User Experience Analysis Based on Physiological Data Monitoring and Mixed Prototyping to Support Human-Centre Product Design

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Abstract. Human-centred design is based on the satisfaction of the user needs mainly related to performances, interaction, comfort, usability, accessibility, and visibility issues. However, the “real” user experience (UX) is hidden and usually difficult to detect. The paper proposes a multimodal system based on the collection of physiological and anthropometrical performance data on field and within a mixed prototyping set-up. The mixed environment makes users interact with virtual and digital items and users’ performance to be capture and digitalized, simulating human-machine interaction, while physiological and anthropometrical data collection allows to objectify the users’ physical and mental workload during task execution. Such a system has been applied to an industrial case study focusing on agricultural machinery driving and control to support the definition of a new cabin and its control board, in terms of seat features, commands’ positioning and grouping, and positioning of additional devices.

Keywords: Human-centred design · User experience
Human-machine interaction · Ergonomics · Mixed prototyping

1 Introduction

Driving and control of agricultural machinery is a stressing activity, from both physical and mental viewpoint. Specifically, with regard to tractors, the driver undergoes a lot of movements which mainly involve the upper part of the body: steering, looking forward and backward, controlling the monitor or the vehicle’s dashboard, using clutch, brake, control levers or joystick [1]. In the long term such activity could generate physical health problems in different upper parts of the body (i.e., arms, neck, shoulders, back, head). The cabin design, including the seat, the control board and the interaction devices, plays an important role in the driver’s comfort. Indeed, a good ergonomic

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disposition of the main commands and organization of the cabin room, together with the adoption of proper operating practices, can potentially reduce or minimize the operator stress. However, in order to properly characterize and assess ergonomics and comfort in a vehicle cabin, an accurate analysis system is needed. An improved human–machine interface design, such as well-accommodated operator enclosures, a comfortable seat and achievable and easy to use commands, can significantly enhance operator productivity, comfort and safety [2].

In this context, the adoption of a human-centred design (HCD) approach is mandatory. It supports the inclusion of human factors in tractor design in order to respond to physical, psychological, social and cultural needs of human beings [3]. Human factors specifically refers to research "regarding human psychological, social, physical, and biological characteristics, and working to apply that information with respect to the design, operation, or use of products or systems for optimizing human performance, health, safety, and/or habitability" [4]. As a consequence, HCD consists of the application of human-related information to the design of tools, machines, systems, tasks, jobs, and environments for safe, comfortable, and effective human use. As far as industrial system design, the optimization of posture, physical overload, perceived effort, discomfort, and physical fatigue is fundamental to satisfy the users' needs, prevent musculoskeletal disorders and stressing conditions [5]. In this context, the analysis of human factors has a central role in the understanding of human behaviors and performance interacting with systems, and the application of that understanding to design of interactions [6].

The paper presents a methodology and a technological set-up to monitor the drivers' performance and to support a human-centred approach. In particular, the proposed set-up integrates different methods for the acquisition of physical and physiological parameters, such as:

- Use of sensors for real-time analyses of the main physiological parameters, which can provide a clear feedback on the driver's state without interference with the driver's activities. The adopted sensors refer to electrocardiography (for heart rate (HR) and heart rate variability (HRV) monitoring), breathing monitoring (for breath rate (BR) analysis), and eye-tracking (for eyes' fixation analysis and visual attention mapping);
- Motion capture for real-time analyses of body movements, to measure the position of the different body parts (e.g., arms, hands, head) and to objectify the human-machine interaction in terms of distance, instantaneous speed or acceleration) by applying well-known methods for comfort analysis (e.g., Dreyfuss);
- CAN (Controller Area Network) data collection for analyses of the human interaction with the control devices and interface, to check whether and what type of interaction is taking place during task execution. Such data are collected thanks to the simulation of the CAN bus on both the real tractor and the cabin prototype.

2 Related Works

The analysis of the ergonomic aspects during interaction with agricultural machinery is of great importance, as the physiological as well as psychological fatigue affects performance of the operator. Objective of ergonomics is not only to improve work performance but also to improve human comfort as well as safety [3]. If ergonomic aspects are not given due consideration, the performance of the system will be poor and the effective working time will be reduced. The goal of ergonomics is to design workplace to conform to the physiological, psychological, and behavioral capabilities of workers. There are many factors acting as stress on the operator during the work. These stresses may be due to workload, immobilization for longer duration work, ambient temperature, relative humidity, vibrations, noise, dust, smoke and other gases. Uncomfortable postures during work, space confinement, overload of information to be handled, complex tasks to be executed, time pressure, and other factors result in psychological fatigue [7]. This fatigue can be measured in terms of strain on the operator. Most common analyses typically include electrocardiography (for heart rate monitoring), electromyography (for monitoring muscles activity through their electrical potentials), the pneumography (for respiration control) or the skin conductivity (to measure sweat activity) [8, 9]. The basic concept is that physical activities stimulate certain physiological responses in human beings; these responses generate the human fatigue. These investigations provide fundamental information on the driver's health condition, even if high competence is required for the understanding and interpretation of physiological data. However, an automatic and non-invasive detection system is very useful, but it does not exist yet. The multimodal dimension of stress makes the research field very broad. However, four main criteria can be distinguished in detecting the human stress, according to ISO 10075-3 [10]: psychological, physiological, behavioral, and biochemical. Psychological responses include the increase of strong emotions, usually negative, such as anger, anxiety, irritation and depression. From a physiological point of view, the increase in SNS (sympathetic nervous system) activity changes hormone levels in the body and provokes reactions such as sweat production, increased heart rate and muscle activation. Breathing becomes faster and increases blood pressure. Usually skin temperature and HRV fall. The diameter of the pupils can vary. Finally, behavioral reactions include eye movements and eye change rates, as well as changes in facial appearance and head movements.

While the analysis of physiological measures has been analyzed by numerous researches in the recent years, other areas such as correlation to postural changes and relation with eye activity have never been investigated for tractors. Furthermore, since the context highly affects the individual's stress response, measurable contextual information can provide important traces of stress levels, which may depend both on the personal characteristics of the subject and on circumstances independent of the subject such as events, places or instants.

Alberti et al. [11] recently presented a review of the main methods for human stress detection. There are many physiological signals to be used in stress detection and some of them have shown to provide reliable information about peoples' real-time stress levels. Table 1 shows the main physiological signals and features present in the literature. The electrocardiogram (ECG), based on the recording on the body surface of the electrical activity generated by heart, is one of the most used signals in stress detection research because it reflects directly the activity of the heart. The most typical and useful features computed with an ECG are probably the ones related to the Heart Rate (HR, defined as the number of heartbeats per minute), the Heart Rate Variability (HRV, defined as the temporal variation between sequences of consecutive heart beats) and LF/HF (low frequency/high frequency) ratio, that hat reflects the activity of the sympathetic and vagal components of the Autonomic Nervous System. In the temporal domain, statistical and geometrical parameters are computed. The most common parameters are the mean value, and the Standard deviation of RR intervals (SDRR). The electroencephalogram (EEG) is a test that measures the electrical activity of the brain, monitored by placing an array of electrodes on the subject's scalp so that the electrical fluctuations are recorded. From EEG signals, mean amplitude, mean amplitudes of Event Related Potential (ERP) components, and the mean power spectra of the different frequency bands are probably the most frequently computed features. Another useful indicator of stress is the Electrodermal Activity (EDA), defined as a change in the electrical properties of the skin. Indeed, under increased cognitive workload or physical activity, the level of sweating increases, changing the skin properties. Statistical values like the mean amplitude, standard deviation (SD) of the amplitude, minimum and maximum values and the Root Mean Square (RMS) are typically used. Also skin temperature (ST) may vary for different reasons, including which physical exertion and physiological changes; mean and the standard deviation are the most used parameters in the literature. The electromyogram (EMG) measures the electrical activity of the muscles by using electrodes placed over the muscle of interest. As it is known that stress elevates muscle tone, many researches have been done to analyze the potential of EMG for measuring stress, considering the mean, median, standard deviation, RMS and peak loads (10th, 50th and 90th percentile of rank ordered RMS values). Finally, eye gaze and blink rates can be measured with infrared eye tracking systems or with image processing techniques applied to visual spectrum images of the eyes. Thus, pupil dilatation exhibits changes under stress situations and can be measured by the dilation mean value, standard deviation, gaze spatial distribution (GazeDis), number of fixations, as well as the blink rate or blinking frequency.

Table 1. Physiological features used for human stress detection (adapted from [11])

Signal	Features	Parameters
ECG	μ, SD, P and E, HR, HRV	μ, min, max
		Temporal: μ, HRV, SDNN, RMSSD
		Frequential: LF/HF
EEG	μ, ERP, spectral features	μ, SD
EDA	μ, SD, min, max, RMS	μ, SD
ST	μ, SD, min, max	μ, SD
EMG	μ, median, SD, min, max	μ, median, peak loads, frequency, median frequency
Eye gaze	Eye position	GazeDis, tracking fixations, μ, SD
Blinks	Blink frequency	Frequency

The combination with physical stress analysis can support data interpretation. For the measurement of the physical stress, different approaches have been proposed in the past, including processing of video-recorded images [12] or implementation of gyroscopes or accelerometers [13], or motion capture cameras [14]. Video-based analysis is relative cheap, but video post-processing is time-consuming and requires several experts for an objective evaluation. Diversely, adopting rotational and linear accelerometers can observe the real-time movements of the different body parts with high accuracy, but often expansive multiple sensors are required for three-dimensional analysis of a whole body, with the drawback of preventing or interfering with the body movement. On the other hand, motion capture allow real-time acquisition of several parts of the body positions, taking advantage of body markers. It represents a good compromise between accuracy and time spent for data analysis, even if the adopted systems, in particular cameras, are suitable for a lab tests, while they cannot be used for on-field tests. Also the costs of motion capture devices are considerably reduced thanks to recent hardware and software advances in the videogame industry.

Furthermore, digital technologies can support human simulation for preventive analysis before products or systems are physically realized. Such tools allow products and interaction tasks to be simulated on digital mock-ups, and human actions and behaviors to be reproduced by digital human models (DHMs) [15]. Examples of virtual

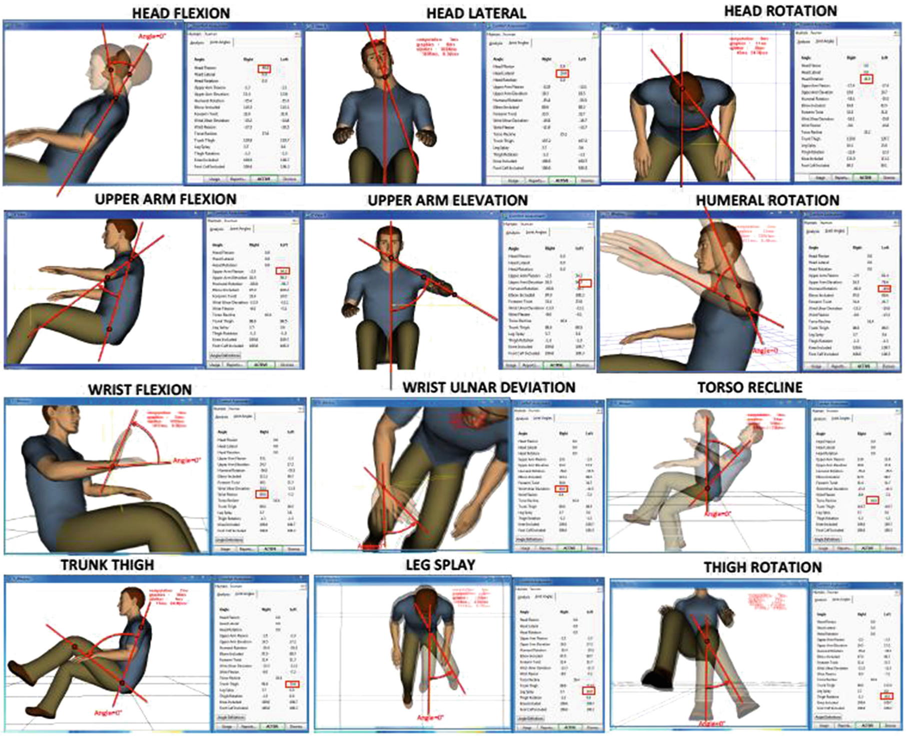

Fig. 1. Main anthropometric measures for postural comfort analysis in seating position

simulation DHM tools used are: Siemens JACK, Dassault Systèmes CATIA/DELMIA HUMAN, RAMSIS, SANTOS, Pro/ENGINEER Manikin Analysis, SAMMIE, 3DSSPP, Anybody® Modeling System. Using these tools, the anthropometrical attributes of specific postures, the visual scope and the reach envelope of users representing specific populations can be analyzed [16]. Figure 1 shows the main anthropometric measures used to predict the postural comfort for seating positions, like those assumed for comfort evaluation in driving a tractor.

3 The Experimental Approach

The research aims at analyzing the UX by collecting data about behavioral and cognitive responses thought a set of metrics, properly selected for the analysis of UX for tractor drivers. Metrics aims at measuring both physical and cognitive workload in terms of postural comfort, physical stress and fatigue, visual interaction with the interface, and use of commands, in order to “measure” in a certain sense the UX. For this purpose, a mixed prototyping set-up was created to simulate the human-machine interaction in lab. The set-up is defined “mixed” since it combines physical items with virtual scenes and digitalization technologies. The set-up is composed by:

- a seating bulk reproducing the cabin parts involved in the interaction, such as the seat, the steering wheel, and the main controls;
- Vicon tracking system for users’ tracking and digitalization, made up of Vicon Bonita cameras for motion capture, and rigid bodies with reflective markers for users’ tracking;
- Siemens JACK toolkit for 3D digitalization and Haption RTI plug-in for connection among real user movements and virtual manikin movements;
- Volfoni 3D Active Glasses for 3D stereoscopic viewing for immersive simulation into the virtual scene;
- Tobii Pro Glasses 2 to capture eye movements and to study visual interaction;
- Zephyr BioHarness 3.0 sensor to record human physiological data, in particular it collects: Heart Rate (HR), Heart Rate Variability (HRV), Breathing Rate (BR), Body activity (expressed in VMU, vectorial sum of activity counts in x-y-z directions), and the angular torso flexion;
- CAN data from the tractor interface and CANanalyzer software toolkit for data elaboration;
- a GoPro camera to record the scene.

Figure 2 shows how the proposed approach has been implemented in the study and how data are collected and elaborated.

From filtering the ECG signal, the following parameters are calculated, where SDNN indicates the standard deviation of normal-to-normal R-R intervals, where R is the peak of a heartbeat, and RMSSD is a short-term variation of HR:

$$RMSSD = \sqrt{\frac{1}{N-1} * \sum\nolimits_{i=1}^{N-1} (RR_{i+1} - RR_i)^2} \tag{1}$$

$$SDNN = \sqrt{\frac{1}{N} * \sum_{i=1}^{N} \left(RR_i - \overline{RR}\right)^2} \quad (2)$$

$$VMU(Vector\, Magnitude\, Unit) = \sqrt{(x^2 + y^2 + z^2)} \quad (3)$$

$$acc(peak\, acceleration) = \sqrt{(x^2 + y^2 + z^2)}_{\_max} \quad (4)$$

Table 2 reports the adopted tools and the monitored parameters for user experience analysis into the virtual set-up. Figure 3 shows the arranged mixed prototyping set-up.

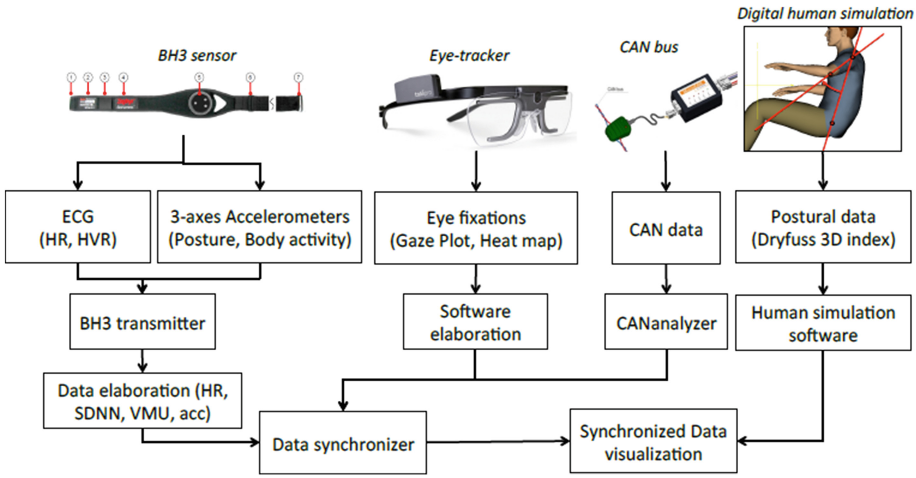

Fig. 2. The research approach and data elaboration framework

Table 2. Tools and monitored parameters for UX analysis

Tools	Typology	Monitored parameters	Collected data
Siemens JACK	Occupant packaging toolkit	Dreyfuss 3D index	Human joint angles
CANanalyzer	Signal monitoring	CAN data	Command sequence and frequency of use
Tobii Glasses 2	Eye Tracker	Eye fixations	Gaze plot, Heat maps
Zephyr BioHarness 3.0	Multi-parametric wearable sensor	Heart Rate (BPM) Body activity (VMU) Peak acceler (acc) Posture (deg) Skin Temperature (°C)	HR diagram, SDNN, RMSSD Activity diagram, VMU Peak acceleration diagram Stooping on sagittal plane Temperature
GoPro Hero 3	Camera	–	Videos of users and surrounding environment

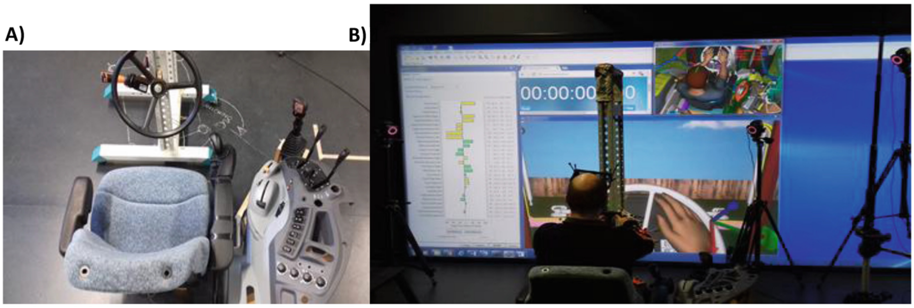

Fig. 3. The set-up for UX monitoring: seating bulk for the tractor cabin (A), and immersive virtual environment with motion capture for virtual task simulation (B)

The experimental study is structured into two phases. First of all, users are monitored during field tests to identify the main critical tasks and the main interaction difficulties, in order to highlight the cabin's parts that need to be redesigned. During this phase, users drive a real tractor and their physiological and anthropometrical data are collected by wearable technologies (BioSensor BH3 and eye-tracking Glass 2), while CAN data are collected.

The second phase consists of lab tests by using the seating buck and tracking the users' movement by motion capture. The main advantage is the use of such set-up during the design phase, in order to validate different design solutions involving users, according to a participatory design approach. Users interact with the physical mock-up (e.g., steering wheel, seat, control and leverages) and are immersed into the virtual scene to have a realistic simulation of the task. The digital simulation of their movements and the product is synchronized in real-time with the real world, so that users' can see the virtual scene changed properly. The analysis of interaction is based on task analysis carried out during the first phase, subdividing the task to be simulated into a set of sub-tasks, identifying the simulation fixed and variable parameters and external conditions, and highlighting the human-system interactions. Digital simulation allows creating a digital environment where users can interact in advance with the product features, to address the main interaction criticalities during the design stage. Predictive analysis can be carried out before the real product realization, and an optimized product will be created, avoiding also late optimization actions. Indeed, the use of digital simulations allows easily comparing different product layouts, replicating the sequence of actions, predicting the user movements, and defining the best design solution.

4 The Industrial Case Study

The industrial case study focused on the analysis of the UX on a CNH tractor (APL16x16), with the final aim to support the cabin redesign. The study was based on task analysis on the real use of the tractor, and the virtualization of the cabin by the proposed set-up as described in the previous section. Monitoring the driver's physiological and anthropometrical data and correlating them with the interface use and visual interaction data, allows analyzing the physical and mental workload in order to understand the level of comfort, the usability of the interfaces, the level of stress, and the perceived quality of interaction. A set of tasks were monitored during field tests and reproduced into the mixed prototyping set-up with optimized cabin designs. For each task, a set of sub-tasks was identified and data collected and properly synchronized. Such synchronization was the most difficult and time-consuming part of the data analysis, but it was very powerful to investigate the users' interactions. Indeed, only correlating physiological parameters and their change over the time, with task execution, visual interaction by eye tracking, and commands' use allowed investigating the human-machine interaction and highlight the main criticalities. Figure 4 shows an example of the monitoring set-up and the main data about commands interaction from CAD data, collected during the field test. On the basis of such data, the main stressing issue where recognized.

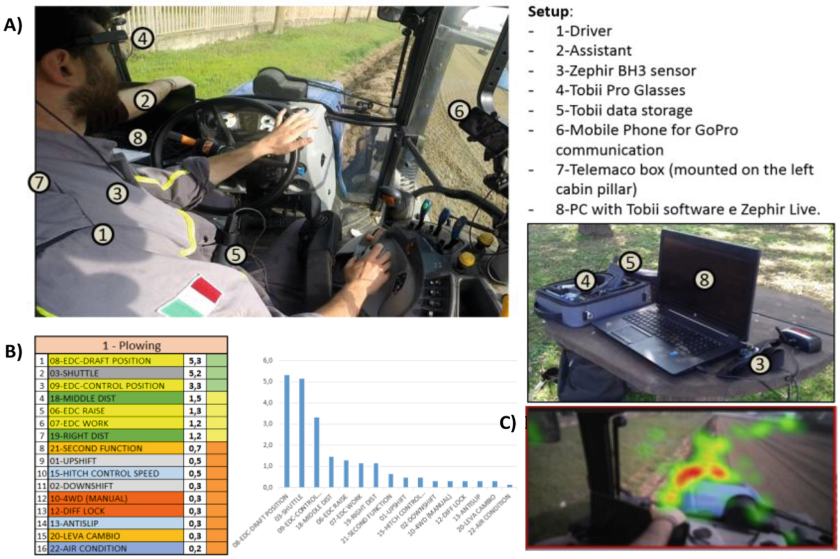

Fig. 4. UX analysis during field tests (e.g. plowing): the adopted set-up (A), the analysis of interaction with commands from CAN data (B), and heat map from eye tracking (C)

Furthermore, the lab tests on the mixed prototyping set-up allowed involving users in the validation of different design alternatives, generated on the basis of the field test feedback. Figure 5 shows data collected and properly synchronized during plowing case. In particular, 8 users were involved during the tests, with different level of expertise, different ages (from 20 to 58 years old), anthropometrical features (from 5 to 80 percentile) and gender (5 males and 3 females). The human simulation software and the plug-in allowed creating a real-time correlation between the real and the virtual scenes so that the user had the impression to be immersed into the virtual environment, simulating the specific task. Contemporarily, the software application simulated generated postural comfort analysis by Dreyfuss 3D and detailed anthropometrical data (to be exported for post-processing). Furthermore, data collected from the biosensor and the eye tracking are collected. The following data post processing allowed finding out information about users' interaction.

Fig. 5. UX analysis during lab tests (e.g. plowing): virtual simulation and anthropometrical data analysis in the mixed prototyping set-up (A), sub-tasks' sequence (B), real-time HR monitoring (C), and interaction with commands during task execution via CAN data analysis (D)

Different design solutions of the cabin, varying in commands grouping and cabin layout, were analyzed. Also the introduction of a monitor was tested. The adoption of the proposed set-up created a solid knowledge, deeper than before, about the interaction with the cabin controls and the practices adopted by different users. It also reduced the time for re-design from 3 months to 2 months, with respect to previous similar projects.

5 Conclusions

The paper focuses on the evaluation of the user experience on the basis of the collection of physiological and anthropometrical performance data on field and in lab, within a mixed prototyping set-up. The mixed environment allows products to be represented both virtually and physically, and humans to be digitalized and monitored in order to easily evaluate the human-machine interaction. The analysis of physiological and anthropometrical data allows objectifying the users' physical and mental workload during task execution. Such a system has been applied to an industrial case study focusing on agricultural machinery driving and control to support the definition of a new cabin and its control board, in terms of seat features, commands' positioning and grouping, and positioning of additional devices. The case study demonstrated that the proposed set-up validly supports human-centred design thanks to the analysis of both physical and cognitive workload, and the possibility to easily compare the effect of different design solutions. Future works will be focused on a more complex data correlation and the definition of robust algorithms for the automatic detection of the users' stress.

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