Revealing Psychophysiology and Emotions through Thermal Infrared Imaging

Arcangelo Merla
Institute of Infrared Imaging Lab., ITAB – Insitute for Advanced Biomedical Technologies,
Department of Neuroscience and Imaging, University of Chieti-Pescara, Via dei Vestini 33, Chieti, Italy

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Abstract: Thermal infrared imaging has been proposed as a tool for the non-invasive and contact-less evaluation of vital signs, psychophysiological responses and states. Several applications have been so far developed in many diversified fields, like social and developmental psychology, psychometrics, human-computer interaction, continuous monitoring of vital signs, stress and, even, deception detection. Thermal infrared imaging has been poorly exploited in the field of human-robot interaction. Therefore, the state of the art of thermal infrared imaging in computational physiology and psychophysiology is discussed in order to provide insights about its potentialities and limits for human-robot interaction and applications with affective robots.

1 INTRODUCTION

Understanding the psychophysiological state of other individuals plays an essential role for planning or adopting congruent strategies for social interaction. To endow artificial agents with the capability of reading and interpreting human psychophysiological and emotional states represents a major issue in the field of human-machine interaction. In addition, in order to favor the ecological dimension of such interaction, it is desirable to non-invasively assess human psychophysiological and emotional states. Monitoring psychophysiological and emotional states is usually performed through the measurements of several autonomic nervous system (ANS) parameters, like skin conductance response, hand palm temperature, heart beat and/or breath rate modulations, peripheral vascular tone, facial expression and electromyography activity. Classical technology for monitoring ANS activity usually requires contact sensors or devices, thus resulting somehow invasive and potentially biasing the estimation of the state, as the compliant participation of the individual is required. Thermal infrared (IR) imaging has been proposed as a potential solution for recording thermal signatures of ANS activity non-invasively (Merla, 2004). Thermal IR imaging, in fact, allows the contact-less and non-invasive recording of the cutaneous temperature through the measurement of the spontaneous body thermal irradiation; it has been proposed for monitoring cutaneous thermal effects associated with emotional response and neurovegetative activity thanks to the integrated use of advanced thermal imaging technology, bioheat transfer modeling and computational physiology (Buddharaju, 2005; Garbey, 2007; Merla, 2004, 2007a, 2007b; Murthy, 2006; Pavlidis, 2007; Shastri, 2009).

As the face is usually exposed to social communication and interaction, thermal imaging for psychophysiology is performed on the subject's face. Provided the proper choice of infrared imaging systems, optics, and solutions for tracking the regions of interest, it is possible to avoid any motor or behavioral restriction on the subject (Dowdall, 2006; Zhou, 2009).

Automatic recording and processing of thermal IR imaging data for psychophysiology is possible. Therefore, it seems that this technology, in combination or in addition with other existing technologies, could potentially contribute to endow artificial agents with the capability of getting insights into the psychophysiological state of the human interlocutor. To this goal, a description of the

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state of the art of thermal imaging in computational physiology and psychophysiology is presented.

2 THERMAL INFRARED IMAGING DATA AND COMPUTATIONAL PHYSIOLOGY

The Autonomic Nervous System has been the object of intense study in psychophysiology. The sympathetic division readies the body for a crisis that may require sudden, intense physical activity and provides a primal survival mechanism. The parasympathetic prompts the body for social relationships. When autonomic activation occurs, an individual experiences changes of the cardiovascular and respiratory activity, with variations in blood pressure, heart rate, breathing rate, and depth of respiration. Thermal signatures of a variety of psychophysiological signals have been identified. In particular, it has been demonstrated and validated that through thermal IR imaging it is possible to compute at a distance the cardiac pulse, the breathing rate, the cutaneous blood perfusion rate, and the electro-dermal response (Garbey, 2007; Merla, 2007a, 2007b; Murthy, 2006; Pavlidis 2007; Shastri 2009). This section summarizes methods and results in the field of computational physiology based on thermal IR imaging.

2.1 Breathing Rate

Breathing consists of inspiration and expiration cycles. During the inspiration, environmental air flows via the nostrils to the lungs. Conversely, in the expiration, air that was heated through its contact with the lungs flows via the nostrils to the environment. This creates a periodic or quasi-periodic thermal signal in the proximity of the nostrils that oscillates between high (expiration) and low (inspiration) values. In conventional respiratory studies, a thermistor is attached near the nostrils to capture this phenomenon and produce a representative breath signal.

Thermal imaging can act as a virtual thermistor, since it captures the same phenomenon, but at a distance (Murthy, 2006). As a periodic signal, the breath signal can be analysed through Fourier transformation on sliding segments (windows) of the normalized breath thermal signal.

The estimation of breathing rate through thermal imaging is very accurate as proved by comparison with respiratory signals taken from respiratory belt at the thorax (Murthy, 2009) (Figure 1), up to achieve correlation values between thermally and mechanically (LifeShirt technology, see Lewis, 2011) recorded breath rate signals as high as 1 over a sample of 25 subjects, in both shallow, normal, and forced ventilation (Lewis, 2011).

2.2 Cardiac Pulse

Thermal IR imaging allows the computation of the cardiac pulse through the spectral analysis of the thermal signature of the superficial vessels' blood flow pulsation (Garbey, 2007). The method is based on the hypothesis that the temperature modulation due to pulsating blood flow produces the strongest variation on a superficial vessel's temperature signal. Garbey and colleagues (2004) proposed a model to simulate the heat diffusion process on the skin initiated by the core tissue and a major superficial blood vessel. They took into account noise effects due to the environment and instability in the blood flow. Their simulation demonstrated that the skin temperature waveform is directly analogous to the pulse waveform, but its exact shape is smoothed, shifted, and noisy with respect to the originating pulse waveform due to the diffusion process. This indicates that the pulse can be recovered from the skin temperature modulation recorded with a highly sensitive thermal camera and processed through an appropriate signal analysis method, as the overall thermal signal that is sensed by the infrared camera is a composite signal, with the pulse being one of its components.

In subsequent works, Sun (2006) and Garbey (2007) proposed a method that, based on the outcome of repeated Fourier analysis and proper filtering of the raw signal, computes the cardiac pulse through an estimation function. In real environment settings, the performance of the proposed method, with respect to standard fingertip laser transducer, ranged from 88.52% to 90.33%, depending on the clarity of the vessel's thermal imprint, over a sample of 34 subjects. Vessels from jugular, wrist and fronto-temporal regions were used for pulse assessment through thermal infrared imaging (Figure 2).

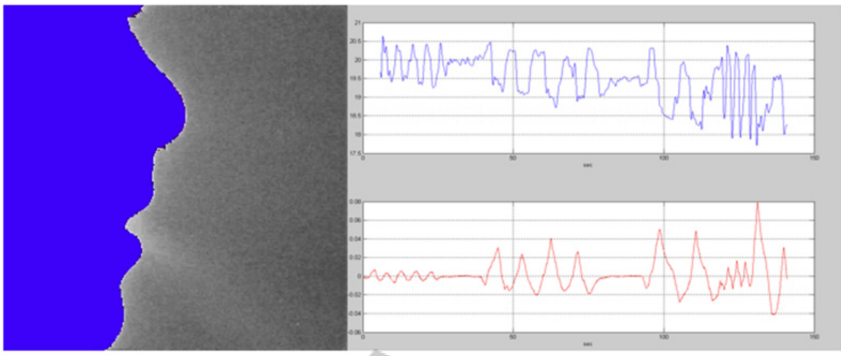

Figure 1: Thermal imaging data. Left: Thermal image showing the thermal track of the airflow. Right: Raw temperature vs. time profile for a region of interest close to the nose tip (upper panel); Signal from thorax respiratory belt (bottom panel).

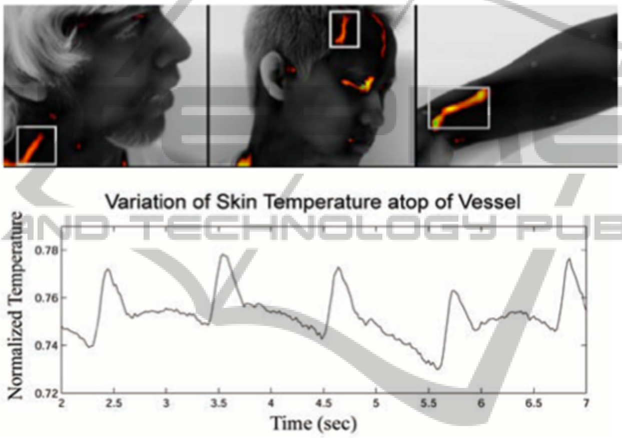

Figure 2: Pulse computation from thermal imaging data. Upper panel: Collection point on the carotid artero-venous complex, the fronto-temporal region and the wrist of the subject. Bottom panel: Temperature profile after removing frequency signals lower than 0.67 Hz (40 bmp) and higher than1.67 Hz (100 bmp). (Adapted from Garbey, 2007).

2.3 Cutaneous Blood Perfusion Rate

Bio-heat transfer models permit the calculation of the cutaneous perfusion from high-resolution IR image series (Pavlidis, 2002; Merla, 2008) (Figure 3). Cutaneous perfusion is a strong indicator of psychophysiological states, being it related to cutaneous vasoconstriction and vasodilation.

Two major advantages for computing cutaneous perfusion from thermal imagery are the achievable frame rate and spatial resolution (up to 100 complete 524x524 pixel images per second using the most advanced commercially available thermal cameras), thus overcoming two of the main limitations of the laser Doppler technique, that is the classical technology for assessing cutaneous perfusion. The models adopted derive from previous works by Fujimasa (1995) and provide a proper estimation for cutaneous perfusion rate in healthy individuals (Merla, 2008). Pavlidis (2002) even suggested to use cutaneous perfusion rate changes in the periorbital region as a performing channel for a new generation of deception detection systems, based on the flight-fight response of the inquired subject to sensitive questions (see section 3.4).

2.4 Electro-dermal Activity and Sudomotor Response

Determination of sympathetic activation through vital sign monitoring is not always straightforward.

As an alternative, sympathetic manifestations through cholinergic postganglionic fibres could be recorded. These fibres innervate sweat glands of the skin and the blood vessels to skeletal muscles and the brain and provide a pathway to selectively enhancing blood flow to muscles and stimulating sweat gland secretion.

In this context, Electro-Dermal Activity (EDA) has been the gold standard for peripheral monitoring of sympathetic responses. EDA is measured through the Galvanic Skin Response (GSR) or the Skin

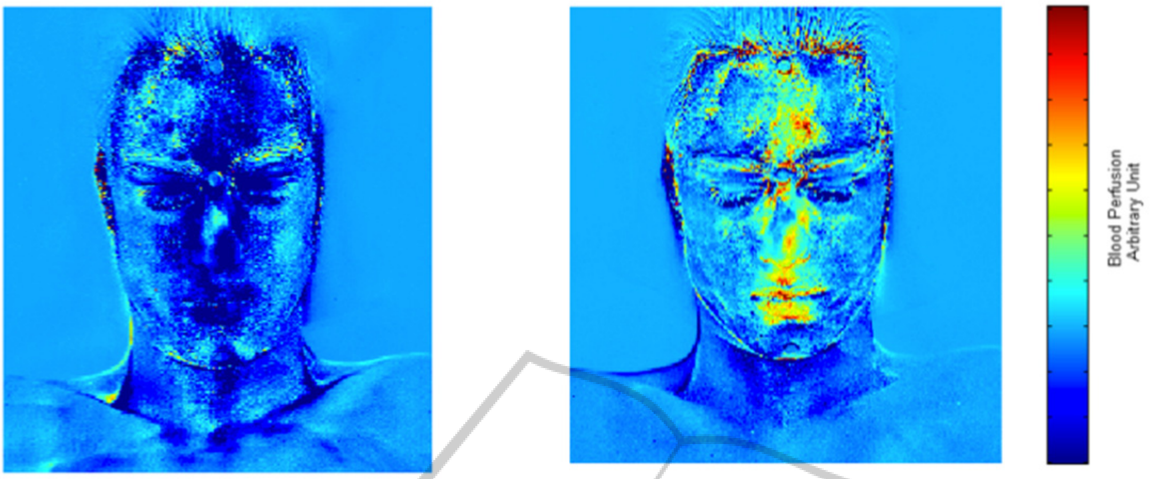

Figure 3: Cutaneous Perfusion Rate computed from thermal IR data. On the left: average rate during the vision of neutral-content movie; on the right: average rate while watching erotic clip (see section 3.3; adapted from Merla, 2007b).

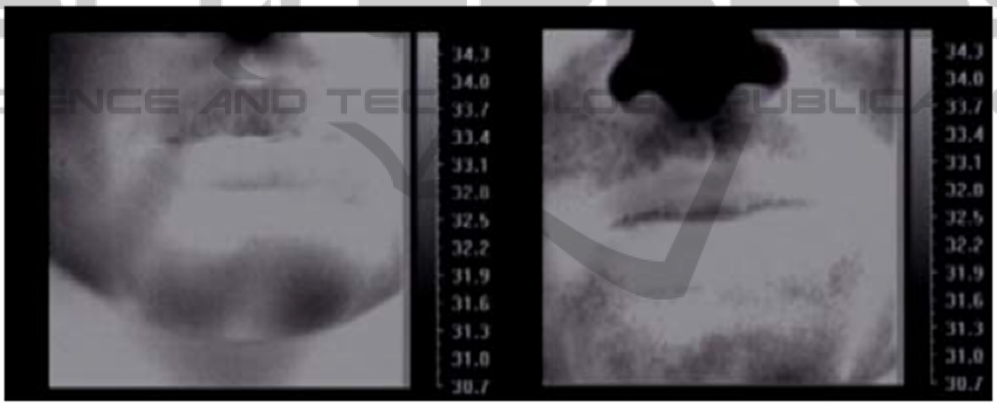

Figure 4: Emotional sweating and sudomotor response. The delivery of emotional pressure (see section 3.2) or stress stimulation (on the right) changes the rest (on the left) temperature distribution. The spotted dark signature is associated with the activity of the sweating glands. (Adapted from Merla, 2007a).

Conductance Response (SCR), which is method for quantifying sweat gland activation in the palm through measurement of the change of the cutaneous electrical conductivity.

Recent researches have demonstrated that facial perspiration activity (i.e., sudomotor response) associated to EDA can be appreciated, recorded and quantified by means of thermal IR imaging (Merla, 2004, 2007a, 2007b; Shastri, 2009). Concomitantly to the palm area, strong sweat gland activation is manifested in the maxillary, perioral, and nose tip regions (Figure 4).

The temperature changes reveal tonic (baseline and /or general) and phasic (event-related) components strongly correlated with GSR sympathetic constituents (Merla, 2007b; Shastri, 2009).

3 THERMAL INFRARED IMAGING IN PSYCHOPHYSIOLOGY

The possibility of recording and monitoring psychophysiological signals in non-invasive and touch-less manner opens the way to the application of thermal IR imaging in psychophysiology. Together with the characterization of the thermal signal in facial regions of autonomic valence (nose or nose tip, perioral or maxillary areas, periorbital and supraorbital areas associated with the activity of the periocular and corrugator muscle, and forehead), to monitor the modulation of the autonomic activity, thermal IR imaging has been indicated as a potential tool to build up, given the use of proper classification algorithms, an atlas of the thermal expression of emotional states (Nhan, 2010).

In this section, an overview of the applications of thermal IR imaging in psychophysiology is proposed.

3.1 Startle

Startle is an uncontrolled reflex that occurs when individuals are engaged with a cognitive task and an unexpected external stimulus or event requires immediate shift of attention, generally followed by autonomic and behavior responses such as increased heart beat rate and sudomotor activity. Startle is part of the flight or fight response and can be easily evoked by using loud and unexpected sounds.

Pavlidis (2001) reported that, during startles, sudomotor response occurs as perspiration pores on the perioral, maxillary and nose area became active decreasing the cutaneous temperature. Temperature increases were observed on the periorbital and neck areas (over the carotid) in contrast to cooling of the cheeks. Researchers explained their observations on the basis of the activation of the adrenergic system, further suggesting the redirection of blood from the cheeks to the periorbital region. Gane (2011) reported a similar temperature drop for the maxillary region while no temperature changes in the periorbital regions could be appreciated.

Shastri (2009) induced startle response by using natural sounds (i.e., glass breaking and phone rings) on subjects engaged in a counting task. The results confirmed the onset of sudomotor response on the maxillary area (Figure 4). In addition, the detection power of the sudomotor response by thermal imaging was found to be similar to that of standard GSR recording.

Coli (2007), within a classic repeated arousal experiment, proved that the thermal signal from the maxillary region and the GSR measurements reveal a high level of affinity in terms of both tonic and phasic components.

3.2 Distress and Fear

Thermal IR imaging has been proposed as a non-intrusive method for assessing distress and mental workload. In a study by Puri (2005) and in a following one by Zhu (2008) signs of distress and frustration in the human-computer interaction were assessed during a stroop task. Based on the frontal forehead temperature, the authors reported an increased blood volume to supraorbital vessels with respect to the rest condition.

Mental workload has been assessed in professional drivers. Participants were exposed to simulator driving tasks while cognitively challenged with a mental loading task. Compared to baseline, significant differences in nose tip temperature were observed on the nose temperature along the simulation procedure in agreement with the required mental load (Calvin, 2007). As for the occupational distress, in a seminal study, levels of stress in expert and novice surgeons were measured during training on three different drilling tasks designed for laparoscopic surgery. The authors, by monitoring the perioral and nose regions of the participants, observed higher levels of distress in novice compared to expert surgeons. Distress signs were assessed by lower temperatures on the peri-nasal region along with the activation of perspiration pores (Pavlidis, 2012).

Thermal IR Imaging has also been used to assess training times by studying learning proficiency patterns on an alphabet-arithmetic task. During the first trials nose temperatures were lower with respect to the baseline. With repeated experience and training, the nose temperatures rose as individuals became more accurate and quicker in their responses (Kang, 2006).

Early evidence of peripheral thermal patterns associated with fear date back to 1998. Kistler and colleagues induced fear in participants by showing to them scenes from thriller movies. They found dramatic decreases of fingertips temperature during the most scaring scenes of the movies.

Merla (2007a) studied facial thermal signals in fear-conditioned individuals (Figure 4). Unexpected sub-painful mild electric stimuli were delivered to the subject's median nerve. Results showed a reduction of temperature and sweating on the perioral region, forehead as well as the palm.

3.3 Sexual Arousal and Interpersonal Contact

Sexual arousal has clear and marked interrelationships with ANS activity.

Merla (2007a) studied the facial thermal response, in terms of facial cutaneous perfusion change, to the view of erotic clips in contrast with the view of sport movies. During the presentation of the erotic movies, the temperature and the cutaneous perfusion of the forehead, periorbital regions, nose and lips increased (Figure 3). Hahn (2012) examined social contact and sexual arousal during interpersonal physical contact. The physical contact was performed on different parts of the body such as the face, chest (high-intimate), arm and palm (low intimate) from both male and females experimenters. It was observed that, when high-intimate regions were touched, temperature increased. The temperature augment was higher when the experimenter was of the opposite sex of the subject. The temperature increase was localized on the mouth, nose, and the periorbital regions of the face.

3.4 Social Neuropsychology

Developmental and social neuropsychology is a particular challenging field where thermal IR imaging has been introduced with very encouraging results.

Early infant attachment was studied using thermal IR imaging in infants exposed to three different experimental phases: i) separation from the mother; ii) a short-lived replacement of the mother by a stranger; and iii) infant in the presence of the mother and the stranger. By observing negative temperature changes on the infants' forehead, the researchers concluded that infants are aware of strangers and that infants form a parental attachment earlier than previously thought, specifically from 2-4 months after birth (Mizukami, 1990).

Mothers' ability to empathically share offspring's emotional feelings is considered integral to primary affective bonds and a healthy socio-emotional development. Ebisch (2012) investigated, in an ecological context, whether maternal empathy is accompanied by a synchrony in autonomic responses by assessing simultaneously the facial thermal imprints of mother and child, while the former observed the latter when involved in a distressing situation (Figure 5). The results showed a situation-specific parallelism between mothers' and children's facial temperature variations, providing evidence for a direct affective sharing involving autonomic responding (Figure 6).

An extension of the above study including an additional group of female participants showed that mothers-child dyads in contrast to other-women-child dyads have faster empathic reactions to the child's emotional state (Manini, 2013).

The above research paradigms used an experiment inducing guilt, further explained in Ioannou et al (2013). All of these studies, once more, highlighted the peculiar role of the nasal temperature as indicator of autonomic activity related to social interaction in children. As for the adults, fewer studies with thermal IR imaging are available about social neuropsychology.

In the only study for embarrassment (Merla (2007a), participants were exposed to the attention of unknown people, while performing a stroop task. The study was designed in order to elicit feeling of embarrassment and mild stress when the participants wrongly performed the task in the presence of others. Temperature decreases associated with emotional sweating were observed on the palm and the face, especially around the mouth and over the nose tip.

Given the capability of thermal IR imaging to capture emotional states, a variety of studies have examined the potentialities of this technique in the context of deception detection. Pavlidis (2002) accurately identified 11 out of 12 subjects as guilty in a mock scenario experiment through cutaneous blood flow rate increases on the forehead and in the periorbital regions. Following the same experimental approach, Tsiamyrtzis (2006) suggested that temperature and cutaneous blood flow monitoring of the periorbital vessel during interrogation provides 87.2% accuracy in detecting deceptive individuals. Zhu (2008) by focusing on the forehead, and particularly on the corrugator muscle supplied by supraorbital vessels, achieved a percentage of 76.3% accuracy for lie detection. Temperature increases were accounted as results of flight or fight response to the sensitive questions and increased blood perfusion to facial muscles as a result of mental stress.

Table 1 reports a list of studies applying thermal IR imaging to psychophysiology.

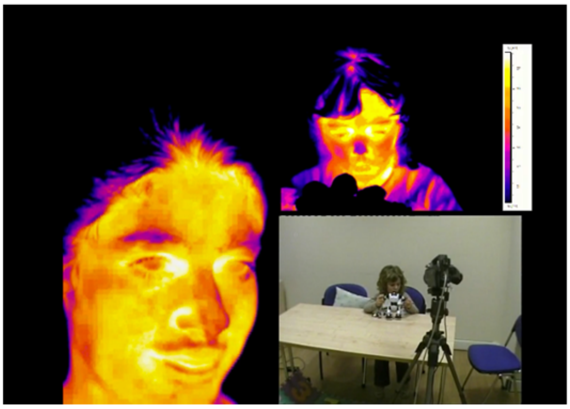

Figure 5: Thermal IR imaging allows the simultaneous recording of individuals sharing a social condition or task. Evidence of the same sudomotor response is found in this thermal picture of a mother looking at her child experiencing a distressful situation.

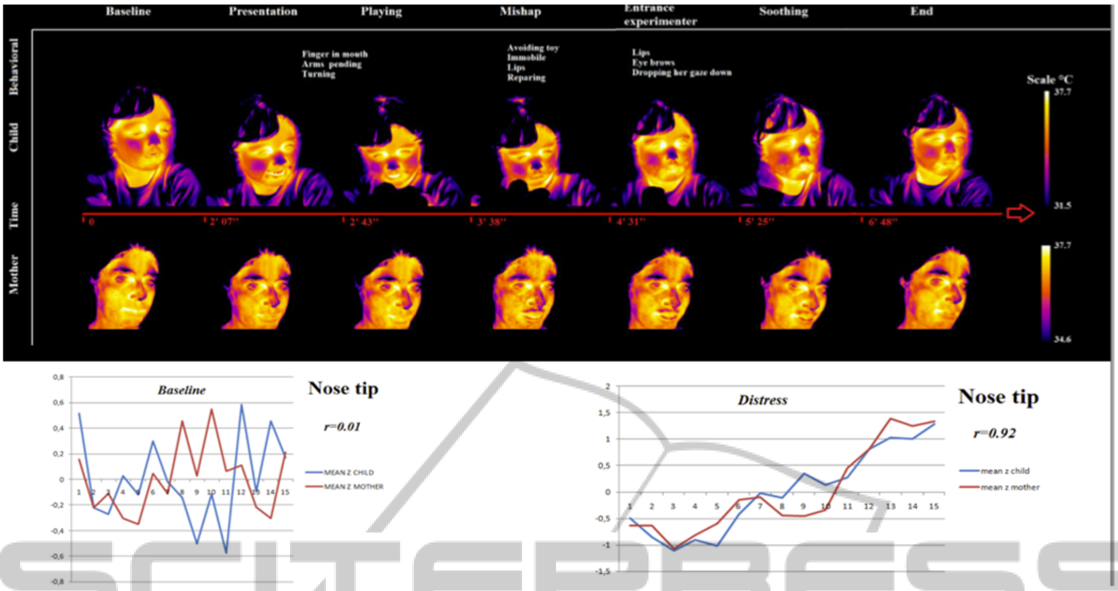

Figure 6: Facial thermal imprints of a mother-child dyad and nose tip temperature synchronization during distressing situation (Adapted from Ebisch, 2012).

Table 1: List of some of the studies applying thermal IR Imaging to psychophysiology

Authors	Year	Subjects	Emotion/Response	Experimental Paradigm	Regions
Mizukami et al.,	1990	34 (pairs)	Mother infant separation-stress	Separation from mother/stranger exposure	Forehead
Naemura et al.,	1993	52	Startle	White Noise (45-100db)	Nasal Region
Kistler, et al.,	1998	20	Fear	Horror Movie	Fingers
Pavlidis, et al.,	2001	6	Startle	Loud noise (60dB)	Periorbital area, Cheeks, Neck area.
Pavlides et al.	2002	12	Lie Detection	Mock interrogation	Face
Puri et al.,	2005	12	Stress	Stroop Test	Supraorbital Vessels
Tsiamyrtzis et al.	2006	39	Lie Detection	Mock interrogation	Periorbital vessels
Kang et al.,	2006	9	Learning process-Stress	Alphabet arithmetic task	Forehead, Nose
Calvin & Daffy	2007	33	Mental workload-Stress	Driving – MLT	Forehead, Nose
Merla & Romani	2007	10	Fear of Pain	Electric stimulation & Trigger	Face, Palm
Nakanishi & Matsumura	2007	12	Laughter	Playing	Nose, Forehead, cheek
Zhu et al.	2008	38	Lie Detection	Mock interrogation	Supraorbital vessels
Shastri, et al.,	2009	10	Startle	Natural startling sounds: glass breaking, phone ringing	Periorbital, supraorbital, maxillary
Gane, et al.,	2011	11	Startle	Loud noise (102dB)	Periorbital
Ebisch et al.,	2012	12 (dyads)	Empathy	Toy Mishap	Face: Nose, Maxillary
Hahn et al.,	2012	16	Sexual Arousal	Touch on high intimate regions	Nose, lip, periorbital
Manini et al.	2013	18 (dyads)	Empathy	Toy Mishap	Face: Nose, Maxillary
Ioannou et al.,	2013	15	Guilt	Toy Mishap	Nose

4 THERMAL IR IMAGING AND HUMAN-MACHINE INTERACTION

Thermal IR imaging is widely spreading in psychophysiology as an adjunct tool for obtaining information of psychophysiological relevance non-invasively and ecologically, that is without interfering with the spontaneous activity of the person.

Computational physiology based on thermal IR imaging is possible and reliable and, being this technique based on digital imaging data, it could be completely automatized and managed by an artificial intelligence agent, without human user-assistance.

Even though most of the available literature relays on measuring or characterizing just one physiological parameter at once, at least from a theoretical point of view, there are no problems with combining together the physiological that can be recorded all together thermal IR imaging to improve the performance of classification of psychophysiological states and emotions (Nhan, 2010).

Facial regions of interest in the thermal video can be automatically detected and identified basically adapting the algorithms for visible videos so far developed for automatic feature extraction (Dowdall, 2006). Software for automatic tracking of regions of interest across the time series of the recorded frames is also available (Dowdall 2006; Zhou, 2009), thus setting the observed subjects free from any motion restriction or requirement. The methodology has been proven to be solid and reliable in a series of studies dealing with moral emotions in three years old children engaged in free activity and games across the experimental room while being recorded (Ebisch, 2012; Manini, 2013; Ioannu, 2013). However, a relevant issue related with automatic tracking is the accurate estimation of the temperature of the facial regions of interest when the subject's face is turned away or rotate from the orthogonal projection with respect to the camera's plane (i.e., out-of-the-plan position), as this may cause underestimation of cutaneous temperature (Dowdall, 2006; Ebisch, 2012).

Real time processing of thermal IR imaging psychophysiological data has been demonstrated (Buddharaju, 2005). Particularly relevant is the demonstrated possibility of real-time estimation of the psychophysiological state of the driver while engaged in real car driving (Merla, 2011). Patent claiming the possibility of automatic computation of the residual efficacy of the man-machine interaction, based on the real-time estimation of the psychophysiological state of the human user through thermal IR imaging, has been issued as well (Merla, 2013).

These results suggest the intriguing possibility of integrating thermal IR imaging with other existing technology in the field on human-machine interaction to provide artificial agents with the capability of understanding the psychophysiological state of the human interlocutor. To the best of our knowledge, no previous studies have analysed such a possibility, while a very few of pilot applications have been so far proposed (Buddharaju, 2005; Merla, 2013).

There are several advantages that could derive from the use of thermal IR imaging for human-machine interaction. From the point of view of the computational physiology, it has to be remarked that there is the concrete possibility of monitoring, in a realistic environment, at a distance and unobtrusively, several physiological parameters and vital signs like pulse rate, breathing rate, cutaneous vasomotor control and indirect estimation of electro-dermal activity. This opens the way for remote monitoring of the physiological state of individuals without requiring their collaboration and without interfering with their usual activities, thus favouring the use of assistive robots, for example, for elder people or for monitoring the regular breathing activity in neonates. Automatic agents devoted to the control of environmental conditions, for example within a car or an house, could take advantage from a biofeedback control of the actuation through the thermal-based monitoring of vitals signs of the human user, in order to achieve and maintain optimal or desired performances of the system user-agent (i.e., adaptive environment).

Another relevant possibility is to capitalize on thermal IR imaging to provide artificial agent with the capability of adopting behavioural or communicative strategies contingent with the actual psychophysiological state of the human interface. This possibility, even though still theoretical, could be particularly effective for affective robots and automatic agents designed for improving and personalizing learning or treatment strategies on the basis of the measured user's psychophysiological feedback.

A major issue that needs to be addressed for a real use of thermal IR imaging in human-machine interaction is how much the method could be specific for identifying specific emotional states at individual level. There are no specific studies available at the moment to answer such an important question, which remains matter of further research. A global limitation derives from the fact that cutaneous thermal activity is intimately linked to the autonomic activity. The question therefore becomes: "How much specific and descriptive of each emotion are the autonomic responses?" No answer universally accepted is available. Also no extensive studies are available about the fascinating possibility of merging together physiological information and automatic recognition of facial expressions for providing an atlas of the thermal signatures of emotions.

5 CONCLUSIONS

Thermal IR imaging is a reliable method for ubiquitous and automatized monitoring of psychophysiological activity. It provides a powerful and ecological tool for studies aimed at assessing emotional arousal, responses, and affective states. Its capability of capturing autonomic responses and psychophysiological states opens the way to innovative and ecological paradigms for studying social relationships, emotional charge and autonomic activity.

The results of the available studies suggest that specific thermal signatures related to specific emotional conditions exist, but further studies are needed to assess the specificity and the sensitivity of the method.

Affective robots or artificial intelligence systems could be endowed with this methodology in order to capitalize on the possibilities offered by thermal IR imaging for reading, classifying, understanding and interacting with individuals' affective and psychophysiological states, and emotions.

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