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Thermal Perception of Ventilation Changes in Full-Face Motorcycle Helmets: Subject and Manikin Study

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We report the effects of full-face motorcycle helmet ventilation systems on heat, airflow, noise, and comfort perception for ventilation changes on the scalp. Eight subjects (aged 28.0 ± 5.4 years) underwent two experimental trials at ambient temperatures of 23.7 ± 0.4°C or 27.5 ± 0.3°C. In each trial, the thermally equilibrated subjects underwent two examination phases, during which four different helmets were assessed at wind speeds of 39.2 ± 1.9 km h^{-1} and 59.3 ± 1.4 km h^{-1}. Vent-induced heat loss in the scalp ranged from −6.1 to 6.1 W, corresponding to vents being closed or opened, respectively. Perception of vent-induced changes was assessed immediately after the change. We find that the vent-induced heat loss, the subject, and the helmet are the most important response factors. In addition, comparison of two helmets with similar vent-induced heat loss suggests that internal airflow patterns may be important in explaining the observed perception differences.

Keywords: headgear; helmet; microclimate; motorcycle helmet; temperature perception; thermal comfort; ventilation

INTRODUCTION

Temperature perception is an important variable affecting the acceptance of occupational protective headgear (Hickling, 1986). This has motivated a number of studies on characterizing and optimizing thermal properties of such headgear (Fonseca, 1974; Reischl, 1986; Spaul *et al.*, 1987; Abeysekera *et al.*, 1991; Liu and Holmer, 1995; Liu, 1997; Liu *et al.*, 1999; Hsu *et al.*, 2000; Holland *et al.*, 2002; Brühwiler, 2003; De Bruyne *et al.*, 2008). As a result, headgear improvement concepts were proposed to improve temperature perception and thermal comfort (Abeysekera and Shahnavaz, 1988; Holland *et al.*, 2002).

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 and Kasantikul, 2006; Houston and Richardson, 2008), motivating continual efforts to study their function (Tan and Fok, 2006; Comelli *et al.*, 2008; Lai and Huang, 2008; Mills *et al.*, 2009; Młyński *et al.*, 2009) and use (Oginni *et al.*, 2007; Houston and Richardson, 2008; Li *et al.*, 2008a; Mayrose, 2008; Gkritza, 2009). Motorcycle helmets are required to cover more of the head than most protective helmets, and those offering the most protection, full-face helmets, greatly reduce the interaction of the wearer with his/her environment. Testing standards address potential limitations of the visual field. However, since the scientific and safety community continues to extend our understanding of the effect of headgear on the wearer, new standards might be formulated. Recent research on potential wearer impairment focused on noise levels (Iho *et al.*, 1980; Ross, 1989; McCombe *et al.*, 1994; Młyński *et al.*, 2009), vision (Lai and Huang,

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2008), general physiological strain (D'Artibale *et al.*, 2008), microclimate CO_2 and O_2 levels (Iho *et al.*, 1980; Brühwiler *et al.*, 2005), and helmet thermal properties (Brühwiler, 2003; Buyan *et al.*, 2006; Bogerd and Brühwiler, 2008; Pinnoji et al., 2008; Bogerd and Brühwiler, 2009). Unfavorable temperature perception and/or thermal discomfort are frequently given arguments for not wearing a motorcycle helmet (Patel and Mohan, 1993; Skalkidou *et al.*, 1999; Li *et al.*, 2008b), which is supported by field observations (Gkritza, 2009). Generally, a substantial fraction of riders do not wear helmets, ranging, e.g., from 7.7% (ACEM, 2004) between 1999 and 2000 for European countries, 40 ± 8% for the USA from 1994 to 2006 (Glassbrenner and Ye, 2006), and 25% in Taiwan between 1999 and 2001 (Keng, 2005). Thus, improving the thermal properties of such motorcycle helmets seems a useful step in improving their acceptance and effectiveness.

We have recently published manikin studies on the effect of full-face motorcycle helmets on heat loss ($\dot{Q}$) under a wide range of conditions (Bogerd and Brühwiler, 2008; Bogerd and Brühwiler, 2009). An important observation is that $\dot{Q}$ from the scalp section is reduced relative to comfortable conditions for the nude head. We hypothesis that fluctuations of $\dot{Q}$ on the scalp section, as measured with a manikin headform, have a large influence on local perception from the scalp of subjects. The fluctuations of $\dot{Q}$ were administered by changing the vent configuration of motorcycle helmets. Local perception is evaluated for temperature, airflow, noise, and thermal comfort. At the same time, we also set out to identifying other variables affecting local perception of vent-induced effects.

METHODS

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 included in this study. 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 <2 weeks. The subjects were dressed comfortably with respect to the thermal environment, including a scarf protecting the neck from excessive 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 attested to have refrained from consuming alcohol, nicotine, and caffeine during the 12 h preceding each trial and did not conduct any panting-inducing exercise between waking and the start of the trial.

Thermal environment

All measurements were conducted in a climate chamber at ambient temperatures (T_a) (average ± 1 SD) of 23.7 ± 0.4 and 27.5 ± 0.3°C (PT100; Roth + CO, Oberuzwil, Switzerland), referred to as neutral and warm, respectively. The warm climate represents the upper ambient temperature in which the thermal manikin 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^{-1}) and high (59.3 ± 1.4 km h^{-1}); v_w was measured beside the head as described elsewhere (Bogerd, 2009). The relative humidity (RH) was kept at 50 ± 2% (145W; MSR, Henggart, Switzerland).

Setup

A schematic representation of the setup is depicted in Fig. 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′ flat screen was positioned under the Plexiglas bottom of the wind

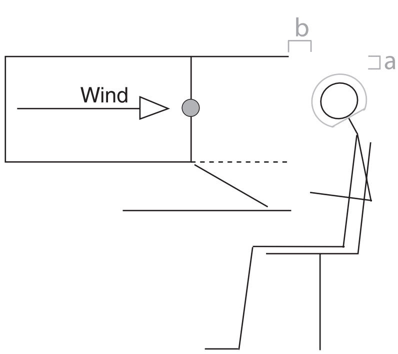

Fig. 1. Schematic of the setup. The head of the subject (or headform) was positioned at the exit of the wind tunnel at an angle of ~20°, allowing viewing of the computer screen. Distances 'a' and 'b' were measured to be 5 ± 1 cm and 8 ± 6 cm, respectively. The dashed line indicates the Plexiglas bottom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

tunnel, which allowed the subject to see the screen clearly. A keyboard and mouse were positioned in front of the screen. Additional details on the setup are given in the supplementary material at *Annals of Occupational Hygiene* online.

Protocol and interventions

Figure 2 illustrates the protocol for the experimental trials. For each subject, the two trials differed from each other in T_a, either neutral or warm; this sequence was balanced over the subjects. The trials consisted of the following phases, during which the subject sat still at the exit of the wind tunnel: (i) 30-min equilibration, (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 equilibration and steady state phases during both visits and the other four wore helmet 130. The remaining 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 equilibration 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 in the scalp section.

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 an attempt to regain values close to those measured during thermal steady state, for which 3 min was taken, (iii) the experimenter manually changed the vent configuration, in the scalp 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 ~5 min. To minimize the effect of helmet exchange on skin and microclimate temperatures, each helmet was preheated to 35°C for at least 5 min on the thermal manikin headform prior to being worn.

Perception assessment

Directly after a change in vent configuration, the subject filled out a questionnaire (Table 1). Question 1 served to determine if any changes were perceived. If so, Questions 2 through 5 were filled out, assessing perceptual effects of local temperature, airflow, noise, and thermal comfort. These variables were assessed in a fixed order, in an attempt to make the questionnaire as unambiguous to the subject as

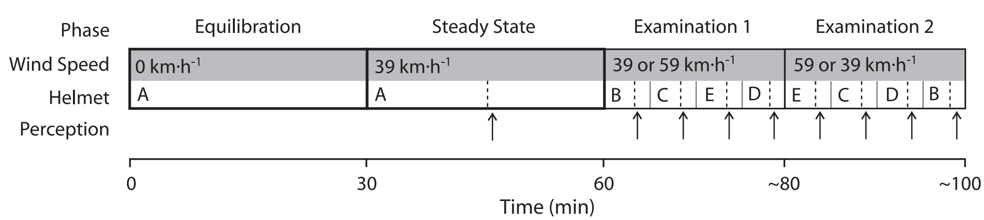

Fig. 2. Schematic of the protocol and interventions during an experimental trial. A dashed gray line (¦) indicates a change of the vent configuration, whereas a solid gray line (|) indicates a change of helmet (during this short period, no wind was applied). Perception assessments are indicated with arrows. Wind speed during the examination periods was offered in a balanced order over all subjects. The helmet used during the equilibration and steady state phase (A) was kept constant per subject and was either helmet 110 or helmet 130. During each examination phase, all four helmets were evaluated in random order.

Table 1. Subjective perception assessment questionnaire

Number	Question	Possible responses		
1	Do you notice a difference from the situation before the change in the scalp section?	Yes	No	
2	Is the temperature of the skin of the scalp section different?	Warmer	Uncertain	Cooler
3	Is the airflow over the scalp section different?	Increased airflow	Uncertain	Decreased airflow
4	Is the noise level different?	Increased noise	Uncertain	Decreased noise
5	How do you perceive the temperature in the scalp section?	More comfortable	Uncertain	Less comfortable

possible. All perception questionnaires were presented as Excel sheets (Office Excel 2003 SP3).

Familiarization trials

Each subject participated in a familiarization trial, the goal of which was to train him to fill out the questionnaires and optimize the exchange of helmets during the examination phases. First, the protocol was explained in detail and the subject was instructed on the use and meaning of each question in the questionnaires. Second, he experienced one examination phase, as described above.

Helmets and sensor integration

Four full-face motorcycle helmets were employed in this study; helmets 110, 130, 201, and 210 (Bogerd and Brühwiler, 2008; Bogerd and Brühwiler, 2009). These helmets were donated by several manufacturers under the condition that they not be identified; as a consequence, only limited information is provided concerning the helmets. Each had at least one operable vent in the scalp section. The helmets were selected to cover the available range of vent-induced heat loss in the scalp section ($\Delta\dot{Q}_S$), based on a previous study (Bogerd and Brühwiler, 2009). $\Delta\dot{Q}_S$ was measured on a thermal manikin headform and quantifies the difference in heat loss of changing the vent configuration in the scalp section. The ventilation system of helmet 210 was closed from the inside so that $\Delta\dot{Q}_S \approx 0$ W.

Helmets 110, 130, and 201 were instrumented with six thermistors per helmet (DS18B20–T3; MSR) in the scalp section, indicated as S2 through S4 and S6 through S8 in Fig. 3. In addition, two combined RH and temperature sensors (SHT15; MSR) were installed in the scalp section, indicated as S1 and S5 (Fig. 3). Because of the limited number of sensors available in our laboratory could helmet 210 not be instrumented. These sensors were sewn or glued into the inside of the helmet 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). A tool was developed to ensure consistent placements of the sensors, described in the supplementary material at *Annals of Occupational Hygiene* online. Furthermore, all sensors were placed on the left side, as symmetry was assumed; they were read out every 10 s to a data logger (MSR 12; MSR).

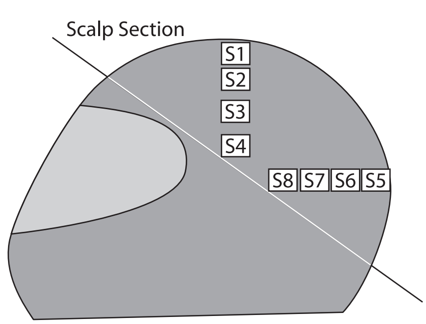

Fig. 3. The temperature sensor locations for helmets 110, 130, and 201. RH was measured by the same sensor at Locations S1 and S5. The area above the solid line indicates the scalp section, consistent with the manikin employed in this study.

Thermal manikin headform measurements

In order to estimate the steady state heat loss experienced by the subjects, headform measurements were carried out under conditions simulating the situation during subject examinations as closely as possible. The specifications of the headform are given elsewhere (Brühwiler, 2003; Bogerd, 2009), and details on the protocol for assessing helmets on the headform were identical to that reported previously (Bogerd and Brühwiler, 2009). The position and orientation of the headform were based on subject examinations as given under Setup. The surface temperature of the manikin was determined so that the microclimate of the scalp during these measurements was statistically indistinguishable from the subject measurements. The resulting surface temperatures for the scalp section of the manikin simulations were 38.6 and 36.8°C, for the neutral and warm climates. The former manikin surface temperature exceeds typical body core temperatures, most likely due to the absence of hair on the manikin employed; additional details are given under Discussion.

Statistics

SPSS 14.0.1 for Windows was used for statistical analysis, with $P < 0.05$ as the significance threshold. The effect of changing the vent configuration on the microclimate variables within a phase was assessed using a paired *t*-test. The responses per questions for the steady state phase were compared to the responses during the examination phase with the same conditions. The nonparametric McNemar test was employed for this purpose because of the categorical nature of the responses.

Multinomial logistic regression analysis was used to quantify the importance of the measured variables in describing the response behavior of the subjects, for Questions 2 through 5. The following variables were considered: $\Delta\dot{Q}$, subject, helmet, ambient air temperature (neutral or warm), and applied wind speed (moderate or high). Furthermore, two procedures were carried out per question, either including or not including the thermal microclimate variables (Fig. 3). This distinction was considered necessary since one helmet was not equipped with sensors. Eight models were generated in this manner, addressing the four questions considered by the subjects, with or without microclimate variables. To estimate the effect of the vent on the microclimate variables, the corresponding thermal data were represented by the slope of the data over a period of 50 s following the change in vent configuration. More detail on the multinomial logistic regression analysis is provided in the supplementary material at *Annals of Occupational Hygiene* online.

RESULTS

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 (Table 2), with vent opening resulting in positive and closing in negative values. Values within this range occur with approximately uniform frequency, except for a greater concentration of values near zero. It can be observed that helmets 110 and 130 result in very similar, high values of $\Delta\dot{Q}_S$, helmet 210 results in the smallest value, and helmet 201 is intermediate. The results for helmets 110, 130, and 201 are consistent with previous work (Bogerd and Brühwiler, 2008; Bogerd and Brühwiler, 2009); those for helmet 210 were not since it was modified for the present study.

Subject examinations

Microclimate temperature reached equilibration in <20 min, for all measured locations. RH did not completely stabilize but did not result in perceptible changes. See the supplementary material at *Annals of Occupational Hygiene* online for further details on microclimate temperature and RH dynamics and absolute values. In addition, microclimate variables were statistically indistinguishable among the steady state and examination phases, with the exception of RH in the scalp section in the neutral and warm thermal environments, which was lower in the examination period by 7.9 ± 7.9% ($P = 0.026$) and 9.2 ± 9.2% ($P = 0.025$), respectively. This indicates that the microclimate in the examination phase was mostly similar to that measured during the steady state phase.

All responses per question, combined for all subjects and response categories, amount to 93. In Fig. 4, these responses are combined with $\Delta\dot{Q}_S$ measured on the headform. The response 'uncertain' was given most often for each question, with a peak in frequency around $\Delta\dot{Q}_S = 0$. Furthermore, the total responses for the other response categories occur most frequent away from $\Delta\dot{Q}_S = 0$; e.g 'warmer', 'less airflow', and 'less noise' tend to occur more frequent at $\Delta\dot{Q}_S < 0$, whereas 'cooler', 'more airflow', and 'more noise' tend to occur more frequent at $\Delta\dot{Q}_S > 0$. This suggests that $\Delta\dot{Q}_S$ was a strong influence on the response behavior of the subjects. However, the response behavior is not purely a function of $\Delta\dot{Q}_S$ for any question since responses were given over the whole range of $\Delta\dot{Q}_S$. This suggests that other variables should be considered when trying to explain the observed patterns. For instance, the fact that $\Delta\dot{Q}_S$ was similar for helmets 110 and 130, but no responses 'warmer' were given for helmet 110, as opposed to the large number for helmet 130, suggests that the helmet worn could be relevant. These observations can be used to check the output of the logistic models below.

Table 2. Vent-induced heat loss from the scalp section of the helmets, for the different conditions. These values represent opening of the vent in the scalp section. Values for closing are of equal magnitude but negative

Climate	Neutral (23.7 ± 0.4°C)		Warm (27.5 ± 0.3°C)	
Wind speed*	Moderate	High	Moderate	High
Helmet				
110	5.1 ± 0.3	6.1 ± 0.7	3.1 ± 0.2	3.7 ± 0.3
130	5.1 ± 0.2	6.1 ± 0.2	3.3 ± 0.1	3.0 ± 0.1
201	1.5 ± 0.1	1.0 ± 0.0	0.8 ± 0.0	1.5 ± 0.1
210	0.2 ± 0.0	0.4 ± 0.2	0.1 ± 0.0	0.1 ± 0.1

*Wind speed moderate = 39.2 ± 1.9 and high = 59.3 ± 1.4 km h^{-1}.

Relationship among variables

Multinomial logistic regression. All models for Questions 2 through 5 were well performing as defined in the supplementary material at *Annals of Occupational Hygiene* online. Table 3 gives the performance of these models and shows the variables included; in the supplementary material at *Annals of Occupational Hygiene* online, a visual representation of the original responses, the modeled responses, as well as the differences between both are given. A smaller value for the variable performance test (likelihood ratio test) indicates a higher importance of the variable for predicting the response behavior.

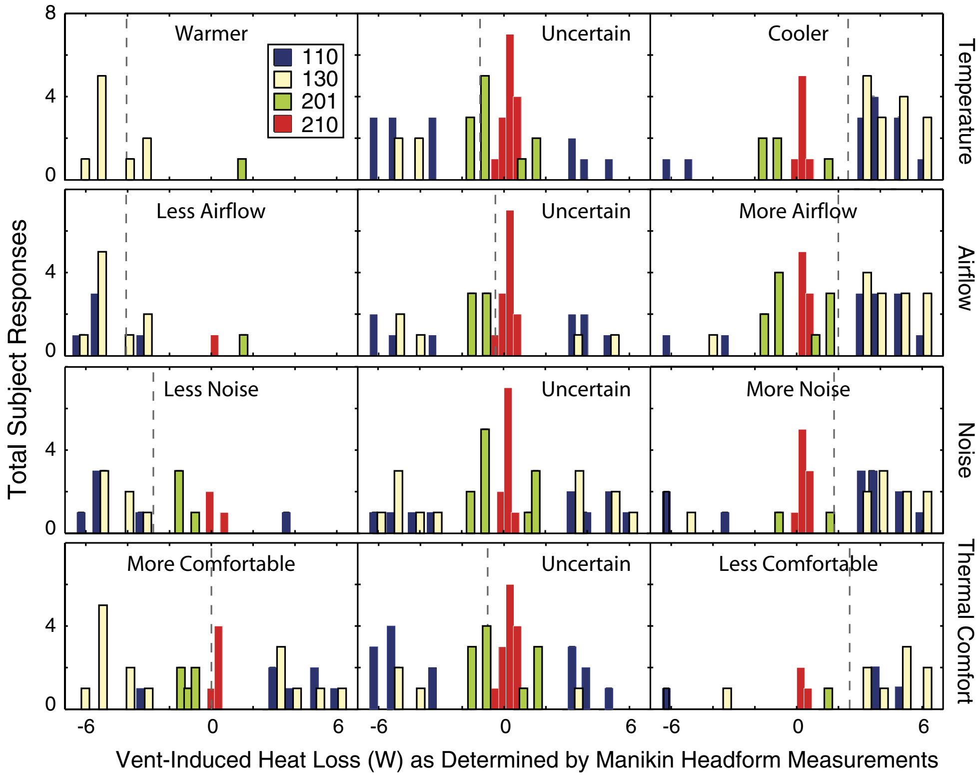

Fig. 4. Number of responses with respect to vent-induced heat loss ($\Delta\dot{Q}$) for all questions and helmets as indicated. The dashed lines indicate the value of $\Delta\dot{Q}$ corresponding to the mean response for all helmets combined, for each response category.

Table 3. Details of the multinomial logistic regression models for the indicated questions. Column MV (microclimate variable) indicates whether the thermal microclimate variables are included in the variable pool. In such cases, only three helmets are included since one helmet was not equipped with sensors; otherwise, all four are included. Variable definitions and further information are provided in the text

	Scalp section		Model performance		Variable performance test[a]					
	Question	MP	Correctly predicted (%)	McFadden r^2	$\Delta\dot{Q}_S$	Helmet	Subject	v_w	S2	S8
2	Temperature	No	85	0.61	$<10^{-6}$	$<10^{-4}$	$<10^{-3}$			
		Yes	86	0.65	$<10^{-6}$	$<10^{-2}$	$<10^{-2}$			
3	Airflow	No	79	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	0.60	$<10^{-2}$	$<10^{-3}$	$<10^{-2}$			
		Yes	80	0.62	<0.05		$<10^{-2}$		<0.05	

[a]Smaller values indicated larger importance of the corresponding variable to the performance of the model. More details on this method are given under Statistics. Missing values indicate that the corresponding variable did not improve the model. McFadden r^2 is roughly comparable to Pearson r^2 for linear regression models; more information is given in the supplementary material at *Annals of Occupational Hygiene* online. $\Delta\dot{Q}_S$ is vent-induced heat loss from the scalp, v_w is wind speed, and S2 and S8 are microclimate temperatures, measured as indicated in Fig. 3.

The model indicates that $\Delta\dot{Q}_S$ was the strongest determinant for the response behavior of the subjects, except for thermal comfort, consistent with the obvious trends in Fig. 4. The models also indicate that the variables ‘helmet’ and ‘subject’ influenced the response behavior, the role of the former variable consistent with observations in connection with Fig. 4. We attribute the more subtle role of the variable subject to individual variations caused by differences in, e.g. thermal perception sensitivity, head shape relative to the helmet and hairstyle. We examined a small pool of subjects and attempted to identify strong correlations between obvious subject-specific characteristics, such as hairstyle and the response pattern differences among subjects, without success. For this reason, we will not consider subject-dependent response differences in what follows. Thus, the output of the logistic models reflects the obvious aspects of the response distributions in Fig. 4.

Local temperature and humidity. Since temperature and humidity can affect human thermal perception and comfort, the effect of changing the vent configuration on the microclimate was studied in the steady state period (Fig. 2). The locations that reached a significant difference between just before and 15 min after the change in vent configuration are visualized in Fig. 5. Locations with a larger vent-induced effect on the microclimate indicate a larger difference in airflow on these locations between open and closed vents. Therefore, the effected microclimate locations visualize the airflow pattern for the corresponding helmet. These vent-induced effects on the microclimate give both the temperature and the RH sensors reacted to changing the vents. 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 changes. These results suggest that for helmet 110, the airflow is more concentrated around the midline, defined in the sagittal direction dividing the head into two even parts. In contrast, the airflow for helmet 130 is most prominent between the midline and the ear.

DISCUSSION

We collected 93 responses to each of four perception-related questions, over a wide range of $\Delta\dot{Q}_S$ (−6.1 to 6.1 W) as determined by manikin headform simulations. The subjects systematically perceived effects caused by changing the vent configuration in the scalp section under the given conditions, with $\Delta\dot{Q}_S$ being the most important determinant for their response frequencies. 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.

As indicated by the logistic models (Table 3), as well as the visual inspection provided under subject examination, it becomes evident that besides $\Delta\dot{Q}_S$, also other parameters affect the response behavior of the subjects. In fact, if logistic models are created only including $\Delta\dot{Q}_S$, than the correctly predicted responses for Questions 2 through 5 are, 65, 59, 53, and 59%, respectively, for all helmets combined. These percentages are substantially lower as for the full models, indicating that also other variables are important for the response behavior of the

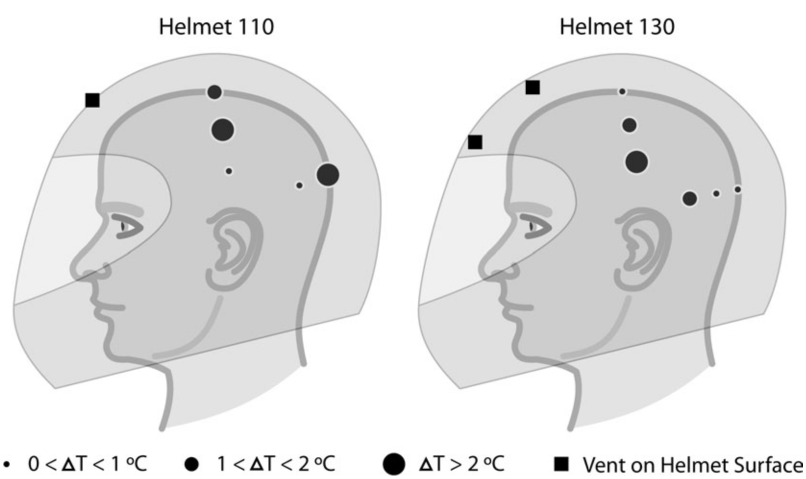

Fig. 5. The effect of changing the vent configuration on the microclimate temperature measured during steady state (only significant changes are shown). Absolute values are given, i.e. without regard to sign, since no differences were found among the absolute temperature changes dependent on closing or opening the vents. In addition, the ventilation opening in the helmet's surface is given.

subjects. The results from the present study (e.g. Table 3 and Fig. 4) indicate that helmet-specific sensitivities are another important variable. Figure 5 indicates that different 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. Effective differences in airflow patterns might be a very general phenomenon and important in comparing different kinds of headgear. Finally, also subject-specific differences are important for the response behavior of the subjects, as indicated by the logistic models. However, no such subject-specific variables could be identified from the eight subjects included in the present study.

Relationship among perceptual variables

The visual similarity of several of the distributions in Fig. 4 strongly suggests the existence of relationships among the perception variables, 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 such model predicted the responses of one of the Questions 2 through 5 using the responses to the remaining three questions (Table 4) as inputs. 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 validates the visual similarity of the response frequencies apparent in Fig. 4; the strong overlap among the responses to these questions 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 higher frequency for less noise when wearing helmet 201.

Local transients and perception

Little is known about effects on perception variables, as measured in the present study, associated with a local transient. One group recently conducted extensive measurements on spatially and temporally nonuniform skin temperature distributions (e.g. Zhang *et al.*, 2004; Arens *et al.*, 2006; Zhang, 2003). 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, in contrast to the present results. 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, the thermal comfort of the corresponding body part was assessed, (iii) it is unclear what the applied rate of change in temperature was. Our results indicate that thermal comfort does not follow temperature perception under conditions of whole body nonuniform 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.

Study limitations

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, this suggests that the present results likely

Table 4. The performance of the multinomial logistic regression models for Questions 2 through 5 and the importance of the variables, with the remaining questions as input

	Question	Model performance		Variable performance test[a]			
		Correctly predicted (%)	McFadden r^2	2 Temperature	3 Airflow	4 Noise	5 Thermal comfort
2	Temperature	82	0.53		$<10^{-6}$		$<10^{-6}$
3	Airflow	77	0.46	$<10^{-6}$		$<10^{-5}$	
4	Noise	56	0.28		$<10^{-6}$		<0.05
5	Thermal Comfort	74	0.39	$<10^{-6}$	$<10^{-2}$	<0.05	

[a]Smaller values indicated larger importance of the corresponding variable to the performance of the model. More details on this method are given under Statistics. Missing values indicate that the corresponding variable did not improve the model.

correspond to an overestimation of $\Delta\dot{Q}_S$. In previous work using a wig, we estimated a reduction of $\dot{Q}_S$ by ~26% (Bogerd and Brühwiler, 2008) under conditions similar to those studied here, but how individual subjects will be affected remains a question for future work. Also (other) discrepancies in airflow between headform and individual subjects can affect $\Delta\dot{Q}_S$, for instance, as caused by helmet-fit-specific differences.

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 the values of v_w studied here of 36 km h^{-1} and 62 km h^{-1} correspond to higher speeds in traffic of 53 km h^{-1} and 80 km h^{-1}, respectively (Brühwiler *et al.*, 2005), which are typical for many traffic situations. In addition, 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 that 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 variables.

Conclusions

We find that subjects are able to systematically perceive effects caused by changing the vent configuration of motorcycle helmets in the scalp section, under simulated riding conditions. Furthermore, the main determinant of the response behavior of the scalp section of the subjects was the vent-induced heat loss, particularly for the perception of temperature, airflow, and noise. These results confirm that a thermal manikin headform is a useful tool for investigating and optimizing temperature and airflow perception of headgear. However, the relationship between vent-induced heat loss and response behavior varied among the helmets. Finally, the observed differences in airflow patterns derived from temperatures between the scalp and helmet suggest airflow patterns as a likely cause of this helmet-specific sensitivity.

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, as well as subject-specific variables explaining differences among subjects. In addition, perception thresholds for vent-induced heat loss, as measured in the present study, will help to set improvement objectives for future helmet ventilation optimization efforts. Future work could improve the present approach by access to a method to continuously vary one or more variables 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 variables under study, e.g. with in-the-ear microphones. For the helmet wearer, improved knowledge of the heat transfer of a given helmet could be of great use in maximizing comfort while riding, by enabling the choice of a helmet, which enables sufficient control of the microclimate.

SUPPLEMENTARY MATERIAL

Supplementary material is available at *Annals of Occupational Hygiene* online.

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REFERENCES

Abeysekera JDA, Holmér I, Dupuis C. (1991) Heat transfer characteristics of industrial safety helmets. In: Kumashiro M and Megaw ED, editors. Towards human work—solutions to practical problems in occupational health and safety. London, UK: Taylor & Francis; pp. 297–303. ISBN 9780748400393.

Abeysekera JDA, Shahnavaz H. (1988) Ergonomics evaluation of modified industrial helmets for use in tropical environments. Ergonomics; 31: 1317–29.

ACEM. (2004) Maids: in-depth investigation of accidents involving powered two wheelers. Brussels, Belgium: Association de Constructeurs Européens de Motorcycles.

Arens E, Zhang H, Huizenga C. (2006) Partial- and whole-body thermal sensation and comfort—part ii: non-uniform environmental conditions. J Therm Biol; 31: 60–6.

Bogerd CP. (2009) Physiological and cognitive effects of wearing a full-face motorcycle helmet. PhD thesis. Zurich, Switzerland: ETH.

Bogerd CP, Brühwiler PA. (2008) The role of head tilt, hair and wind speed on forced convective heat loss through full-face motorcycle helmets: a thermal manikin study. Int J Ind Ergon; 38: 346–53.

Bogerd CP, Brühwiler PA. (2009) Heat loss variations of full-face motorcycle helmets. Appl Ergon; 40: 161–4.

Brühwiler PA. (2003) Heated, perspiring manikin headform for the measurement of headgear ventilation characteristics. Meas Sci Technol; 14: 217–27.

Brühwiler PA, Stämpfli R, Huber R, Camenzind M. (2005) CO_2 and O_2 concentrations in integral motorcycle helmets. Appl Ergon; 36: 625–33.

Buyan M, Brühwiler PA, Azens A *et al*. (2006) Facial warming and tinted helmet visors. Int J Ind Ergon; 36: 11–6.

Comelli M, Morandi A, Magazzù D *et al*. (2008) Motorcycle and helmet bright colours reduce the odds of a class of road accidents: a case-control study. Biomed Stat Clin Epidemiol; 2: 35–42.

D'Artibale E, Tessitore A, Capranica L. (2008) Heart rate and blood lactate concentration of male road-race motorcyclists. J Sports Sci; 26: 683–9.

De Bruyne G, Aerts J-M, Van der Perre G *et al*. (2008) Spatial differences in sensible and latent heat losses under a bicycle helmet. Eur J Appl Physiol; 104: 719–26. doi:10.1007/s00421-008-0828-1.

Deutermann W. (2004) Motorcycle helmet effectiveness revised. Washington, DC: US National Highway Traffic Safety Administration.

Fonseca GF. (1974) Heat transfer properties of military protective headgear. Natick, MA: US Army Natick Laboratories.

Gkritza K. (2009) Modeling motorcycle helmet use in Iowa: evidence from six roadside observational surveys. Accid Anal Prev; 41: 479–84.

Glassbrenner D, Ye J. (2006) Motorcycle helmet use in 2006—overall results. Washington, DC: National Highway Traffic Safety Administration.

Hickling EM. (1986) Factors affecting the acceptability of head protection at work. J Occup Accid; 8: 193–206.

Holland EJ, Laing RM, Lemmon TL, Niven BE. (2002) Helmet design to facilitate thermoneutrality during forest harvesting. Ergonomics; 45: 699–716.

Houston DJ, Richardson LE. (2008) Motorcyclist fatality rates and mandatory helmet-use laws. Accid Anal Prev; 40: 200–8.

Hsu YL, Tai CY, Chen TC. (2000) Improving thermal properties of industrial safety helmets. Int J Ind Ergon; 26: 109–17.

Iho L, Jonasson H, Petersson JI, Stridh G, Ljung C. (1980) Measurement of aerodynamically generated noise and concentrations of carbon dioxide and oxygen in protective helmets for motorcycle riders. Sweden, Borås: Statens Provningsanstalt.

ISO 8559. (1989) Garment construction and anthropometric surveys—body dimensions. Geneva, Switzerland: International Organization for Standardization.

Keng S-H. (2005) Helmet use and motorcycle fatalities in Taiwan. Accid Anal Prev; 37: 349–55.

Lai H-H, Huang H. (2008) Evaluation of visibility of tinted helmet visors for motorcycle riders. Int J Ind Ergon; 38: 953–8.

Li GL, Li LP, Cai QE. (2008a) Motorcycle helmet use in southern china: an observational study. Traffic Inj Prev; 9: 125–8.

Li LP, Li GL, Cai QE *et al*. (2008b) Improper motorcycle helmet use in provincial areas of a developing country. Accid Anal Prev; 40: 1937–42.

Liu X. (1997) Evaluation of thermal comfort of head gear. PhD thesis of Department of human work sciences. Lulea, Sweden: Lulea University of Technology.

Liu X, Abeysekera J, Shahnavaz H. (1999) Subjective evaluation of three helmets in cold laboratory and warm field conditions. Int J Ind Ergon; 23: 223–30.

Liu X, Holmer I. (1995) Evaporative heat transfer characteristics of industrial safety helmets. Appl Ergon; 26: 135–40.

Lower MC, Hurst DW, Claughton AR *et al*. (1994) Sources and levels of noise under motorcyclist's helmets. Proc Inst Acoust; 16: 319–26.

Mayrose J. (2008) The effects of a mandatory motorcycle helmet law on helmet use and injury patterns among motorcyclist fatalities. J Safety Res; 39: 429–32.

McCombe AW, Binnington JA, Nash D. (1994) Wind noise and motorcycle crash helmets. J Low Freq Noise Vibr; 13: 49–57.

Mills NJ, Wilkes S, Derler S *et al*. (2009) FEA of oblique impact tests on a motorcycle helmet. Int J Impact Eng; 36: 913–25.

Młyński R, Kozłowski E, Żera J. (2009) Attenuation of noise by motorcycle safety helmets. Int J Occup Saf Ergon; 15: 287–93.

Oginni FO, Ugboko VI, Adewole RA. (2007) Knowledge, attitude, and practice of nigerian commercial motorcyclists in the use of crash helmet and other safety measures. Traffic Inj Prev; 8: 137–41.

Ouellet JV, Kasantikul V. (2006) Motorcycle helmet effect on a per-crash basis in thailand and the united states. Traffic Inj Prev; 7: 49–54.

Patel R, Mohan D. (1993) An improved motorcycle helmet design for tropical climates. Appl Ergon; 24: 427–31.

Pinnoji PK, Haider Z, Mahajan P. (2008) Design of ventilated helmets: computational fluid and impact dynamics studies. Int J Crashworthines; 13: 265–78.

Reischl U. (1986) Fire fighter helmet ventilation analysis. Am Ind Hyg Assoc J; 47: 546–51.

Ross BC. (1989) Noise exposure of motorcyclists. Ann Occup Hyg; 33: 123–7.

Skalkidou A, Petridou E, Papadopoulos FC *et al*. (1999) Factors affecting motorcycle helmet use in the population of greater Athens, Greece. Inj Prev; 5: 264–7.

Spaul WA, Reischl U, Rosenau DE *et al*. (1987) Ventilation analysis of industrial head and face protection systems. In Asfour SS, editor. Trends in ergonomics/human factors IV. Amsterdam, NL: Elsevier; pp. 437–44. ISBN 0444702466.

Tan FL, Fok SC. (2006) Cooling of helmet with phase change material. Appl Thermal Eng; 26: 2067–72.

Van Brecht A, Nuyttens D, Aerts JM *et al*. (2008) Quantification of ventilation characteristics of a helmet. Appl Ergon; 39: 332–41.

Zhang H. (2003) Human thermal sensation and comfort in transient and non-uniform thermal environments. PhD thesis. Berkeley, CA: University of California.

Zhang H, Huizenga C, Arens E *et al*. (2004) Thermal sensation and comfort in transient non-uniform thermal environments. Eur J Appl Physiol; 92: 728–33.