Sweat Detection with Thermal Imaging for Automated Climate Control and Individual Thermal Comfort in Vehicles

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Abstract: In addition to autonomous driving, the automation of comfort functions is currently one of the development focuses of the automotive industry. In particular, the automation of the climate function is considered, as manual operation often leads to distraction from the driving task. In order to implement this automation, various data about the vehicle interior and the occupants are needed. Besides interior temperature, gender or air speed, the sweat status of the occupants is relevant. In this work it is examined to what extent the sweat status can be detected with the help of a thermal imaging camera. The aim is to show if it is possible to distinguish the status *not sweating*, *shortly before sweating* and *sweating* using thermal imaging. For this the part of the thermal image showing the forehead is analyzed. More specifically, the difference between minimum and maximum temperature is compared for the different sweat statuses. At an ambient air temperature of 21 °C the thermal comfort level and sweat status of 20 subjects is inquired and skin temperature is measured by a thermal camera during sport activity. Results indicate that there is a significant difference ($p < 0.05$) between status *not sweating* and *shortly before sweating* and also between status *not sweating* and *sweating*. Sweat can therefore be detected with the help of thermal imaging cameras. This result provides important input for automated air conditioning. If sweat is detected for one or more occupants, then with the climate control a corresponding regulation can take place to dry the sweat and to prevent further sweating.

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1 INTRODUCTION

Autonomous driving is currently the focus of the automotive industry. But in addition to the autonomous vehicle, the interior is more and more automated to keep the overall value within the vehicle constant. So the aim is to design and set an ideal interior for each occupant. Functions such as the automatic seat adjustment, individual massage functions, and also the independent adjustment of the climate control are developed. Especially when setting the air conditioning, the driver can easily be distracted from the road and the driving task. Another problem with manually handling the climate in the car is that a wrong temperature tends to reduce the attention state (Dentel and Dietrich, 2013), (van Hoof, 2008). Both results in an increased risk for car accidents. To minimize this risk, the climate control in vehicle should have a personalized temperature, personalized air outlets and personalized air flow. Therefore an automated system has to recognize the individual demand for thermal comfort. Thermal comfort is a subjective sensation and is defined as the condition in which satisfaction is expressed with the thermal environment (ASHRAE, 2004), (Epstein and Moran, 2006). To ensure this, much information about the individual behavioral factors and also the interior of the vehicles, so called environmental factors, has to be known. For the in-cabin space, the ambient temperature, radiant temperature, air humidity and air movement speed is relevant (Fanger, 1970), (Epstein and Moran, 2006). Currently all these environmental parameters are measured by different sensors in the car. But to automate the complete system, we also need information about the behavioral factors from the individual persons in the car. These include:

- Age, Origin, Sex (Nakano et al., 2002), (Karjalainen, 2007), (De Dear, 2004);
- Clothing (Fanger, 1970);
- Arousal Level, Emotion (Fanger, 1970), (Ebisch et al., 2012), (Merla and Romani, 2007);
- Size, Weight (Fiala et al., 2001);

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- Sweating (Fanger, 1970), (Djongyang et al., 2010).

It is possible to detect most of the required data like age, sex, clothing, and arousal with an RGB camera or a time of flight camera. But there is little information in literature about measuring methods for sweat especially without direct contact to the human skin. Sweating or perspiration is apart from shivering the main mechanism for regulating body core temperature (Kuno, 1934). If the body core temperature is too high, down-regulation of this temperature is the most important role of perspiration. During sweating, thermal energy is released by evaporation of water from the surface of the skin, so that the skin and also the body core temperatures are lowered. Besides for regulating the body core temperature because of extreme ambient temperature or physical activity, sweating can be stimulated by emotional stress or spicy food (Kuno, 1934), (Wilke et al., 2007). The cooling process on the skin is especially visible on the human face, because of a high number of sweat glands (Wilke et al., 2007). Hence the process of sweating should be visible on the thermal image of the face. In the vehicle a contact free measurement is important to not interfere with the driver and the other passengers. So placing a humidity sensor or a thermocouple on the forehead is obviously not feasible. Another possibility is to include these sensors in the car seat. But then the sensor cannot measure the temperature on the skin because it is covered with clothes. In addition one goal of the automobile industry is to detect many attributes with one sensor, instead of having specialized sensors for each function. Concerning this matter a camera for example can not only detect sex, body parts, and emotions, it can also detect temperature and sweat, especially with a thermal camera. The thermal camera is measuring the skin temperature with infrared thermography. Infrared cameras generate thermal images by electromagnetic waves (Fernández-Cuevas et al., 2015). The measured radiation is directly related to skin temperature. The research question is to find out if there is a significant difference on the thermal images during *not sweating*, *shortly before sweating* and *sweating*. The dependent variable is the sweat status and the independent variable is the facial skin temperature.

2 STUDY DESIGN AND METHOD

2.1 Subjects

14 male and 6 female volunteers between 20 and 45 years were recruited to participate in the experiment. All subjects were free of any known cardiac abnormalities. Verbal and written informed consent was obtained from each subject. Subjects wore regular sportswear like a sport shirt, trainers and running shorts or leggings.

2.2 Instrumentation

Subjects face skin temperature was measured with a thermal camera (Thermal Expert Q1). The face was chosen as a measuring point, as it is usually not covered by clothing. Especially in the forehead area where you can find a lot of sweat glands (Machado-Moreira et al., 2008). Another positive aspect of focusing onto the forehead is that in most cases the area is not covered by facial hair. The representation of the thermal camera image is a false color image. In this study we used a color map where colder temperatures are represented as more red to purple colors and higher temperatures are represented as more orange and yellow. The camera was installed in a car's rear view mirror area. During the measurement the subject was seated in a car, viewing to the camera and breathing deeply while not talking. The measure interval was 2.5 minutes (Sammito and Böckelmann, 2015), (Liu et al., 2011).

Besides of thermal image measurement, different biofeedback indicators (HasoMed) were tracked. A blood-volume-pulse sensor was attached to the left hand and a skin conductance sensor on the right hand. The biofeedback sensors were included in the measurement for having a reference for sweating. In this paper only the subjective sweat status from the questionnaire was used to analyze the possibility of sweat measurement via thermal image and not the biofeedback data. Air temperature and air humidity were kept as stable as possible throughout the experiments.

2.3 Experimental Protocol

The experiment was performed in a climate chamber with 21 °C and approximately 50 % air humidity during May to July. Each subject needed 1.5 hours for the experiment. The experiment was done for one or maximum two subjects on a single day.

Before the experiment was started, the subject had 15 minutes time to accommodate to the climate chambers temperature. During this time the subject changed clothes and filled out the letter of consent. After that, the main part of the study started. First question for each participant was about thermal comfort with ASHRAE scale. ASHRAE scale is a 7-point scale used for occupant thermal sensation vote. The scale is based on a measure how cold or how hot the subjects feel. Subjects can choose between cold, cool, slightly cool, neutral, slightly warm, warm, and hot. In literature a sensation vote of cold, cool, warm and hot is connected with uncomfortable feeling in the ambient condition (Liu et al., 2011). Whereas a sensation vote of slight cool, neutral, and slightly warm represents a comfortable ambient condition. The thermal comfort question was followed by the question about individual sweat status. The sweat status was differentiated between *not sweating*, *shortly before sweating* and *sweating*. The scale was a modification from the questionnaire by (Nielsen et al., 1989). After the questions the first measurement started. The subjects were seated in a BMW 7 series on drivers place. After the first sensor measurement the subjects got out of the car and started a high intensive interval training (HIIT) for 1 minute and 50 seconds. Then the thermal comfort and the sweat status were queried again. If the sweat status changed, the subject had to go back to the car seat to measure the second sweat status (*shortly before sweating*). If the status didn't change, another HIIT part with 1 minute 50 seconds was started. This was repeated until the sweat status *sweating* was accessed. Then a last measurement in the car was made and the study was finished. The work resulted in a collection of 60 recordings with three sweat status recordings for each of the 20 participants.

2.4 Method

To find out a significant difference between the different perspiration statuses, the face was recorded with the thermal camera. For each of the 60 recordings a part of the forehead area was cut from the image and analyzed for specific values like the minimum temperature in the area, the maximum temperature, and the average value. The minimum temperature is important as it represents the cooling process of sweating. Sweating causes perspiration to come out of the sweat glands on the forehead. The sweat, which mainly consists of water (Kuno, 1934), cools directly when evaporating. This has a cooling effect on the body core temperature. In addition, the cooling effect is directly visible on the thermal image. The maximum values on the forehead vary less strongly due to the perspiration status. This increases the difference between the minimum and maximum temperature values due to the onset of sweating.

3 RESULTS

First, the results of the subjective perspiration status and the associated thermal comfort vote are evaluated. The results show that with increasing sweating the condition is described as less comfortable. When *not sweating*, most subjects feel more comfortable than with the status *shortly before sweating* and *sweating*. Figure 1 illustrates this fact.

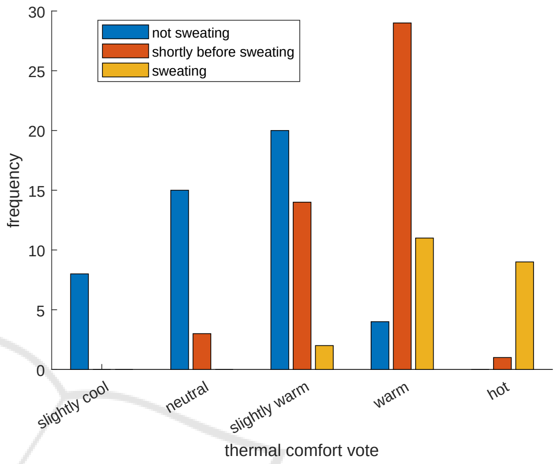

Figure 1: Thermal Comfort with Different Sweat Status of the Individual Subjects. When Sweating Is Starting the Comfort Level Tends to Be More Warm and Hot. Without Sweating the Comfort State Is More Neutral and Comfortable.

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Next, the recorded thermal images are evaluated in detail. The subjects came on average after 2.1 sport intervals to the status *shortly before sweating* and after 4.6 intervals to the status of *sweating*. Some participants sweat already after the second sports interval and others after the seventh. The subjects most often start to sweat after the sixth sports interval. This shows that the onset of sweating is individually different, which is consistent with results from the literature (Kuno, 1934). The thermal images show that there is a visible difference in temperature depending on sweat status. *Not sweating* forehead areas have a lower temperature, visible as a more yellow color on the false color rendering and the *sweating* forehead areas have a warmer and more blotchy temperature distribution as seen in figure 2. This is related to the high number of sweat glands on the forehead (Machado-Moreira et al., 2008),(Thomson, 1954).

The average values over all subjects for the minimum, maximum and average temperature for each sweat status are shown in table 1.

On the sweating forehead image some locations are still yellow caused by the less strong variation of the maximum temperature. This is because the distri-

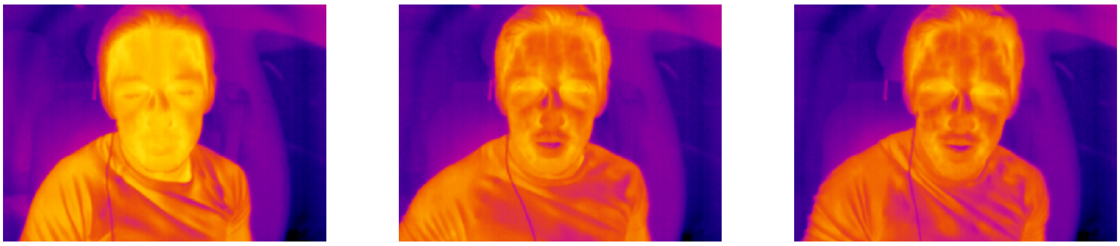

Figure 2: Thermal Images of Face during Study. From Left to Right: Status “not Sweating”, “shortly before Sweating” and “sweating”. the Color on the Forehead Changes from Yellow to More Orange and Red. This Represents the Cooling Process Caused by the Sweating.

Table 1: Minimum, Maximum and Average Temperature Values in Forehead Area during the Different Sweat Statuses.

	Not sweating	Shortly before sweating	Sweating
T_{Min} in [°C]	33.66	31.20	30.82
T_{Max} in [°C]	35.08	33.66	33.23
T_{Avg} in [°C]	34.41	32.45	32.19

bution of the sweat glands on the head and thus also on the forehead is individual and not uniform (Randall, 1946). So the difference between minimum and maximum temperature in this area is a good indicator for sweating. The bigger the difference, the more sweat is on the humans face. Because of that, the difference between maximum and minimum forehead area temperature is analyzed for a significance test. The next table 2 shows the differences for each sweat status.

To find out whether there is a significant difference on the thermal image between the different sweat statuses a 1-way analysis of variance (ANOVA) for repeated measures is used. The SPSS program is employed to make the statistical analysis and alpha is set at < 0.05 level.

The variance analysis with repeated measurements (assumed sphericity: Mauchly-W (2) = .844, p = .218) shows that the sweat status is related to the temperature difference on the forehead (F (2.28) = 51.656, p = .00, η_p^2 = .731, n = 20). The η_p^2 says that 73.1% of the variation between the sweating states can be explained via the temperature difference. Bonferroni-corrected pairwise comparisons show that the sweat status not sweating (M = 1.43, SD = 0.32) is significantly higher than *shortly before sweating* (M = 2.47, SD = 0.60) and *sweating* (M = 2.69, SD = 0.60). It can be seen that the temperature difference between *not sweating* and *shortly before sweating* ($p < .05$) and *not sweating* and *sweating* ($p < .05$) differ significantly. In contrast, the temperature difference does not differ significantly between these two measuring times *shortly before sweating* and *sweating* (p = .46). The effect size f according to Cohen (1988) is 1.65 and corresponds to a strong effect. In order to consider the unexplained variance and to check whether another factor influences the change in the temperature difference, the residuals and their distribution are considered. The histogram of the residuals is shown below in Figure 3, including a normal distribution curve (red). The residuals are normally distributed, as assessed by the Kolmogorov-Smirnov test showed (α = .01, p = .03). It is therefore assumed that there is no missing variable that has an influence on the calculation. This means that no data transformation has to be carried out.

The biofeedback data is used as a kind of reference to the subjective perspiration status. The evaluation of the skin conductance data indicate an increase with increasing sweating. From the measurement of the blood volume pulse sensor, heart rate variability (HRV) data is considered. In particular, the time-based RMSSD value and the frequency-based LF/HF rate is evaluated. RMSSD is the square root of the mean squared differences of the successive heartbeat

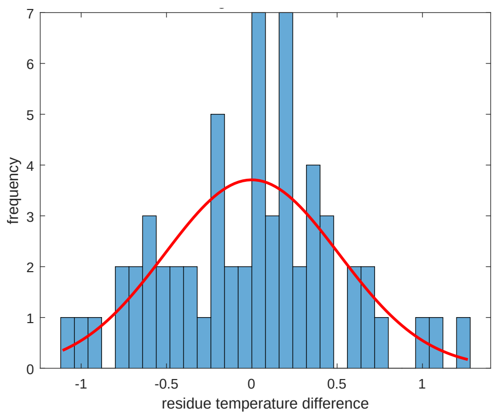

Figure 3: Histogram for the Residuals with Normal Distribution. It Can Be Seen, That the Residues Follow a Normal Distribution. A Kolmogorov-Smirnov Test with α = .01 Also Reflects This.

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Table 2: Descriptive Statistics for the Difference between Maximum and Minimum Temperature in the Forehead Area with Mean and Standard Deviation (SD) for Different Sweat Statuses.

	Not sweating	Shortly before sweating	Sweating
Mean ± SD in [K]	1.43 ± 0.31	2.47 ± 0.58	2.69 ± 0.58

interval (Bricout et al., 2010). LF/HF ratio reflects the balance of the autonomic nervous system with the low frequency part (LF), which is representing the parasymathetic and sympathetic activities (Pomeranz et al., 1985) and the high frequency part (HF), which is representing the parasympathetic activity. As described in the literature (Liu et al., 2008), (Liu et al., 2011), (Nkurikiyeyezu et al., 2018), (Bricout et al., 2010), the RMSSD value decreases with sweating and the LF/HF rate increases.

4 DISCUSSION

The results show, that there is a significant difference between status *not sweating* and *shortly before sweating* and also between status *not sweating* and *sweating*. The study found no significant difference between the status *shortly before sweating* and *sweating*. One possible reason for this could be the study design, because the subject has passed about 2 minutes between the query of the perspiration status and the actual measurement. During this time, the subject was sit into the vehicle and the sensors were put on. One possibility would be, that the sweating has set within this 2 minute time break and thus the second measurement time actually represents the status of *sweating*. Therefore, in the following discussion only between *not sweating* and *sweating* is differentiated. The status *shortly before sweating* is counted to status *sweating*.

For a final decision if a person is sweating or not, the temperature difference is not perfect, because of overlapping values for both statuses. In the following boxplot (figure 4) it is possible to see the critical values. Critical values are all the values appearing in status *not sweating* and also status *sweating*. For finding a criterion to differ between the statuses only with the temperature difference, it is possible to use the boxplot boxes without the whiskers as a criterion for status *sweating* or *not sweating*. If the temperature difference on the forehead is lower than 1.58 K the subject is detected as *not sweating*. If the value is higher than 1.96 K the subject is identified as sweating. Between these two values the status is unclear.

For these data sets, with these limits, sweat status can be correctly distinguished between status *not sweating* and status *sweating* in 78% of cases. In 17% of the recorded images, no precise statement can be made because the value lies between the two limits. Only 5% of the images would be misclassified with the decision support.

With the given thermal images, other data can be used to differentiate the sweating status in addition to the temperature. For example, spotting can be detected using a frequency analysis and can therefore be used as a further decision factor. The results of this will be presented in further publications.

For having a more accurate decision of the system, other values like heart rate variability or skin conductance are interesting to know. In addition to the method of sweat detection based on the temperature difference on the forehead, there are other ways to detect whether a person is sweating or not. For example, the average temperature value of the forehead area can be considered or also the spatial frequency over the area can be analyzed. These possibilities are currently being evaluated in detail.

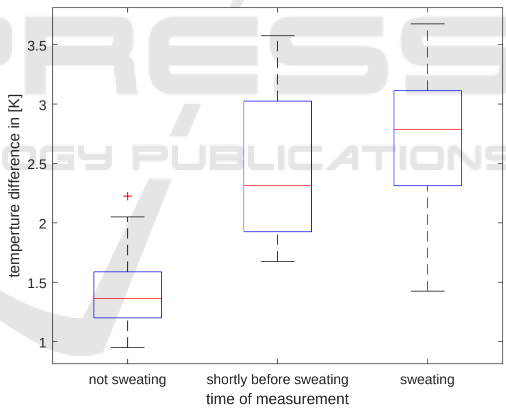

Figure 4: Boxplot of the Different Sweat Status. The Values Show the Difference between the Minimum and Maximum Temperature for a Forehead Area. The Higher the Difference Value, the More Sweating.

Further investigation handle with sweat detection using a machine learning algorithm. For this, the recorded images of the subjects and the forehead areas are labeled and then a network is taught.

5 CONCLUSION

This work investigates whether it is possible to detect in the vehicle if an occupant is sweating or not. To

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test this, a study was designed that records the individual subjects in different sweat status using a thermal imaging camera. For evaluation a forehead area is used to find out the difference between the maximum and minimum temperature. Due to the set decision thresholds, 78% of the images can be classified correctly. This means that then the status *not sweating* was distinguished from *sweating*. The result also shows that there is a significant difference between the sweating and the non-sweating subjects based on a temperature difference in a forehead area. With this result, an important step in the direction of climate automation is done. For this automation, in addition to already known interior data and personal data, data about the sweat status of the various occupants is required. So far, there was no way to detect this status without contact. Only humidity sensors and thermocouples were previously used for sweat detection. With the non-contact sweat detection by thermal imaging cameras, it can be easily detected in the vehicle, which climate setting is suitable for the individual occupants.

Since the presented method found only a recognition accuracy of 78%, further alternative methods are examined to increase the accuracy. Other alternatives of sweat detection without thermal camera are currently under investigation.

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