock & Dirkin, 1982; Neave et al., 2004), and two did not (Holt & Brainard, 1976; Hancock, 1983), using similar methods in some cases. Therefore, the effect of passive headgear on cognitive performance remains unclear, although studies on heating the head indicate an effect.

It is perhaps relevant that the headgear employed in these studies did not substantially cover the face, which is, e.g., more sensitive to temperature changes than the scalp (Essick et al., 2004). Whereas, from the point of view of impact protection, the safest type of motorcycle helmets include facial protection (Chinn et al., 2003). Such helmets are commonly referred to as full-face motorcycle helmets. It has long been known that they can increase microclimate carbon dioxide levels (Iho et al., 1980; Aldman et al., 1981; Brühwiler et al., 2005), reaching an average microclimate carbon dioxide level, under wind still conditions, of the order of 2%. Two pilot studies have examined the effect of inhaling ambient air containing 2.5% carbon dioxide on cognitive performance (Sun et al., 1996; Yang et al., 1997). Both studies found a delay of reaching the learning-plateau on a stereoacuity test. However, these studies must be considered preliminary, since only three subjects took part. Investigations of the effects of similar concentrations for periods of days show deterioration of tracking performance, but may not be relevant for periods of hours or less (Manzey & Lorenz, 1998). Hence the highest carbon dioxide levels measured in motorcycle helmets (under wind still conditions) might affect cognitive performance.

We conclude that the role of increased temperatures and/or increased carbon dioxide concentrations experienced while wearing a full-face motorcycle helmet on cognitive performance is not well understood. Pilot studies in our laboratory suggest that such effects, if they exist, are subtle and may require tens of minutes to develop. The goal of the present study was to evaluate the effect of wearing a full-face motorcycle helmet on cognitive performance under moderately warm, low wind conditions, compared to not wearing such a helmet. A moderately warm environment was chosen since in such environments the reduction in heat loss caused by such helmets (Chapters 3 and 4) is less easily counterbalanced by increasing the heat loss from another body part, compared to a cooler environment. This also allows the subject to be thermally comfortable, so that any observed effects would be likely due to the helmet, and not other clothing, allowing a better comparison to the work in Chapters 3 and 4.

To develop an approach to measuring these effects, a model is useful. Hancock and Warm (1989) have proposed a potentially useful model with attention performance as output, and stress as input. The basis of this model is the inverted U hypothesis (Yerkes & Dodson, 1908), which postulates the existence of an optimum cognitive performance between hypo-stress and hyper-stress. This input stress is thought to be of psychological and physiological nature. Higher or lower levels of stress compared to the optimum result in a reduction of performance. Hancock and Warm (1989) proposed that the optimum does not correspond to one level of stress, but a range. In this range stress effects can be buffered by the attention capacity until it saturates.

This model implies that an intervention which affects psychological or physiological stress might not affect attention if the effect of the intervention can be buffered by the attention capacity. In turn this suggests that a study of detriments to attention as a function of stress must choose a high enough attention load so that the stress caused by the intervention cannot be buffered. The present study therefore mainly focuses on attention, and aims to provide the subjects with an attention load that does not allow the buffering of a possible helmet-induced effect (Figure 6.1). Most studies on cognitive performance of headgear have assessed vigilance, during which sustained attention is demanded from a subject (Hancock & Dirkin, 1982; Neave et al., 2004; Tikuisis & Keefe, 2005; Cheung et al., 2007). Such tasks present a subject with an attention-loading signal interspersed with random presentations of a target. This target is explained to the subject before the start of the task, and the subject is asked to respond as quickly as possible upon each sighting. The two studies of which we are aware that found an effect of headgear on cognitive performance employed such a test (Hancock & Dirkin, 1982; Neave et al., 2004), motivating the present use of the Hancock and Warm model.

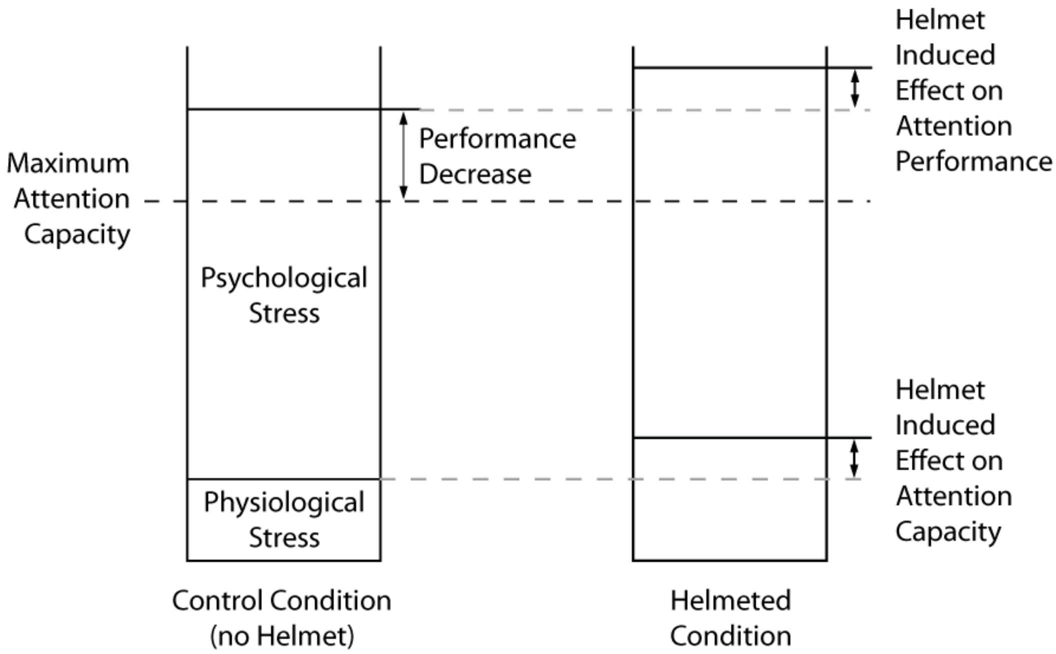

Figure 6.1: Schematic of the theory of attention capacity applied to the current study. It is the aim of the current study to load the subjects beyond their capacity to buffer a potential distracting effect caused by a helmet. More information is given in the text.

6.2. Methods

6.2.1. Subjects

Nineteen healthy male subjects aged 28.3 ± 4.7 years completed the study. The head circumference of the subjects ranged from 53 cm to 62 cm. The exclusion criteria were the taking of medications on a regular basis, or suffering from claustrophobia or an attention disorder. All subjects were instructed to refrain from alcohol, drugs and caffeine 12 hours prior to each trial. In addition, all subjects refrained from panting-inducing exercise between waking and each experimental trial, and were advised to get sufficient sleep. Finally, after experiencing the first familiarization trial the subjects were instructed to choose their clothing in order to be thermally comfortable during the consecutive visits. All subjects gave informed consent before participation. This study was approved by the Cantonal Ethical Committee of St. Gallen (Switzerland).

6.2.2. Thermal environment

All measurements were conducted in a climate chamber maintained at a temperature of 27.2 ± 0.6 ºC, and relative humidity (RH) of 41 ± 1%. Temperature was measured as defined in Section 2.1, RH was at the same location, and stored every 10 s (145W, MSR, Henggart, Switzerland). The wind speed (v_w) was 1.8 ± 0.2 $km \cdot h^{-1}$; measured beside the head as explained in Section 2.1. This ensured a controlled direction of v_w.

6.2.3. Setup

The setup was similar to that described in Section 2.1. In brief, the subjects sat at the exit of the wind tunnel (Figure 6.2). A 19' LCD screen of 1280x1024 pixels was positioned just below the wind tunnel, which allowed the subject to see the screen clearly. A conventional keyboard and joystick (Attack 3, Logitech, Fremont, USA) were positioned in front of the screen. The average vertical distance from a subject's head to the top of the wind tunnel was 5 cm, and average horizontal distance from the end of the housing of the wind tunnel to the forehead was 8 cm. During the trials the subject was the only person occupying the chamber and did not have any contact with the outside.

6.2.4. Cognitive performance tests

The following three cognitive performance examinations were employed: i) a simultaneous visual vigilance and tracking test (VTT), ii) an auditory vigilance test (AVT), and iii) a letter cancellation test (LCT). We found the LCT to be sensitive to a motorcycle helmet intervention in pilot studies, and the VTT has been used in previous work (e.g. Van Dorp et al., 2007). The AVT was developed in a pilot study as a secondary load simultaneous to the VTT in an attempt to improve the sensitivity of the method, consistent with the idea of providing an attention capacity load high enough so that the stress caused by the intervention cannot be buffered, as discussed in the Introduction. In what follows we present further details.

An older version of the VTT has frequently been used to assess cognitive performance, for instance on the effect of carbon dioxide (Van Dorp et al., 2007). The present version consisted of a tracking task in which a red annulus was presented at the middle of the computer screen, in addition to a blue ball (see Figure 6.2) The ball received random impulses from the software and the goal of the subject was to keep it in the middle of the annulus, using the joystick to control the acceleration direction and amplitude. On the screen, the outer diameters of the annulus and ball were 4.3 cm and 2.6 cm, respectively. The visual vigilance task of the VTT was based on continual observation of a black square in the center of the screen which appeared to rotate 45º once per second. At random intervals the square changed into a black circle of similar size (diameter 1.1 cm); upon perceiving this black circle, the subject was to press the 'fire'-button of the joystick as soon as possible. The following raw data were recorded at 20 Hz: i) the horizontal and vertical distance of the center of the ball to the center of the annulus, ii) the instance of responding to a target (up to 2 s after the presentation of the target), and iii) the instance of an incorrect response (response without a stimulus). From these raw data the following parameters were calculated: i) the distance of the center of the ball to the center of the annulus, ii) the reaction time of responding to the circle stimulus, iii) the number of correct responses (response up to 2 s following a stimulus), and iv) the number of incorrect responses (response without a stimulus).

Figure 6.2: A subject during a pilot measurement, carrying out the simultaneous visual vigilance and tracking test (VTT) and auditory vigilance test (AVT); the screen shows the VTT. The AVT was experienced through the earphones.

The AVT was an audio examination of vigilance, in which the subjects heard a tone every 0.8 s, at either 2.5 kHz or 2.0 kHz. A random tone sequence was generated in which one three-repetition sequence was randomly presented each 20 s; similar tones did not occur more than three times consecutively. The subjects were instructed to indicate perception of each such triplet as quickly as possible by pressing the spacebar of the keyboard. The following data were recorded with an accuracy of at least 50 ms: i) the instance of responding to a triplet (up to 2 s after the presentation of the triplet), and ii) the instance of an incorrect response (response without a stimulus). The raw data were processed to yield the following parameters: i) response time, ii) number of correct responses, and iii) the number of incorrect responses. The tones were presented over earphones (CX300, Sennheiser Electronic, Wedemark, Germany) which occupied relatively little space outside of the ear; these earphones were therefore only minimally affected by putting on a helmet. Furthermore, each subject chose the volume with which the tones were presented during the first familiarization trial, which was kept constant over the remaining trials. The AVT was developed for the purpose of this study in Matlab R2006b for Windows with use of the Psychtoolbox version 3.0.8 (Brainard, 1997). A unique AVT was generated each time the program was started.

The LCT as employed here is a pen and paper test widely used to assess visual attention, as described previously (Lezak et al., 2004). Six lines of 52 characters were printed in landscape orientation over the full width of a white A4 page, with a 1 cm margin to the left and right of the text. Random sequences of capital letters made up each line, interspersed with nine ‘K’ and nine ‘N’ characters, randomly placed. The task of the subject was to highlight all characters ‘K’ and ‘N’ using a marker, as quickly and accurately as possible. The number of correct responses and the time to completion were registered. The font type used was Courier New, printed in black with font size 10. For each assessment the subject was presented with a unique LCT. Each LCT was generated with Matlab R2006b for Windows.

6.2.5. Protocol

Each subject visited the climate chamber for five trials; the time of day of which was kept constant to avoid influence of the circadian rhythm. The first three visits served as familiarization trials and were followed by two experimental trials. The first and last trials occurred within two weeks, in order to prevent loss of familiarization. Before the start of each trial the subject completed a mood questionnaire (Monk, 1989), and indicated the quality and quantity of their sleep during the previous two nights on two 10 cm-wide visual analogue scales. Finally, each trial was finished with the assessment of whole body temperature perception and thermal comfort (ISO10551, 2001).

The familiarization trial started with 10 min of simultaneous VTT and AVT (VTT+AVT), followed by an LCT. The helmet was worn only in the first familiarization trial. The first 10 min of an experimental trial corresponded to a familiarization trial (Figure 6.3), to provide the subject with an additional practice session. Depending on the condition under study, the subject continued wearing the safety goggles or donned the helmet, not taking it off until the trial was completed. Following the LCT, a 20 min acclimation phase started, the purpose of which was to facilitate achievement of thermal steady state. This period was found to be sufficient, as described in Chapter 5. During this phase the subject read, or could carry out computer work. Subsequently, the subject completed one LCT, followed by 30 min VTT+AVT, and finally completed another LCT. The choice of the given protocol and cognitive tests was based on several documented pilot studies, which are available on request.

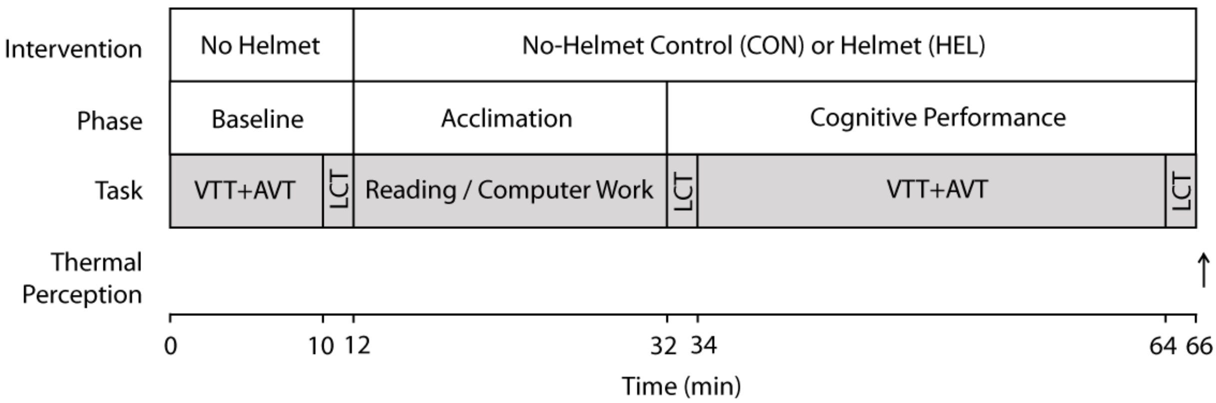

Figure 6.3: The protocol and interventions in an experimental trial. VTT stands for vigilance and tracking test, AVT for auditory vigilance test, and LCT for letter cancellation test, as detailed in the text.

6.2.6. Helmet intervention

During one experimental trial the subject wore a motorcycle helmet (HEL), while the other served as a control condition in which the subject wore only goggles (CON). In preparation for the first trial, the subjects chose the most comfortable of three helmet models (helmets 130, 201, and 250); since there was minimal wind in the laboratory, the choice of model is not expected to affect heat loss, which we have discussed in detail in Chapters 3, 4, and 5. The subject was presented with the helmet size (as indicated by the manufacturer) corresponding to his head circumference, which was measured according to ISO8559 (1989). If the subject judged the helmets to be uncomfortably tight or loose, the next appropriate size was used. During the trials the visor and vents of the helmet remained closed. In CON, the subject wore clear standard safety goggles (Astrospec 3000, Uvex, Fürth, Germany), in an attempt to match the visual conditions to those when wearing a helmet. Finally, the visor or goggles were cleaned with ethanol and a cloth before use, in order to ensure reproducible vision.

6.2.7. Heart rate and heart rate variability

R-R intervals for all subjects and both experimental trials were measured with a Polar belt via a wrist watch (RS800, Polar Electro Oy, Kempele, Finland). The R-R intervals were analyzed in the time domain for heart rate variability (HRV), according to the standards defined by the European Society of Cardiology (Malik et al., 1996). The following parameters were obtained: i) the standard deviation of the R-R intervals (SDNN), and ii) the difference between two consecutive R-R intervals exceeding 50 ms as a fraction of the total R-R intervals (pNN50). Only these two HRV parameters were chosen, since it is established that they can be reliably measured with a wireless Polar heart rate monitor for supine and standing subjects at rest (Radespiel-Tröger et al., 2003; Gamelin et al., 2006), and during low-intensity exercise (Kingsley et al., 2005). The analysis was carried out using Matlab R2006b for Windows.

6.2.8. Statistics and data processing

The data collected during the 30 min VTT+AVT was converted to averages over six 5 min intervals for VTT, AVT, HR, and HRV. The data of the majority of the measured parameters were not Gaussian distributed, as indicated by a Shapiro-Wilk test. Therefore, non-parametric statistics was used for statistical analysis. In an attempt to generate similar information as given by repeated measures ANOVA for within-subject effects, three separate analyses were carried out per parameter; yielding the intervention effect, the time effect, and an interaction effect between both parameters. The intervention effect (CON vs. HEL) was tested with a Wilcoxon test, on the paired results for a given parameter for all time periods combined. The same test was employed to investigate differences between CON and HEL for all six time periods, yielding the interaction effect between intervention and time. Finally, the time effect was analyzed by first combining CON and HEL for each time period and subjecting this to a Friedman test; a Wilcoxon test with a Bonferroni-corrected α level was used for post-hoc comparison. Mood, temperature perception, and thermal comfort were compared using a Wilcoxon test. All these non-parametrically analyzed results will be reported as median (25^{th} percentile; 75^{th} percentile). Statistics was carried out with SPSS 16.0 for Windows, and Matlab R2006b for Windows was used for data processing.

6.3. Results

Mood, sleep quality and sleep quantity were indifferent for all interventions.

6.3.1. Visual vigilance and tracking test

The VTT indicated an increased displacement for the tracking task with 7.2% (-9.9; 23.7) for HEL compared to CON (p = 0.021). In more detail, CON and HEL yielded 21.1 pixels (13.5; 30.9), and 21.7 pixels (13.7; 36.2), respectively. The other parameters did not indicate a general intervention effect. Correct responses indicated an interaction effect, where HEL resulted in 4.4% (0; 11.4) more correct answers compared to CON between 10 min and 15 min after start of the 30 min VTT+AVT. Finally, all parameters, with the exception of reaction time, indicated a reduction in performance with increasing time (Figure 6.4).

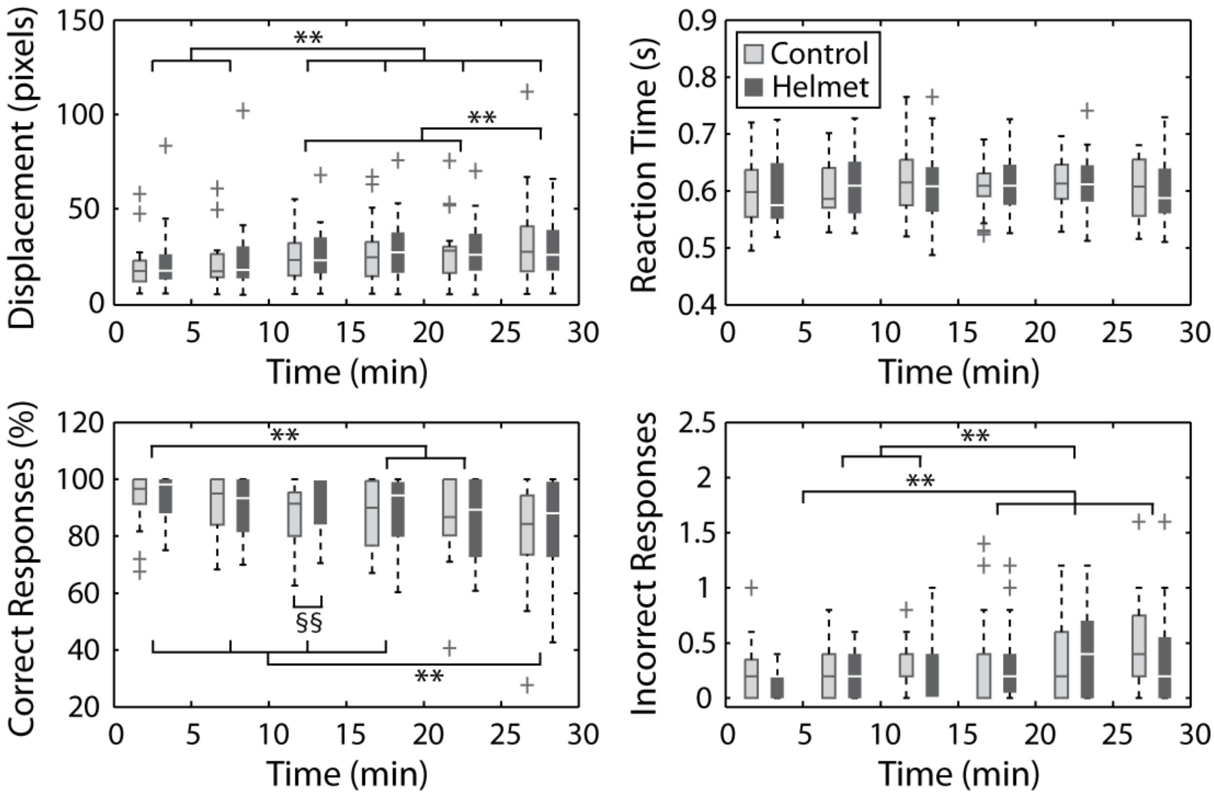

*Figure 6.4: Box-plots of the vigilance and tracking test (VTT) performance, for all measured parameters, for the control and helmet conditions as indicated. Note that the correct responses are expressed as percentages since the number of responses per 5 min was not always constant. Significant differences of the time effect are indicated by: ** $p < 0.01$, and significant differences of the interaction effect by §§ $p < 0.01$; and + indicates an outlier (included in the statistical analysis).*

6.3.2. *Auditory vigilance test*

The AVT did not indicate a general intervention effect, although the number of correct responses did approach significance (p = 0.073). However, each AVT parameter showed one interaction effect (Figure 6.5). Reaction time was larger for HEL by 10.2% (1,1; 20.4) compared to CON, for 20 min through 25 min after start of the VTT+AVT (p = 0.049). Furthermore, 13.3% (0; 25.8) less correct responses were given for HEL, between 10 min and 15 min (p = 0.034). Finally, 73.3% (0; 171.4) more incorrect responses were given for HEL compared to CON between 10 min and 15 min (p = 0.035). In addition, the number of correct and incorrect responses indicated a time effect (p < 0.01), as shown in Figure 6.5.

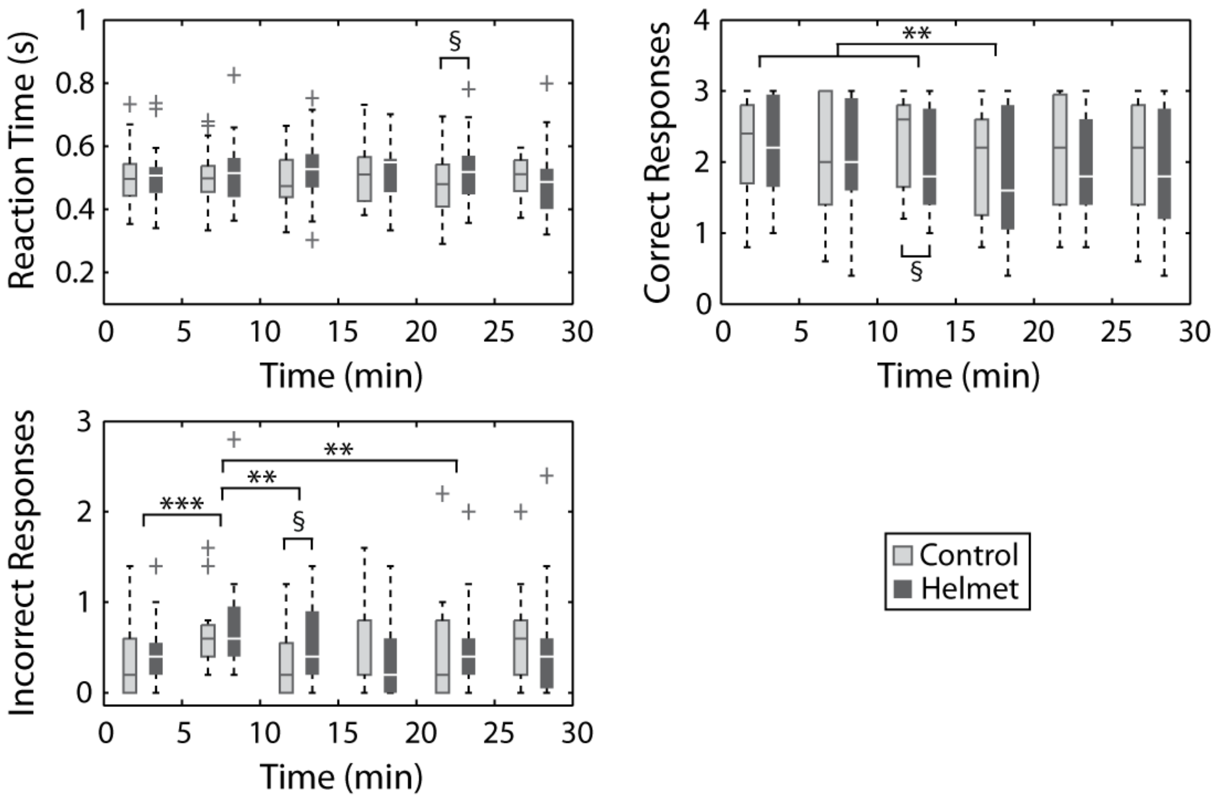

*Figure 6.5: Box-plots of the auditory vigilance test (AVT) performance, for all measured parameters, for the control and helmet conditions as indicated. Significant differences of the time effect are indicated by: ** p < 0.01, and *** p < 0.001, and significant differences of the interaction effect by § p < 0.05; and + indicates an outlier (included in the statistical analysis).*

6.3.3. Letter cancellation test

The LCT performance is visualized in Figure 6.6; no intervention effect was found. However, an interaction effect was found for the time to completion for the pre 30 min VTT+AVT assessment, which was 4.0% (-0.7; 6.7) longer for HEL compared to CON ($p = 0.021$). Furthermore, for time to completion also a time effect was found ($p = 0.017$), indicating that the subjects needed 2.0% (-2.5; 6.7) more time to complete the LCT after VTT+AVT.

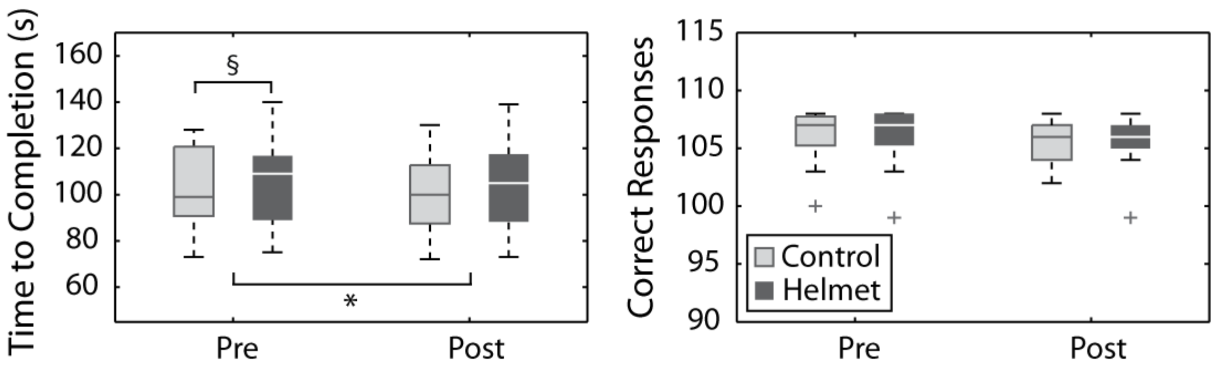

*Figure 6.6: Box-plots of the letter cancellation test (LCT) performance, for all measured parameters, for the control and helmet conditions as indicated, the pre-examination took place before the 30 min VTT+AVT and the post-examination was taken consecutively to the 30 min VTT+AVT. Significant differences of the time effect are indicated by: * $p < 0.05$, and significant differences of the interaction effect by § $p < 0.05$; and + indicates an outlier (included in the statistical analysis).*

6.3.4. Heart rate and heart rate variability

Figure 6.7 visualizes the HR and HRV results. pNN50 indicates an intervention effect ($p = 0.028$), yielding 17.5% (-26.9; 62.1) larger values for HEL compared to CON. In addition, HR resulted in a close to significant effect for the intervention ($p = 0.068$). No interaction effect was found among HR, pNN50, and SDNN. Finally, each of these parameters indicated a time effect (Figure 6.7), indicating lower values compared to the first time period.

6.3.5. Perception

Whole body temperature perception and thermal comfort assessed at the end of each experimental trial were different ($p < 0.01$). Temperature perception was higher for HEL (2.0 (1.3; 2.0)) compared to CON (1.0 (1.0; 1.0)). Whole body thermal comfort was rated less favorable for HEL, with values of -2.0 (-2.0; -1.0), and -1.0 (-1.0; -0.3), respectively.

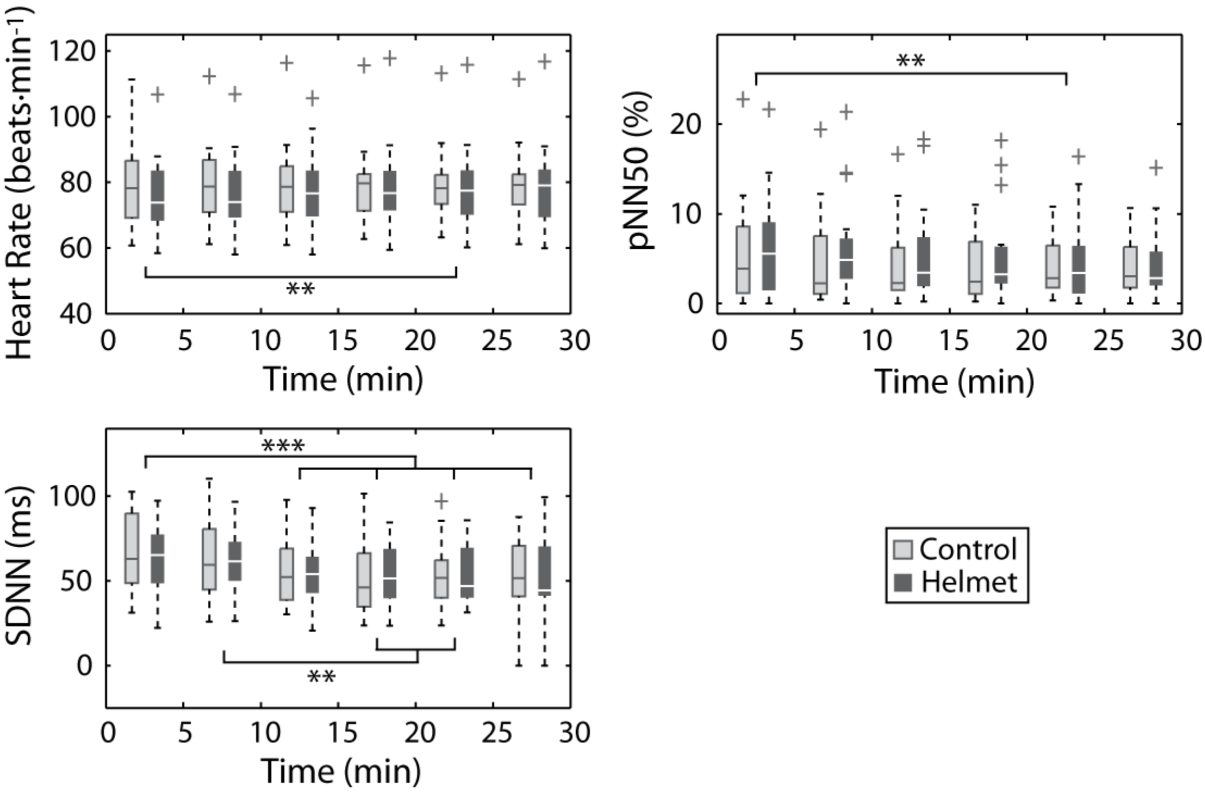

*Figure 6.7: Box-plots of the heart rate (HR) and heart rate variability (HRV) parameters, for the control and helmet conditions as indicated. Significant differences of the time effect are indicated by: ** $p < 0.01$, and *** $p < 0.001$; and + indicates an outlier (included in the statistical analysis).*

6.4. Discussion

Wearing of a full-face motorcycle helmet resulted in a less favorable whole body temperature perception and thermal comfort, an increase in pNN50, and impaired tracking performance. In addition, some interaction affects were found between time and intervention, indicating impaired performance for HEL compared to CON in four out of five cases. Interestingly, these interaction effects were found in three out of four cases between 10 min and 15 min after start of the VTT+AVT. This could indicate an attention shift during that time period. Such shifts are possible disadvantages of having multiple cognitive tasks at a given time. In an attempt to control for this, the combined performance was analyzed. For each parameter and subject, a performance measure normalized for the range of the data was calculated, determined as follows: First, the 30 min median was subtracted from each 5 min interval for each subject; secondly, the sign was corrected for each parameter so that negative values represented worse performance relative to the 30 min average, and vice versa; thirdly, these differences were divided by the range between 0^{th} and 100^{th} percentile obtained from the entire 30 min interval; finally, the median was taken from these normalized differences for all subjects and parameters measured during VTT+AVT. The results only indicate a time effect ($p < 0.001$), indicating a deterioration of performance between the first 10 min of VTT+AVT compared to the last 15 min. However, a potential drawback of this approach is that each parameter has an equal weight, which might not be representative of a relevant cognitive state.

Notably, some subjects reported experiencing moments in which they lost awareness of the tracking task during both CON and HEL. Therefore, the number of outliers in the displacement of each of the 6 time periods of the tracking task was counted. An outlier was defined as a displacement larger than 75^{th} percentile over 30 min. However, the number of such outliers only revealed a time effect ($p < 0.001$), with about twice as many outliers found during the last 5 min compared to the first 5 min. Hence, after taking into account other methods of analysis no additional intervention effects of wearing a motorcycle helmet were found.

Only one out of nine parameters showed an intervention effect, and five interaction effects were found out of 46 possibilities. Furthermore, no interaction effects were found for displacement, whereas this parameter showed an intervention effect. This suggests that the effect of wearing a full-face motorcycle helmet is small, but measurable in the present study. As reviewed in the Introduction only two studies on the effect of passive headgear on cognitive performance found an intervention effect (Hancock & Dirkin, 1982; Neave et al., 2004), whereas two other studies did not (Holt & Brainard, 1976; Hancock, 1983). One of the former studies only found an effect after grouping their cognitive performance parameters into different global parameters (Neave et al., 2004), which had been developed in previous work (Wesnes et al., 2000). On the contrary, no effect on cognitive performance was found, if the single parameters were analyzed separately (personal communication with Neave, 2008). Thus, one out of four studies (Hancock & Dirkin, 1982) found an effect of passive headgear on single cognitive parameters. Taken together, this tends to support the conclusion that the effect of wearing a motorcycle helmet on cognitive performance is small.

Of the two HRV parameters, only pNN50 showed an intervention effect, indicating larger values for HEL compared to CON. Contrary to SDNN, pNN50 is an indicator for short-term components of HRV (Malik et al., 1996), indicating that an effect in pNN50 does not have to coincide with an effect in SDNN. Only one publication is known to the authors in which cognitive performance is related to pNN50 (Lee et al., 2007). This study found a reduced pNN50 while one subject carried out a simulated driving task compared to doing no task at all. Another study measured pNN50 during short-term exposure to a hot environment (74 ºC) compared to a warm environment (27 ºC) (Bruce-Low et al., 2006). They found a reduction of pNN50 in the hot environment. However, HR showed a large increase (ΔHR = 61%) in the hot environment, which therefore seems likely to be the primary cause of the reduced pNN50. Thus, it remains unclear if the effect of HEL on pNN50 is caused by an increased cognitive stress. In addition, other effects of wearing a full-face motorcycle helmet might also have affected pNN50, e.g., increased microclimate temperatures, or increased microclimate carbon dioxide levels.

Approximately two-thirds of the measured parameters during the VTT+AVT revealed a time effect, and always indicating worse performance toward the end compared to the start of the examination. Others have also reported such time effects (Grier et al., 2003). This time effect could be caused by a reduction of the attention capacity (Hancock & Warm, 1989; Grier et al., 2003), suggesting that the cognitive tests and protocol employed in the present study are sensitive to time effects in a manner compatible with this previous work.

The present study assessed cognitive performance during wind still conditions. It is expected that if wind were applied in the given climate, any possible effect on cognitive performance due to temperature, humidity or carbon dioxide would be reduced, since greater wind speed increases heat loss from the head (Section 4.3.3) and reduces skin and microclimate temperatures (Chapter 5), as well as reducing microclimate carbon dioxide concentrations (Aldman et al., 1981; Brühwiler et al., 2005). Notably, the subjects reported feeling warm and thermally uncomfortable during HEL. In contrast to the clothing worn by subjects in the present study, in the field riders are likely to wear protective clothing, thereby experiencing a different temperature perception and/or thermal comfort. One study examined heat transfer from a rider during motorcycle riding in different weather conditions while wearing clothing of different thicknesses (Woods, 1986). The highest ambient temperature reported was 23 ºC. In Section 1.3.1 these results are extrapolated, indicating that heat strain can be expected to occur at ambient temperatures higher than 25 ºC (see also Figure 1.5, Section 1.3.1). However, the Woods study examined one subject, the riding speed was not reported, and the article was published in 1986, making it difficult to compare results due, e.g., to changes in the clothing state-of-the-art. We nevertheless assume that heat strain can be expected to occur in the field under the thermal environmental conditions created in the present study.

6.5. Conclusions and outlook

Wearing a full-face motorcycle helmet negatively affected whole body temperature perception, thermal comfort, and tracking performance. In addition, a helmet-mediated effect was found on the heart rate parameter pNN50. Moreover, the results from the present study indicate a small impairment of cognitive performance.

Given the differences between the laboratory and field conditions, it is unclear how the present results relate to traffic safety. Therefore, future studies on this topic could evaluate the effect in under more realistic situations, such as employing a realistic motorcycle simulator (Chiyoda et al., 2002; Ferrazzin et al., 2003; Cossalter et al., 2006), and/or more realistic clothing conditions combined with higher wind speeds.

7. Concluding remarks

The aim of this thesis was to investigate whether thermally-mediated effects of wearing a full-face motorcycle helmet affect parameters associated with traffic safety. Literature suggests such a relationship, but no studies investigated this directly. The aim was pursued in the present work by studying i) the external thermal boundary conditions created by these helmets, ii) how different ventilation systems of different motorcycle helmets affect temperature perception and thermal comfort, and iii) whether wearing a motorcycle helmet affects cognitive performance. The results are put into a common context, and their consequences for traffic safety are discussed here.

Unfavorable temperature perception and thermal discomfort are reasons given for not wearing motorcycle helmets (Patel & Mohan, 1993; Skalkidou et al., 1999; Li et al., 2008a). In this thesis, the effect of wearing a full-face motorcycle helmet on subjects' rating of perception was investigated (Chapter 5). This study clearly shows a negative effect of wearing a helmet on whole body temperature perception and thermal comfort ($p < 0.01$). The heat loss ($\dot{Q}$) measurements of 27 helmets (Chapter 3) indicated that, especially for the scalp section, $\dot{Q}$ was reduced below values measured in a comfortable office climate (Froese & Burton, 1957; Clark & Toy, 1975; Rasch et al., 1991). In addition, these thermal manikin headform measurements at an ambient temperature of 22 ºC and a wind speed of 50 $km \cdot h^{-1}$, indicated that $\dot{Q}$ ranged between 0 W to 4 W for the scalp section, and 8 W to 18 W for the face section. This indicates that especially the poorer performing helmets can be improved, and optimization suggestions have been given (Chapters 3 and 4).

The ventilation systems of these helmets should be aimed at providing some control over $\dot{Q}$, and therewith providing some control over temperature perception and thermal comfort. Therefore, a study was targeted at investigating the relationship between vent-induced heat loss ($\Delta\dot{Q}$) and perception, with special attention paid to the scalp section (Chapter 5). This study derived thresholds for perception of decrements of temperature in the scalp section, quantified in the range $1.5 \text{ W} < \Delta\dot{Q} < 3.1 \text{ W}$. However, headform measurements indicated that for the scalp section, only three helmets out of a sample of 27 yield $\Delta\dot{Q} > 1.5$ W (Chapter 3). Thus, the vent-induced effects of most helmets do not exceed the threshold for temperature perception, although lower ambient temperatures or higher wind speeds might increase the number of helmets exceeding this threshold. The large variations of $\Delta\dot{Q}$ for the different helmets show a great potential for improvements in many helmets.

Giving subjects perceivable control over a situation results in more favorable ratings on whole body thermal comfort, compared to similar conditions without control (Zhang et al., 2004). Thus, increasing $\Delta\dot{Q}$ seems an effective approach of reducing thermal discomfort of motorcycle helmets, although the exact thresholds of $\dot{Q}$ and/or $\Delta\dot{Q}$, resulting in an increased helmet usage are not yet known.

It has to be emphasized that perception of subjects and not $\Delta\dot{Q}$ per-se should be optimized. Although $\Delta\dot{Q}$ was found to be the strongest predictor for the response behavior of subjects, also other factors had an influence (Chapter 5). The second most important predictor was helmet type, indicating that specific helmet characteristics independent of $\Delta\dot{Q}$ affect sensitivity. From the same study a first indication arose that airflow patterns might affect subjects' sensitivity, and therewith, at least partly, explain these helmet-specific sensitivities. However, more research is needed to understand this relationship. Finally, it became clear that local temperature perception and local thermal comfort are not directly related under transient conditions, such as created when changing the vent configuration (Chapter 5).

Full-face motorcycle helmets reduce $\dot{Q}$, and cause less favorable temperature perception as well as thermal discomfort (Chapter 6). These effects possibly cause distractions, deteriorating cognitive performance. Some publications have found relationships between cognitive performance and non-optimal conditions, such as discomfort of clothing (Bell et al., 2003; Bell et al., 2005), and ii) reduced skin temperatures (Cheung et al., 2007). The present work found a small impairment on tracking performance of 7.2% when wearing a full-face motorcycle helmet, in addition to an increase of the heart rate parameter pNN50 (Chapter 6). However, it remains unclear how the small effect on cognitive performance affects traffic safety.

7.1. Conclusions

Wearing a full-face motorcycle helmet negatively affected whole body temperature perception, thermal comfort, and tracking performance, in addition to an increase of the heart rate parameter pNN50. Moreover, the results from the present study indicate a small impairment of cognitive performance.

Vent-induced heat transfer, $\Delta\dot{Q}$, was the most important determinant for perception of temperature, airflow, and noise, although each helmet affected the sensitivity of the wearer in a slightly different manner. Finally, for temperature and airflow, perception thresholds were defined.

Only three helmets of a sample of 27 state-of-the-art full-face motorcycle helmets exceeded these perception thresholds measured at 22 ºC at a wind speed of 50.4 ± 1.1 $km \cdot h^{-1}$. However, the number of helmets exceeding these thresholds will be slightly larger at higher wind speeds or lower ambient temperatures. This indicates that the ventilation systems of most helmets are ineffective at stimulating perception of a change, and that these systems can be optimized for most helmets.

8. References

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10. Curriculum Vitae

10.1. Biography

Cornelis Peter Bogerd finished high school at the OSB in Amsterdam, the Netherlands, at the pre-science level (athenaeum). Following an exchange year at the Colorado Mountain College, United States, he studied Human Movement Science at the Vrije Universiteit in Amsterdam, the Netherlands. In 2003 Cornelis Peter obtained a medical-biological science teaching degree from the same faculty. He successfully defended his Master of Science (M.Sc.) thesis in 2004. This M.Sc. work was carried out at TNO, and consisted of two separate parts i) a literature review on health effects of sustained heat strain (supervised by Prof. dr. HAM Daanen), and ii) a study of the benefit of external cooling applied during endurance exercise in a warm environment (supervised by drs. R Heus and drs. JWM Willems). In addition, he was asked by his supervisors to work on several projects aimed at optimizing clothing and headgear of Dutch Olympic athletes, in preparation of the 2004 summer Olympics held in Athens, Greece. The work at TNO resulted in the first scientific contributions of Cornelis Peter in the form of two conference papers and a publication in a Dutch peer-reviewed medical science journal. In 2005 he was selected from a pool of promising young scientists to attend a workshop on Human Sensibility at the Kyushu University in Fukuoka, Japan, organized by Prof. dr. Y Tochihara. Since 2005 is Cornelis Peter employed by Empa in St. Gallen, Switzerland, first as a visiting scientist, and since 2006 as a Ph.D. student under main supervision of Prof. dr. PA Brühwiler. Finally, since 2006 is Cornelis Peter enrolled in the Ph.D. program of ETH Zurich, at the institute of Human Movement and Sport Sciences. Currently he continues work at Empa as a scientist until mid-2010.

More work-related information is available on: www.nielsbogerd.com

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