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Thermal Imaging of the Face: Mental Workload Detection in Flight Simulator

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ABSTRACT

Thermography-based physiological measurement is a contact-free approach that can be particularly helpful for detecting pilots' mental state in operational settings. In particular, thermal infrared imaging of the face is a powerful, unobtrusive and non-invasive tool that enables rapid and automatic analysis of changes in regional facial blood flow. These blood flow changes index sympathetic activity and are measured by capturing thermal imprints of particular facial regions such as nose or forehead. Although several studies suggest a relationship between mental workload and facial thermoregulation profile, evidence about this link has not yet been sufficiently investigated. In this work, we investigated how thermal measures can allow robust and continuous assessment of mental workload variations of pilots undergoing simulated flight tasks. We analyzed thermal data and heart rate of 20 participants in a flight simulator. Mental workload was modulated by the difficulty of the landing scenario or by an in-flight N-back task. Participants also performed a resting task (called cool-off) in the flight simulator. Thermal imprints did not vary significantly with landing difficulty or N-back difficulty. However, we found that the nose tip and nose area became significantly colder (signal slope was negative) during all piloting scenarios vs the rest period. Heat rate was slightly more sensitive to the piloting difficulty since it was marginally higher during the difficult vs easy landing. Results are promising but further analysis is needed to confirm that the thermal measures could identify fine-grained mental workload variations in a flight simulator setting.

Keywords: Facial thermal imaging, Heart rate, Aviation, Mental workload

INTRODUCTION

Facial thermal imaging is a promising technique for estimating unobtrusively human physiological activity (Goulart et al., 2019). It provides remote, passive, and contact-free access to the distribution of the temperature of the face, by interpreting the emitted electromagnetic radiations reflected by the surface of the skin according to the variations of blood flow in the head vessels. The thermal radiation of a cutaneous surface depends on the perfusion controlled by the autonomic nervous system, which controls the vessels that irrigate the skin (Dzedzickis et al., 2020). Using thermal cameras, researchers classically studied the effects of emotions (Dzedzickis et al., 2020; Merla, 2014) and tried to classify different affective states (Nhan & Chau, 2010) based on the temperature profile of the face. This technique has also been used to examine fear conditioning in post-traumatic stress disorder (Di Giacinto et al., 2014). Most proposed techniques used a region-of-interest (ROI) on the face to delineate the area on which the temperature is investigated. The location of the ROI implicitly defines the type of physiological behavior to study. As an example, task-induced stress is assumed to be correlated to blood flow on the forehead frontal vessels (Puri et al., 2005).

Continuous surveillance of pilots' mental state is highly needed in complex environments (Lee et al., 2020; Wilson, 2002), in particular with the possible emergence of single-pilot operations (SPO) during which the pilot will be alone in the cockpit, without the direct assistance from a copilot. In the case of degraded situations with challenging conditions, SPO would potentially result in increased error rates (Liu et al., 2016; Vu et al., 2018). In either case, flying can increase mental stress, whether it results from the surveillance of the multi-channel instruments or from dealing with the occurrence of unexpected events (Kinney & O'Hare, 2020). When difficult situations occur, particularly on relatively long periods, mental workload can exceed acceptable levels and compromise piloting performance and flight safety (Morris & Leung, 2006). Therefore, it is critical to be able to detect an inappropriate level of mental workload. Other instruments that detect mental workload have been widely studied. For example, the fNIRS (functional near-infrared spectroscopy) has been used to assess prefrontal oxygenation levels in airline pilots (Causse et al., 2017; Gateau et al., 2015). However, fNIRS measures can be compromised by head movements (Kikukawa et al., 2008), which can be limiting in the cockpit. More importantly, even though fNIRS is considered non-invasive, it has to be tightly attached to the subject's head and it is relatively uncomfortable after a certain period of time. Contactless and robust ways to measure mental workload during ecological situations such as piloting is therefore needed. Compared to more established instruments, the advantage of thermal imaging is its remote monitoring aspect. The non-invasive recording of the thermal imprints with an easy-to-set-up device makes it an optimal solution for environments such as a flight deck where there already exist multiple instruments in the immediate vicinity of pilots. It allows reducing the stressful situation where equipment has to be placed on the subject's head. A distant monitoring device based on thermal imaging may detect pilots' changing mental workload, and may trigger assistance systems. From an experimental point of view, since no direct contact with the sensor is required, the data analysis would be less impacted by the Hawthorne effect (McCambridge et al., 2014) since the awareness of the participants being evaluated is reduced.

Research suggests that during high mental workload contexts, the blood flow increases in the forehead veins of a person. This change in blood flow, in turn, augments the local temperature of the forehead region (Abdelrahman et al., 2017). The temperature can be acquired through remote thermal imaging. Similarly, it is possible to measure the change in temperature of the nose area (Cho et al., 2019) and the nose tip. While many studies use the forehead to evaluate the change in temperature, results are not always consistent. With the StressCam methodology, Puri et al. (2005) calculated the mean temperature of the 10% hottest pixels on the forehead ROI, assuming that they correspond to the underlying frontal vessels in the forehead ROI, reportedly responsible for changes in skin temperature. Engert et al. (2014) developed a taxonomic classification and measured the temperature of several regions simultaneously to investigate the more sensitive ones for a given task. Later, researchers studied the nose (Diaz-Piedra et al., 2019) and forehead (Gioia et al., 2021) regions and suggested that the nasal region provided better results.

The contribution of the current work was two-fold: 1) First, we proposed a novel method that automatically provides mapping models that track different face regions on thermal images, in free head movement conditions, with higher accuracy compared to the state-of-the-art approaches. Instead of studying a fixed region and constraining the user to remain with the head still during the tasks (e.g., Abdelrahman et al., 2017), we propose an approach that automatically tracks the areas of interest from the thermal imaging using a combination of deep learning and computer vision algorithms. To date, few works investigated unconstrained facial regions tracking in an ecological situation. 2) Second, we evaluated the mental workload of 20 participants during different landing scenarios, based on the change in temperature in three selected facial regions (Abdelrahman et al., 2017). We recorded the data with a thermal imaging camera pointed towards the pilots' faces. We hypothesized that the mental workload elicited by our piloting scenarios and in-flight N-back task would yield changes in temperature profiles in comparison to a rest period. We also hypothesized that temperature profiles should change across low vs high piloting difficulty or low vs high in-flight N-back levels.

METHOD

Participants

Twenty participants (age M = 25.05, SD = 2.78) were involved in the study. They were asked to avoid taking any substance that may have an effect on heart rate (e.g., alcohol, caffeinated drinks) at least 2 hours before the experiment. The study was approved by an international review board (N°: IRB00011835-2020-09-22-298, Université Fédérale de Toulouse, France) and performed in agreement with the Declaration of Helsinki. All participants signed an informed consent prior to their participation and were reminded that they could withdraw from the experiment at any time.

Flight Ccenario and In-Flight N-Back Task

The participants performed four landing scenarios in a flight simulator (each landing lasted ≈ 5 min) and a rest period. The flight simulator setting allowed reproducing a real-world piloting task while keeping good experimental control. The experiment was divided into two experiments (they were both performed by all participants). During *experiment 1*, the participants were instructed to land the aircraft in two different conditions: an easy landing with clear visibility (Clear), and a more difficult landing with bad weather conditions during which the participant could not see the runway and had to land the aircraft with the navigation instruments (ILS). During *experiment* 2, the participants were asked to perform two times an easy landing (Clear), while performing a parallel auditory in-flight N-back task to simulate dense communication with air traffic controllers. The N-back task was performed across two levels of difficulty (0-back and 2-back), manipulated by modifying the value of *N*. The two landings, and thus their respective N-back levels, were performed randomly. **0-back:** the participant was asked to press a green button on a response box when the heard number equaled 50, or to press a red one otherwise. **2-back:** the participant was requested to compare the current number n with the number heard two times ($n - 2$) before. He had to press the green button if the numbers were the same or to press the red one otherwise. The participants were asked to complete one practice session beforehand to make sure they familiarized with the flight simulator. After entering the flight simulator, the participants were asked to rest for three minutes to regulate their temperature in the new environment. Participants were also given a 3-min resting time between each landing scenario to limit fatigue effects. This resting time also allowed the cardiovascular activity to return to its baseline. Moreover, after the participants finished all experimental conditions, they were instructed to rest for five minutes (cool-off phase).

Analysis of Facial Temperature

We measured together the nose tip/area regions and the forehead (situated above the supraorbital ridge) of the participants (Figure 1), which are all believed to index the sympathetic nervous system activity (Panasiti et al., 2019). A wealth of studies used fixed ROI defined by the experimenter to retrieve the temperature profile. In addition to constraining the participants to keep their head still, recording data can be lost if the participant moves abruptly. As an example, Panasiti et al. (2019) removed 8 participants ($\approx$ 24,24%) from their data analysis due to head movements. In this paper, a face detection algorithm was used to automatically track the face of the participant. The algorithm registers the mean temperature of the polygon throughout the experiments. The algorithm is guided by the modern understanding of 2D and 3D facial alignment. Firstly, we performed skin generation to convert the raw thermal face images into a standard RGB space. This step adds features, textures, and colors to the thermal face image. Secondly, a face localization is performed on the skin-generated face to detect the face region. Finally, to retrieve the different regions-of-interest, 68 2D and 3D landmarks detection are applied. These allow retrieving the position (in pixels) of specific points on the face which helps to delineate different regions of the face.

The thermal imprints were recorded using an Optris Xi 400 infrared thermal camera (Optris GmbH, Germany) with an optical resolution of 382 x 288 pixels, 27 Hz, 80 mK thermal sensitivity, and the capability to collect thermal radiation in the 8–14 μm band. The instrument was black-bodied calibrated for thermometrically correct measurements. Due to additional processing of the raw data, the sampling rate was lowered to approximately 15-19 frames per seconds. Each facial region gives one measurement at time t. Duplicated measurements were conserved and untracked frames were

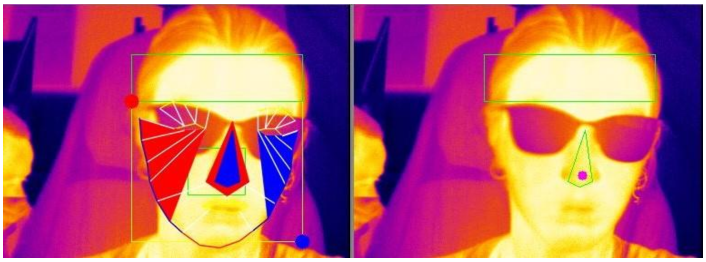

Figure 1: A participant sitting in the cockpit during the experiment. Left: the participant's face is segmented into different regions of interest. Right: selected face regions: forehead (green rectangle), nose area (green polygon), and the nose tip (red dot on the nose).

excluded. Dedicated software was developed especially for the experiment. The thermal images were captured with the dedicated software running on an Intel(R) Core(TM) I7-4712HQCPU @ 2.30GHz, 4 cores, 8 processes, 16 GB RAM. In-house scripts were used to analyze the variations of the facial temperatures in the 3 selected ROIs.

To assess the quality of the recorded data, the facial temperatures were visually inspected. In cases of excessive head rotation, the frame was skipped. We did not see any short-lasting artifacts as observed by Engert et al. (2014). To further get evidence of the proper working of the method, we checked that the ROIs thermal measures were stable during the initial recording phase. The Optris thermal camera was located at a distance of approximately 0.35 m and fixed at the forehead level of the participant. This ensures a good distance for the proper focus of the thermal camera, see Figure 2. The flight deck temperature was controlled (21°C ± 1.5).

Data Analysis

Each participant completed all 4 experimental conditions plus the final cool-off phase. We collected thermal and cardiac data from the 5 phases, easy landing (Clear), difficult landing (ILS), easy landing with Inflight (i.e. in parallel to the piloting activity) 0-Back, easy landing with Inflight 2-Back, and the rest period (cool-off). We also evaluated 3 facial regions (nose area, nose tip, and forehead) for a total of $5 \times 3 = 15$ conditions. For each facial ROI, the thermal data was defined as the mean slope per phase. For cardiac activity, the data was defined as the mean heart rate per phase. The temperature of one participant was missing during the cool-off period and was interloped by the mean of the group. Only one cool-off period was performed, it was thus used for the two experiments.

RESULTS OF EXPERIMENT 1

Facial temperature. The developed method was successful to track the temperature of the three facial regions without notable loss of data, despite the free head motion conditions, see Figure 3 for the nose tip temperature tracking during the difficult landing.

Figure 2: Illustration of the experimental setup. A participant sitting in front of the thermal camera mounted on the flight simulator cockpit. Thanks to the used algorithms, no chin-rest was used during the whole experiment, thus participants could move their heads freely.

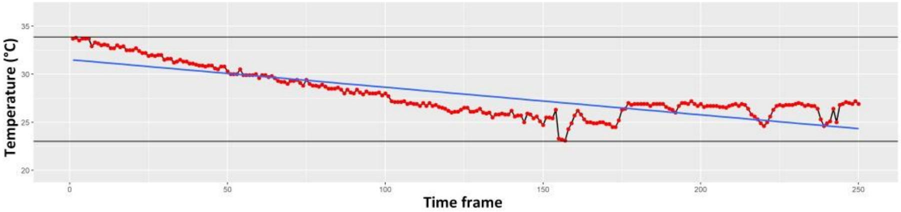

Figure 3: Tracking of the nose tip temperature of one participant during the difficult landing.

A 3 (Face area (Nose tip, Nose area, Forehead)) x 3 (Phase (Rest period, Easy landing, Difficult landing)) ANOVA revealed a significant main effect of the phase, $F(2, 38) = 4.99$, $p = .012$, $= .21$, with negative temperature slopes during the easy and difficult landings vs a positive slope during the rest period (LSD, both *ps* < .050), see Figure 4. Temperature slopes did not differ significantly between easy and difficult landing (LSD > .050). The interaction term was also significant, $F(4, 76) = 2.82$, $p = .031$, $= .13$, showing that the temperature slopes of the nose tip and nose area were positive during the rest period and negative during the two landing scenarios (LSD, all *ps* < .050). In other words, temperature in this region became colder during piloting whereas it became hotter at rest. The forehead temperature slope did not differ significantly during the two landing vs the rest period (LSD, both *ps* > .050), despite a visible less negative slope during both landings vs rest. During the rest period, temperature in nose area/tip increased (positive

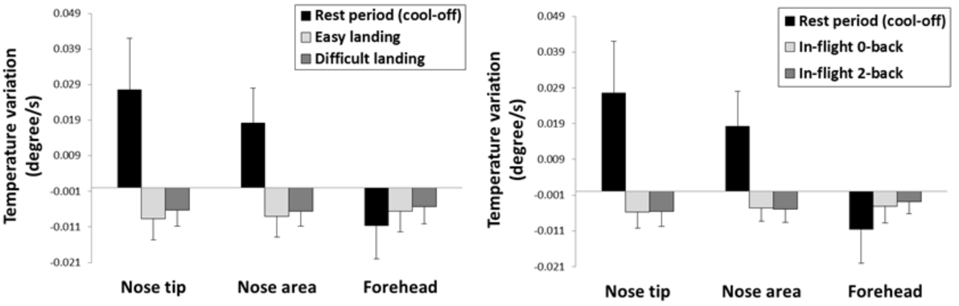

Figure 4: Left: temperature slopes during the first (left) and second (right) experiments.

slope) whereas it decreased (negative slope) in the forehead (LSD, both *ps* < .001).

Heart rate. A one-way ANOVA revealed a significant main effect of the phase, $F(2, 38) = 237.9$, $p < .001$, = .45, with a higher heart rate during the easy and difficult landings vs the rest period (LSD, both *ps* < .001), see Figure 5. Heart rate was marginally higher during the difficult vs easy landing (LSD, $p = .060$).

RESULTS OF EXPERIMENT 2

Facial temperature. A 3 (Face area (Nose tip, Nose area, Forehead) x 3 (Phase (Rest period, in-flight 0-back, in-flight 2-back) ANOVA revealed a significant main effect of the phase, $F(2, 36) = 5.00$, $p = .011$, = .21, with negative temperature slopes during the in-flight 0-back and in-flight 2-back vs a positive slope during the rest period (LSD, both *ps* < .050), see Figure 4. Temperature slopes did not differ significantly between in-flight 0-back and in-flight 2-back (LSD, $p > .050$). The interaction term was also significant $F(4, 76) = 2.69$, $p = .024$, = .13, showing that the temperature slopes of the nose tip area/tip were positive during the rest period and negative during the two N-back levels (LSD, all *ps* < .050). The forehead temperature slopes did not differ significantly during the N-back levels vs rest (LSD, both *ps* > .050), despite visible less negative temperature slopes during the piloting periods (irrespective of the N-back level) vs rest. Like in experiment 1, during the rest period, temperature slopes in nose tip and nose areas were positive whereas it was negative in the forehead (LSD, both *ps* < .001).

Heart rate. A one-way ANOVA revealed a significant main effect of the phase, $F(2, 38) = 289.2$, $p < .001$, = .50, with a higher heart rate during in-flight 0-back and in-flight 2-back vs. rest period (LSD, both *ps* < .001), see Figure 5. Heart rate was not different during in-flight 0-back vs in-flight 2-back (LSD, $p > .050$).

DISCUSSION AND CONCLUSION

The objective of this study was to experimentally evaluate the usage of infrared thermal imaging in mental workload research during ecological conditions, namely when performing landing scenarios in a realistic flight

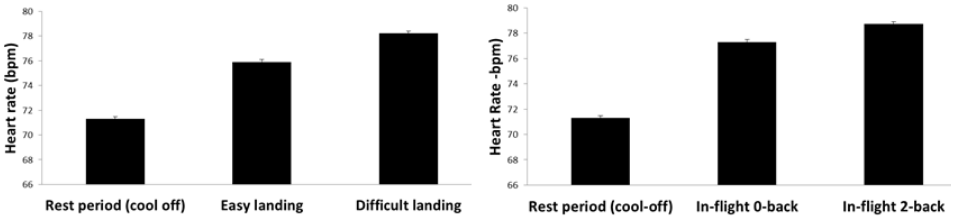

Figure 5: Mean heart rate during the first (left) and second (right) experiments.

simulator. We developed a novel approach combining deep learning and computer vision algorithms that successfully captured the temperature of specific facial regions despite free head motions conditions (participants' head was not constrained). We focused on how facial region thermal imprints oscillate due to mental workload during two different landing scenarios varying in difficulty and two additional landing scenarios with a parallel N-back task that was used to manipulate difficulty. In the first experiment, results showed that temperatures of the nose tip and the nose area became colder during the four landing scenarios whereas it became hotter during the rest period (cool off). This is in line with previous studies (Abdelrahman et al., 2017; Engert et al., 2014) and confirms that increased mental workload decreases the flow around the nose area. The forehead followed an opposite pattern, with a temperature that became slightly colder during the rest period vs the piloting activity, but this result was not significant. Regarding the effects of the difficulty of the landing task, for the nose tip and the nose area, no significant result was found. The heart rate significantly increased during the two landing scenarios (easy and difficult) vs the rest periods, and was marginally higher during the difficult vs easy one.

In the second experiment, results were generally consistent with the first experiment, with the temperature in the nose area and nose tip that became colder during piloting vs rest, and no significant change occurred in the forehead. The effect of the difficulty of the N-back task was not significant. Heart rate increased during the two landing scenarios (irrespective of the N-back level) vs the rest periods, but this time, it was not (marginally) higher during the difficult (in-flight 0-back) vs the easy condition (in-flight 2-back).

Taken together, our results suggest that nose area and nose tip temperature decline during a marked increase of mental workload, i.e., piloting vs rest. We were unable to detect more subtle variations due to landing difficulty or parallel N-back task difficulty. We used the slope signal of the whole conditions to index temperature variations. This approach is maybe not optimal as it generates a loss of data, which is not suited for the detection of rapid temperature variations. In the future, other metrics will be examined to try to better capture rapid temperature oscillations.

Several limitations may persist when using infrared thermal cameras. In real-world scenarios, because of the homeostasis, the cutaneous temperature is continuously adjusted to take into account the environmental conditions (Merla, 2014). Temperature regulation or acclimatization must be taken into account to avoid falsely confounding changes due to external adaptation.

Moreover, it is worth noting that a thermal camera is a radiometric device, i.e., it does not actually directly measure the temperature of the focused object, but rather it calculates the electromagnetic radiation emitted by the object and converts it into temperature measurements. Therefore, the camera also records the radiation from the object, plus the radiation coming from surrounding objects that bounce on the focused object's surface. This could induce estimation error and induce bias by the attenuation of the radiation signals when they pass through the air. In addition, in the flight deck, the direct exposition of the pilot to the sun may locally change the temperature of the pilot's face. Solutions must be found to circumvent all these issues. Finally, one cannot exclude that physical activity may contribute to modify the temperature of the face. But this result cannot explain why the nose tip and nose area became colder during piloting vs rest, since movements performed during piloting should rather increase the temperature of the body.

While EEG or fNIRS has provided valuable insight in mental workload measurements (e.g., Ayaz et al., 2012; Causse et al., 2016, 2017; Parent et al., 2019), their use in operational settings is currently nearly impossible due to the long installation time, the relative inconvenience of the devices, the pain due to the pressure of the cap, or the artifacts generated by movement or flight deck instruments (especially for EEG). This paper examined another technical solution, facial thermal imaging, which would represent a contactless and very convenient method for estimating operators' mental state in the flight deck. We tackled a challenging problem, which is the automatic detection of regions of interest on the face, which allowed the participant to move their head freely during the flight. This approach allowed to precisely measure the temperature of the nose area, nose tip, and forehead regions, despite the participants' head movements. The results of the studies showed that thermal imaging was sensitive to marked variations of mental workload. During piloting, the temperatures of the nose area and nose tip decreased in comparison to a rest period. The temperature of the forehead region remains relatively stable. We were unable to detect more subtle mental workload changes, between two landing scenarios difficulty, or between two levels of N-back difficulty. Heart rate was slightly more sensitive since we could dissociate the easy from the difficult landing in the first experiment.

This work confirmed the importance of choosing an appropriate facial region to index mental workload. While this study provides additional evidence of the benefit of thermography, an in-depth evaluation with more facial regions and different devices would extend this research. More fine-grained measures than the global temperature signal slope will be also explored in the future, which may help increase sensitivity to more rapid and subtle mental workload variations. Also, research on other mental states (e.g., stress, startle effect) will be undertaken.

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