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U-biofeedback: a multimedia-based reference model for ubiquitous biofeedback systems

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Abstract Biofeedback is a well-accepted approach in preventative and alternative healthcare. It is known to promote wellbeing and help prevent and treat a wide variety of disorders related to the human physiology and psychology. With the exceptional growth of wearable sensor technologies, the potential for devising biofeedback systems that blend into everyday living is immense. Therefore, we present our vision for U-Biofeedback, a reference model for systems designed to continuously monitor our physiology and convey to us important messages regarding our status. Also, we present a case study for an application that implements our reference model. The application is designed to monitor the stress of individuals working in an office setting and provide an assistive response whenever stress reaches elevated levels. By devising an algorithm for stress detection that makes use of Heart Rate Variability (HRV) measures, we were able to identify negative stress situations with an accuracy of 89.63 % and a false positive detection rate of 5.55 % during our evaluation.

Keywords Biofeedback · Multimedia health systems · Heart rate variability · Stress management · Health monitoring · Occupancy-based services

1 Introduction

1.1 Historical perspective

The metaphorical structural foundation of human wellbeing is supported by two pillars: the body and mind, and is based on two fundamental researches: human physiology and psychology, as shown in Fig. 1. The word 'Biofeedback' was not coined until 1969, but the concept has been known for thousands of years in the form of meditation and various yoga techniques. For

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Fig. 1 Body-mind coordination

example, yogis have been consciously controlling their Autonomic Nervous System (ANS) (such as slowing their heart rate or increasing their body temperature) by observing their body's performance. It is believed that the basis of biofeedback research was established in the 1930's when progressive relaxation techniques [24] and autogenic training [31] were introduced. These techniques involve a daily practice that lasts for a certain time interval (for example 15 min) during which the practitioner repeats a set of visualizations that induce a state of relaxation. Such practices, supplemented with information relating to the mind and body (collected by electronic sensors), would later form the foundation for biofeedback [31].

The term biofeedback was introduced at the first annual meeting of the Biofeedback Research Society (1969) as the acquisition of biological feedback through electrical instrumentation [46]. This era was marked by the development of a variety of biofeedback techniques (such as temperature biofeedback, EMG biofeedback, EEG biofeedback, and galvanic skin response) [50]. For instance, Miller and colleagues conducted a series of experiments on animals in order to determine whether the ANS could be volitionally controlled [35]. They demonstrated, through a series of articles, that responses such as blood pressure, blood flow, cardiac functioning and intestinal activity could to some extent be voluntarily managed. This led to other researchers demonstrating the same results on human beings. The works of Basmanjian [4] and Kamiya [26] are good examples of early human biofeedback experiments.

Biofeedback evolved from a research field into a clinical practice and eventually the term clinical biofeedback was coined [39]. Clinical biofeedback is defined by [39] as a type of operant conditioning wherein, with the help of a trained therapist, an individual can learn to control specific physiological functions by changing the thoughts and perceptions that produce them. Changing the mind state of the individual requires that several physiological parameters are electrically measured and presented in a comprehensible way. Today, clinical biofeedback is a well-recognized tool for self-regulation and stress relief. According to the Mayo clinic (one of the largest integrated medical centers in the world), biofeedback is a complementary and alternative medicine technique for treating more than 100 illnesses [33]. In contrast with clinical biofeedback that requires clinical setup and a coach to facilitate the subject's awareness of their physiological functions, we formalize the concept of Ubiquitous Biofeedback (U-Biofeedback): a system that utilizes software tools to provide continuous and long term management of physiological processes. Such systems are typically part of the user environment or worn on the subject's body. They do not require the user to attend clinical sessions in order to benefit from biofeedback techniques. Moreover, U-biofeedback systems can implement automated response techniques that guide individuals through a procedure aimed at controlling their physiological parameters.

The biofeedback research, from an engineering perspective, comprises the design, development, and testing of smart and precise instruments that measure physiological activities such as brainwaves, heart functions, breathing, muscle activities and skin temperature, and generate an appropriate feedback response. The biofeedback system adapts the ambient environment or provides multimedia contents to trigger the user's mind, which eventually tunes the physiological parameters to optimize the body's performance. The biofeedback system should be able to detect, for instance, when a user is suffering extreme stress and present her or him with appropriate multimedia contents (or manipulate the ambient environment) as a stress relief response.

1.2 Biofeedback loop (mind-body loop)

Humanistic psychology emphasizes the unity of body and mind. Biofeedback takes this emphasis to a completely new dimension to create a mind-body medicine. The mind-body relationship can be formulated as follows: "Every change in the physiological state is accompanied by an appropriate change in the mental-emotional state, conscious or unconscious, and conversely, every change in the mental-emotional state, conscious or unconscious, is accompanied by an appropriate change in the physiological state" [19]. This concept is demonstrated in Fig. 2.

Biofeedback is a closed loop feedback system in which information taken from the human body is translated into a language perceivable by any of the human senses. The loop begins with the human body, which is connected to a biomedical sensor(s). The sensor reads the body's energy and converts it to an electric signal (after being conditioned—such as filtered or amplified). The electrical signal is then interpreted and converted to a recognizable stimulus and then relayed back to the individual through one of the five senses. Once the biofeedback information is consumed by the human brain, a change in the mind state will occur, which stimulates a change in the human physiological state, and the cycle starts again. A high level of body-mind synchronization strengthens and builds harmony within the individual and eventually results in a higher level of wellbeing.

1.3 Types of biofeedback devices

Traditionally biofeedback devices have been classified as stationary versus mobile, wired versus wireless, analog versus digital, and binary versus proportional. For instance, some

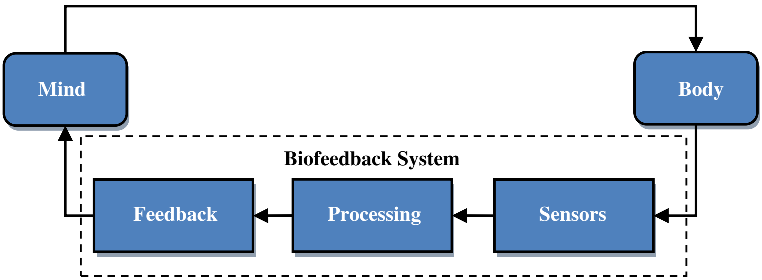

Fig. 2 The biofeedback loop (body-mind loop)

devices are small and portable that can be implanted onto the human body or be held in the hand, while others involve large instrumentation in a wall unit. Wired devices use a wired medium (such as copper wires or fiber optic cables) to communicate the biofeedback information to the computing system whereas wireless devices use the air interface as the communication medium (such as Bluetooth, infra-red, and Zigbee technologies). Analog devices generate analog signals whereas digital devices generate digitized information. Finally, binary devices provide on/off information about a particular physiological parameter whereas proportional devices reveals the amount of changes occurring for a particular physiological parameter [44].

The generally accepted classification is that biofeedback devices fall into two categories: binary and proportional [44]. A binary device informs the individual only whether he or she is controlling a specific physiological function or parameter. For example, a biofeedback device aimed at correcting the body posture would measure the neck curvature and a light goes on when a threshold is surpassed (unhealthy body position), and goes off when the curvature is less than the threshold (a safe body stand). On the other hand, proportional biofeedback provides the amount of change in a particular physiological attribute. For instance, a biofeedback device would measure the heart rate and display that information to the user via a gauge or a digital display. Because it provides more information to the user, proportional biofeedback is thought to be more effective in terms of coaching users on how to control their physiological parameters.

1.4 Biofeedback applications

Biofeedback has been researched extensively to facilitate treatment for a wide variety of illnesses and regenerative therapies such as migraine in both adults and children [43], cardiovascular disorders, hypertension, anxiety and duodenal ulcers, and in many cases the results obtained have been notably positive [12]. Furthermore, several researches have proposed that respiratory biofeedback training has assisted patients who suffer stutters [29], alleviated panic attacks [10], asthmatic conditions [48], treated hyperventilation syndrome, sleep apnea [3], as well as posttraumatic stress disorder [55]. Furthermore, often, biofeedback complements the use of medication in pain management [14].

Biofeedback may also be used to control the biological responses that are associated with health problems, such as chronically tense muscles due to injuries or accidents, asthma, high blood pressure, and cardiac arrhythmias [14]. Some experiments even demonstrated the effectiveness of biofeedback in controlling autonomic body functions [36]. For examples, researchers in [36] studied 33 subjects, all females aging from 17 to 25, that are divided into two groups: one group was told verbally to decrease their heart rate while running on a treadmill and being monitored on an ECG machine, the other group was told to decrease their heart rate but also were shown the ECG signal as a form of biofeedback. The results showed that participants trained with ECG biofeedback information showed a great degree of control of their heart rate compared to those who were trained with only verbal instructions.

2 A reference model for U-biofeedback systems

Two branches of the biofeedback field can be defined: clinical biofeedback and U-Biofeedback (see Fig. 3). In this section, we formulate the concept of U-Biofeedback and draw the distinction between this technique and classical clinical biofeedback. Clinical biofeedback as the name suggests is performed under the supervision of a health practitioner, typically in a clinical

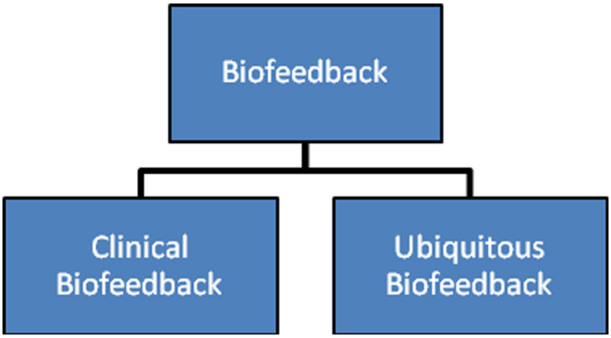

Fig. 3 Branches of the biofeedback field

setting. The subject is guided through exercises where she or he is made aware of key physiological parameters and guided through exercises to control them. These sessions are typically bound by time and the setting in which they are performed (typically a clinic). U-Biofeedback, on the other hand, is a continuous process that is neither bound by time nor setting. For instance, a system designed to monitor mental stress can be activated at any time at work or at another environment where the individual feels that her or his stress level increases. Many studies describing systems that fall under the umbrella of Ubiquitous Biofeedback have been published [15, 18, 30]. Nonetheless, to the best of our knowledge, a reference model for such systems has not been defined. Therefore, in this paper, we will introduce the Ubiquitous Biofeedback reference model, which describes our vision for such applications and standardises the main component that are habitually involved in such systems.

2.1 Awareness process

Biofeedback is like a horse-race track where the starting and finishing points are the same. As shown in Fig. 4, the awareness process begins with the human body (physiology), which is connected to various sensors that measure physiological parameters. The captured data is fed to the Signal Processor component that performs various signal conditioning activities

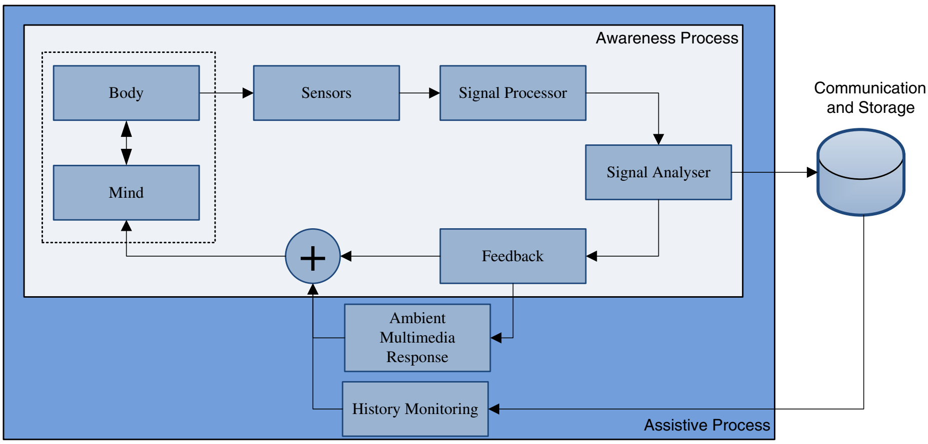

Fig. 4 U-biofeedback reference model

and forwards the processed information to the Signal Analyser. The Signal Analyser implements algorithms to analyse the collected data and compute the response strategy. The drawn conclusions are communicated back to the human mind through the feedback component (via one of our five senses). Finally, the mind stimulates the body and the loop starts over again.

All captured information is stored in a data repository for short and long term trend analysis. Furthermore, the collected data can be optionally communicated to a remote system for health monitoring or statistical analysis by interested researchers.

2.1.1 U-biofeedback sensors

A sensor is an instrument that converts a physical phenomenon into an electrical signal. The types of sensors that can be used for U-Biofeedback applications are identical to the ones employed in health monitoring systems. They are typically worn directly and noninvasively on the body. They can also be embedded into clothes, eyeglasses, belts, shoes or wrist-watches [13]. These sensors are in charge of continuously performing measurements on features describing the physiological state or movement of a human body [13]. Reference [38] provides a good overview of wearable medical sensors.

2.1.2 Signal processor

The signal processor component is responsible for performing different types of signal conditioning actions on the acquired sensory data. Examples of signal processing algorithms include, but not limited to, signal filtration methods, amplification, multiplexing, isolation, and linearization. Signal filtration removes unwanted components from the signal that is being measured. Signal amplification, a very common chore undertaken during signal conditioning, is used to increase the resolution of the signal and reduce the noise levels. Signal multiplexing is needed for measuring several signals with a single measuring device (for example when several biofeedback signals are read simultaneously into the biofeedback system). Another common task executed during signal conditioning is the isolation of the sensory signal from the computer for safety purposes. Finally, many biofeedback sensors have a nonlinear response to changes in the phenomena being measured and thus should be corrected to a linear behaviour (known as linearization).

2.1.3 Signal analyser

The Signal Analyser component has the distinct responsibility of making sense of the collected sensory information. It is thus in charge of analysing the physiological state of the individual being monitored. For instance, if a subject is being continuously examined for elevated stress levels, the Signal Analyser would be pouring over information reflecting the status of the user's ANS in order to assess the stress situation.

Signals collected by sensors are functions of time. A time domain signal expresses how its amplitude changes over time. Habitually, a time domain analysis of such signals can reveal an enormous amount of information regarding the state of a subject. For instance, to measure the heart rate from an ECG chart, a time domain examination of the signal is required. On the other hand, in some situations, frequency domain analysis renders valuable information that might be otherwise hard to unearth in a strict time domain investigation. Simply put, a frequency domain examination of a signal illustrates how often its amplitude changes over time. For example, many important Heart Rate Variability (HRV) parameters of an ECG signal can most effectively be measured in the frequency domain. Such parameters are important in assessing the level of fatigue and mental stress of an individual being monitored. The topic of HRV will be later discusses in more details. Sometimes researchers resort to time-frequency analysis where a comprehensive study of the signal is performed in both the time and frequency domains simultaneously [40].

For prolonged monitoring activities, a considerable amount of data is usually collected. Combing through the enormous amount of information can be a tedious task even for the fastest computing devices. Good care is usually taken to filter out unwanted records while data mining techniques can be employed to find important events [27].

2.1.4 Feedback

Feedback is the process by which a user is made aware of her or his physiological status. This is an essential part of the biofeedback loop where all collected and analysed information are fed back to the user. The ways in which the information is fed back are countless and can make use of conceivably any or a combination of the subject's senses. For instance, for a simple application that makes a subject aware of her or his heart rate, the type of feedback can range from a simple interface showing the number or heartbeats per minute on a visual display to a complex multimedia system showing a 3D graphical representation of a heart beating with auditory effects.

2.2 Assistive process

It is during the assistive process that the U-Biofeedback model diverts from the classical biofeedback process represented in Fig. 2. During this process, the user is assisted in modulating her or his internal processes to achieve a higher level of wellbeing. This goes beyond the simple feedback reflecting physiological information and into helping the user adjust detrimental physiological or psychological situations. Also, this process is concerned with allowing the user to monitor short and long term progress achieved during the use of the U-Biofeedback system.

2.2.1 Ambient multimedia response

In order to provide external assistance to the mind in controlling the body, the biofeedback system extends the awareness model by proposing an assistive component: the Multimedia Response (as shown in Fig. 4). The Multimedia Response component is accountable for aiding the user in manipulating her or his physiological or psychological parameters. For instance, in a stress management application, instead of simply informing users that they are stressed through a feedback module, the system attempts to guide them through relaxation exercises. Perhaps, it can also manipulate the ambient environment by changing light intensity, playing music, displaying multimedia content or even opening or closing a window etc.…

2.2.2 History monitoring

The use of biofeedback tools usually takes place over a period of weeks or months. Therefore, a mechanism offering a historical view of psychological or physiological information measured directly or deduced from measurements over time is required.

For instance, if a U-Biofeedback system is used for stress management, a method that allows the user to review previously measured stress indicators with different levels of granularity can be of great benefit. Using a coarse grained historical review allows the user to examine which days, weeks or even months have been less (or more) stressful and therefore question what factors contributed to that situation. Analysing the source of stressors might enable the user to avoid or cope with certain stress inducing situations. A more granular assessment allows the user to evaluate which hours of the day are less stressful. Such functionality would likely manifest in the form of graphs expressing various physiological or psychological parameters with respect to time. Also, such form of historical monitoring enables the user to perform trend analysis to assess whether the monitored physiological function has improved over time.

2.3 Guidelines for U-biofeedback application development

The following are proposed guidelines for U-Biofeedback systems design and development:

1. The data acquisition devices should continuously capture physiological information without disturbing the daily life of the subject. The sensory devices should be very lightweight in the case they are wearable to minimize the burden they might create;
2. The U-Biofeedback system should be able to perform in a completely autonomous way (have the ability to be fully automated);
3. The U-Biofeedback system must perform over a long period of time (in the order of days, weeks, or months, rather than hours or minutes);
4. The U-Biofeedback system must capture one or more physiological parameters that reflect the status of the body performance; capturing more parameters can potentially increase the accuracy of the system;
5. The U-Biofeedback system must ensure data confidentiality;
6. The U-Biofeedback system must be able to log and store information for long periods of time (may utilize data compression/reduction techniques).

3 Proof of concept: U-biofeedback stress management application (SMA)

This section presents the Stress Management Application (SMA) as an example U-Biofeedback system. The SMA is intended for office employees who are interested in detecting potentially perilous stress manifestations. Not only would the SMA detect such stress events, but also assist the user with a corrective action. This is achieved as follows (Fig. 5):

1. Sensors, worn on the body of the user, relay relevant physiological information to a computing device (in this case, the employee's own work computer or nearby computing device)
2. At the computing device, a local program running the Signal Analyzer and Signal Processor modules processes the received data and devises a Feedback and Multimedia Response
3. The Feedback and Multimedia Response are conveyed back to the user through multimedia display devices

In the next section of this paper, we will discuss the development and evaluation of the proposed SMA. But before we delve into the aforementioned topic, we will introduce the subjects of stress and Heart Rate Variability (HRV). HRV is the physiological measure that will be using to assess stress. Also, we will present the results of an in lab experiment we performed to validate our measurement method and the effectiveness of our stress analysis so that we can better design a long term stress management system.

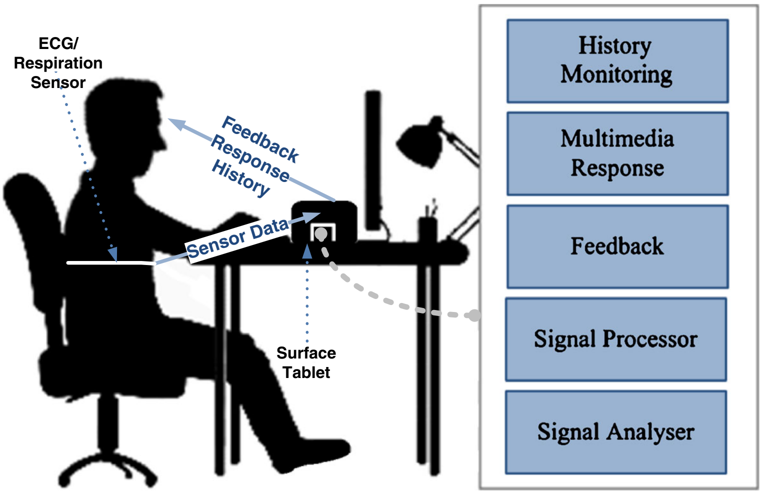

Fig. 5 Stress management application

3.1 Stress and consequences

Stress has been the topic of numerous research endeavours, yet investigators still have to agree on a well-established definition for this concept [45]. In general, stress is an innate response to an environmental threat or psychological distress that triggers chemical and hormonal reactions in the body [2]. Reference [16] provides a classification of stressors based on duration and course. It defines five categories of stress:

1. Acute time-limited stressors involve temporary periods of nervousness brought upon various exercises such as public speaking or mentally challenging problems. Such stressful stimulus can be typically instigated in a controlled manner in a laboratory setting in order to monitor various physiological effects.
2. Brief naturalistic stressors are ones that occur naturally in a person's environment. Typical examples include an academic examination or a job interview.
3. Stressful events sequences pertain to traumatic events that might create additional stressors. The loss of a loved one for instance is an example of such stress.
4. Chronic stressors alter a person's identity or social role. Such stressors are characteristic by their stability. That is, the person is completely unaware when the challenge will end or acknowledges that it will never end. Stress triggered by a life changing disability or illness falls under this category.
5. Distant stressors are generated by past distressing events that continue to negatively affect the immune system because of long-lasting cognitive and emotional effects [5]. Examples of such stressors include child abuse and war trauma.

The American Institute for Stress lists 50 common signs and symptoms of stress ranging from headaches to heart palpitations [1]. Perhaps the difficulty with defining stress is exasperated by its subjective nature; it is indeed a phenomenon that differs for each individual [1]. There are various disorders that have been linked to stress. Heart attacks [52], depression [53], immune system disturbances [45], migraine [28] and vertigo attacks [47] are just few examples of such disorders. Creating a complete list of stress related ailments would be a very exhaustive endeavour due to its sheer size. Nonetheless, that highlights the importance of studying stress and exploring methods to effectively reduce its potential harmful effects on our wellbeing.

3.2 Stress relief biofeedback

Some of the most basic and efficient biofeedback systems are already built into our bodies. For instance, we can often sense tension during stressful periods. It is the body's natural response. In fact, listening carefully to our bodies can offer us a plethora of information regarding our mental and physical state. Nonetheless, enrolling the help of electronic sensors' based biofeedback systems allows for the detection of subtle and rapidly changing signs of stress that can sometimes go unnoticed without such assistance. One of the earliest electronic biofeedback systems employed for psychotherapy is introduced in [9]. The aim is to reduce tension headaches through a biofeedback supported relaxation technique. EEG sensors are used to measure the alpha waves which are more pronounced during wakeful relaxation. Auditory feedback is used to indicate the level of alpha waves and thus direct patients to increase relaxation. The same authors later developed a system based on multiple sensory feedbacks (galvanic skin response and skin temperature) [8]. Reference [17] demonstrates the effectiveness of biofeedback-aided relaxation in comparison to traditional relaxation methods. The study makes use of GSR2 biofeedback device from Thought Technology Ltd. [51] to measure stress level and of the Benson relaxation technique [6] for stress relief. Other commercial solutions have been introduced. For instance, Heart Wizard presents products to track a subject's stress level (stress monitor) and to direct the subject through relaxation exercises (stress sweeper) [21]. It is worth mentioning that several other commercial products claim to provide biofeedback based stress relief, nonetheless, in many cases, to the best of our knowledge, the scientific basis for these systems has not been presented in peer reviewed publications nor the validity of the claims has ever been independently verified.

3.3 Heart rate variability and stress

Assessing stress level using non-invasive techniques is no easy feat. Since we experience and cope with stress differently, it is difficult to compute a universal index that indicates when a person is stressed, and how stressed they are. In this paper, we focus on a well known approach to detecting stress that makes use of Heart Rate Variability (HRV). HRV refers to changes in the time intervals between successive heart beats. The usefulness of such measurement was first demonstrated in [23] when the authors discovered that a decrease in HRV was associated with fetal distress. Perhaps, the importance of the HRV measurement stems from being a reflection on the ANS. The ANS is an important part of the nervous system that non-voluntarily acts as a controller for all the organs of the body, including the heart. Two branches of the ANS collaborate to regulate the body organs: the Sympathetic Nervous System (SNS) and the Parasympathetic Nervous System (PNS). The latter stimulates the organ's functioning while the last inhibits it. Together, they achieve the balance needed for an efficient organ functioning.

The idea of assessing HRV parameters in order to induce conclusions regarding the mental state of individuals has been the subject of many papers. For example, reference [13] made use of HRV measure to examine the psychophysiological effects of mental workload in single-task and dual-task human-computer interaction. Several other papers focused on the effectiveness of HRV analysis to monitor mental stress in individuals [7, 11, 20, 22, 25].

When it comes to HRV parameters, numerous time and frequency domain measurements have been used to extract useful information from an HRV signal. Note that an HRV signal is computed as a series of intervals between heart beats, or what is referred to as R-peaks (see Fig. 6). (On an ECG graph, the peak of electrical activity, which coincides with the beating of the heart or more specifically the rapid depolarization of the left and right ventricles, is called the R-peak.) These intervals are commonly referred to as NN intervals (period between two normal heart beats). Reference [49] provides a comprehensive list of such measurements. In the time domain, the standard deviation of an HRV signal is denoted as SDNN, which stands for Standard Deviation between NN intervals. SDNN is the most commonly measured parameter time domain. A decreased SDNN value has been associated with "lowered coping ability to various emotional/physical stressors" [34]. SDNN has also been used to assess acute stress levels for individuals [42]. Nonetheless, frequency domain based approaches for detecting stress received more attention from researchers [7, 11, 20, 22, 25]. Perhaps the main reason is that specific frequency bands have been associated directly with components of the ANS [32]. These methods rely on the estimation of the power spectral density (PSD) of an HRV signal and retrieving specific frequency bands that are known to reflect the ANS status. Three major power bands have been generally recognized:

- Very Low Frequency (VLF): 0.003 to 0.04 Hz
- Low Frequency (LF): 0.04 to 0.15 Hz
- High Frequency (HF): 0.15 to 0.4 Hz

Two commonly accepted durations of measurement exist: long term (24 h) and short term (3 to 5 min). The significance of the VLF band in short term measurements is still widely debated and mostly undefined [49]. While the topic of HRV is still somewhat of a controversial one in the medical community, there is general consensus about few important factors. For instance, the HF band has been closely associated with parasympathetic activity [32]. On the other hand, the LF band has been found to contain both sympathetic and parasympathetic components [32]. The LF/HF ratio has also been linked to the balance between sympathetic and parasympathetic nervous branches [32]. Numerous studies have found a significant decrease in HF component and an increase in the LF/HF ratio during stressful situations [7, 11, 22, 32, 41].

Detecting stress in individuals always relies on one essential factor: history. It is almost impossible to take one physiological measurement, whether it is blood pressure, HRV, or skin conductance (all of which have been used to assess stress [20]) and conclude that a person is stressed. Let alone analysing how stressed is the person. All measurements are compared to previous ones. A straight forward approach would base the assessment on

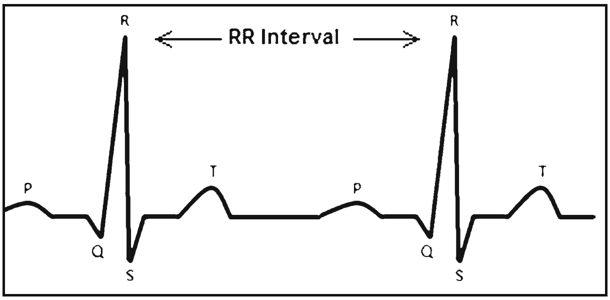

Fig. 6 Typical ECG signal of health heart

previous measurements collected during a period where the subject was not under a considerable amount of stress. The new measurement would then be compared to these previous ones and a conclusion would be inferred.

As per the above discussion, the relationship between HRV and mental stress has been well documented. Nonetheless, the works presented in [7, 11, 20, 22, 25, 32, 41] were all intended to collect HRV measurements for later offline analysis. None produces online conclusions regarding the stress status of subjects. On the other hand, the SMA presented in this paper aims at achieving the following:

- Detecting stress events online using a flexible algorithm that can be customized by the user
- Providing an easy way to visualize HRV parameters
- Providing a reference that describes the relationship between the measured stress parameters and the ANS

3.4 Lab experiment

We have conducted an in-lab experiment on subjects to monitor the changes in their HRV parameters during stressful situations. The experiment is needed to assess the validity of our setup (composed of a program performing real time measurements and an ECG sensor). More importantly, while many papers cover the topic of mental stress and its effects on HRV, various factors can affect the values obtained for the frequency domain parameters (sampling rate and PSD method). Therefore, it is important to establish a baseline for our configuration that can be used as a basis for developing the real time stress detection algorithm. Therefore, the goals of this activity can be summarized as follows:

- Verify the validity of our measurement method by comparing the HRV results with a subjective assessment of the stress status of individuals
- Using the results of the experiment, conceive a automated method to detect whether a subject is experiencing a stressful situation

In order to perform the experiment, we implemented a Java based computer program that receives a string of NN intervals, appends them into a continuous HRV signal and calculates some time domain and frequency domain parameters. These calculations are done on 3 min worth of HRV data. The ECG measuring device is BioHarness from Zephyr [54]. The device is composed of an electronics module and a Smart Fabric garment that is worn comfortably on the torso (see Fig. 7). It samples the ECG data at 1 KHz, which surpasses the minimum recommended sampling rate (250 Hz) for accurate HRV signal calculation [49]. The device is also capable of measuring the respiration rate with a sampling frequency of 25 Hz. Five HRV parameters are of interest:

- Standard Deviation of HRV signal (SDNN)
- Heart Rate (HR)
- Low Frequency band of HRV Power Spectrum Density signal (LF)
- High Frequency band of HRV Power Spectrum Density signal (HF)
- Low Frequency to High Frequency ratio (LF/HF)

Figure 8 depicts the steps involved in extracting the aforementioned parameters from an HRV signal using a non-parametric PSD estimation algorithm for the frequency domain components. The HRV signal processing operation can be summarized as follows:

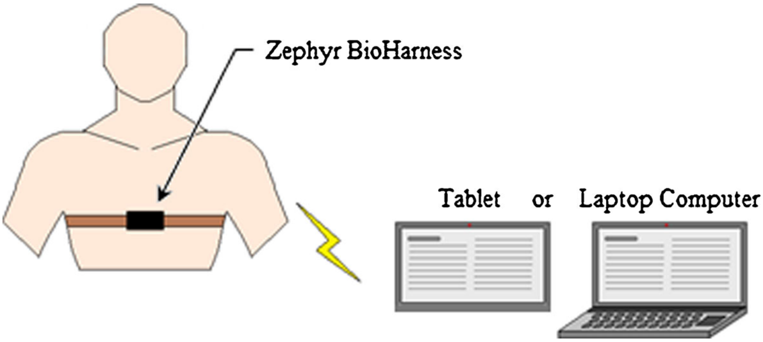

Fig. 7 HRV monitoring setup

1. Compose HRV signal
2. Remove NN intervals that differ by more than 30 % from their predecessors in order to clean out possible artifacts
3. Calculate the time domain HRV parameters
4. Resample the HRV signal at 4 Hz using the cubic spline method so that it can be represented with respect to time (Fig. 9)
5. Calculate Power Spectral Density (PSD) of signal using Welch's periodogram (window size of 256 with 50 % overlap)
6. Calculate the frequency domain HRV parameters

The lab experiment is composed of three sessions: control, stress and rest. For the control and stress sessions subjects are asked to complete a math computer based exercise. For the rest session, subjects are asked to relax and not perform any task. The math exercise consists of a series of multiplication questions that should be answered within a time limit (see Fig. 10). In the control session, a 7 s period is given for every question. In the stress session, the exercise is made considerably harder since only 2 s are allocated for each question. The participants are informed that the control session serves as an introductory exercise while the stress session is a test of their knowledge and skill. Each session is 3 min long. A break of 30 s is given between sessions during which the subject is asked to rate the following

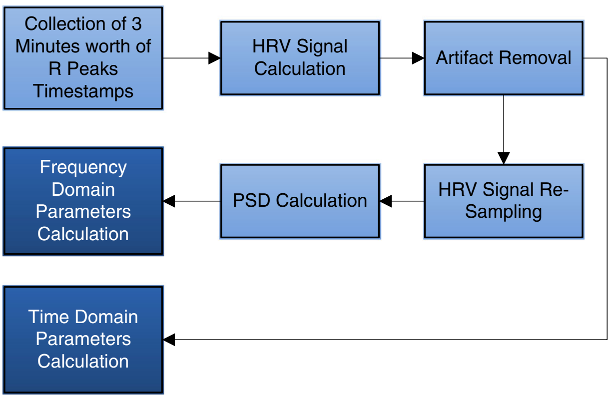

Fig. 8 HRV signal processor

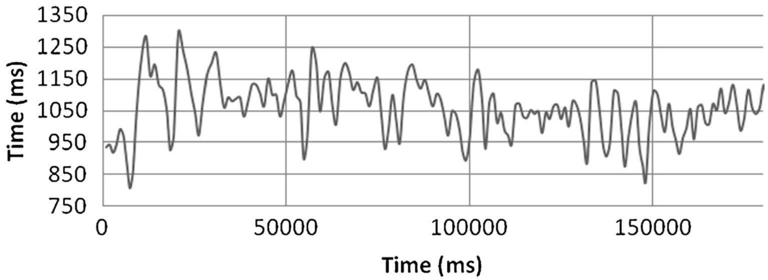

Fig. 9 An example of a resampled HRV signal

emotions on a scale of 0 to 5 (with 5 being the most intense) (see Fig. 11): stressed, nervous, happy, angry and bored.

Five consenting adult subjects participated in the experiment, 3 males and 2 females, with an average age of 31.6 (12.8) years and average weight of 71.8 (11.3) kg. Subjects were seated in front of a computer desk on an adjustable office chair with arm rests. The results of the HRV measurements and subjective emotional assessments are displayed in Tables 1 and 2 respectively.

The results of the experiment came in as predicted and documented in previous studies [7, 11, 22, 32, 41, 42]. On average, in the time domain, an increase in the Heart Rate (HR) and a decrease in SDNN are observed. Also, on average, in the frequency domain, a decrease in HF, an increase in LF/HR is evident. Figure 12 shows an example of the PSD curves calculated during the control and stress sessions for subject 4. These results are reflected in the subjective assessment where an increase in stress, nervousness and anger is reported in various degrees during the stress session. Now that we have established the correlation between our HRV analysis and subjective assessment and thus have verified our measurement method, our next goal is to establish a reliable method to automatically detect mental stress.

To achieve the aforementioned goal, our first instinct was to develop a stress index that would metrically indicate the amount of stress a subject is experiencing. Nonetheless, after careful analysis of our results, we decided against it for the following reasons:

- The pertinent HRV parameters reflect different properties of the ANS. No single property is more or less important than the other, and therefore, it can be counterproductive to allocate relevant weights to the various pieces of data being collected when it comes to determining a definite stress index.

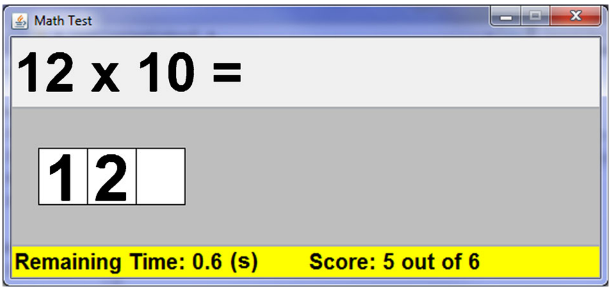

Fig. 10 Math exercise graphical user interface

Fig. 11 Sequence of experiment sessions

- Summarizing all the information into a single index would render the stress assessment operation hidden from the user. In our opinion, one of the focal goals of biofeedback is to relay as much information as possible to individuals regarding their psychophysical status and thus better acquainting them with their bodies. Nonetheless, users should not be overwhelmed with huge amounts of data that they cannot process or understand. A careful balance must be established to relay just the right amount of information.
- Such index could not be universal. This means that it can be not be compared between different individuals. That is if subject A experiences a stress index of x and subject B registers a stress index of y. If x > y, it does not necessarily mean that A must be more stressed that B. We identify two main reasons for such conclusion: First of all, HRV measurements reflect far beyond than the mental stress status of the individual and therefore many factors come into play like age, weight, medical history, etc. Second of all, stress is a very subjective experience; every individual perceives it and copes with it differently.

Therefore, any application in charge of monitoring stress levels should be flexible, customizable and highly personalized. The next section presents our approach to stress management using an HRV monitoring application. The application is intended to monitor stress situations for office workers and to alert them when out of the ordinary stress levels are detected. It also assists them in diffusing their stress through a simple relaxation exercise. Its architecture is a faithful implementation of the U-Biofeedback reference model.

3.5 Stress management application (SMA)

The program is implemented in a Java 7 environment running on the Microsoft Windows Platform and makes use of the Zephyr BioHarness device for ECG measurements. The program was tested for compatibility on a Windows 8 Surface Tablet and Windows 7 PC. The architecture of the program is displayed in Fig. 13. Also, the application follows the U-Biofeedback reference model by implementing its various components (signal processor, signal analyser, feedback, history and multimedia response modules). The HRV processor module implements the algorithm provided in Fig. 8 with 50 % overlap between the measurements.

The objective of a typical biofeedback system is to give subjects insights into the inner workings of their bodies so that they can remedy unhealthy patterns. In order to achieve this goal, an understanding of what the biofeedback device is measuring and what is the significance of these measurements is important. The idea is that such knowledge is vital for the active participation of subjects in the biofeedback process. Consequently, the system operates in three phases. The first phase in the system operation is the User Education (UE). In this phase, the user acquires the necessary knowledge to adeptly use the SMA. The learning material covers the following topics (see Fig. 14):

- Introduction to ANS and an exploration of its two branches (PNS and SNS)
- Explanation of the significance of HRV and its relation to the ANS
- Most importantly, the significance of the HRV parameters the SMA measures:

Table 1 In lab stress experiment HRV results

Subject number	Control session					Stress session					Rest session				
	LF[a]	HF[a]	LF/HF	HR[b]	SDNN[c]	LF[a]	HF[a]	LF/HF	HR[b]	SDNN[c]	LF[a]	HF[a]	LF/HF	HR[b]	SDNN[c]
1	1833	488	3.76	70	41	1944	468	4.15	81	30	1672	511	3.27	79	39
2	6619	5144	1.29	65	72	6652	3509	1.90	72	57	3485	3079	1.13	72	62
3	37109	17351	2.14	60	153	14794	4966	2.98	67	93	18789	9077	2.07	63	118
4	8708	9895	0.88	64	87	7594	4332	1.75	73	75	20586	11981	1.72	66	128
5	1966	1034	1.90	85	30	2276	873	2.61	90	32	3214	1180	2.72	86	38
Average	11247	6782	1.99	69	77	6652	2830	2.68	77	58	9549	5166	2.18	73	77
STDEV	14760	7013	1.10	10	48	5208	2043	0.97	9	27	9302	5090	2.03	9	43

[a] Expressed in ms^2

[b] Expressed in ms

[c] Expressed in heart beats per minute

Table 2 In lab stress experiment subjective results

Subject number	Control session					Stress session					Rest session				
	S	N	H	A	B	S	N	H	A	B	S	N	H	A	B
1	2	2	3	0	0	5	4	1	3	3	2	1	1	1	1
2	1	1	4	0	0	2	1	4	1	0	0	0	4	0	0
3	3	3	2	0	3	3	4	1	0	2	1	1	1	0	1
4	2	3	4	0	0	3	2	3	4	0	1	1	4	0	0
5	1	3	2	1	0	3	4	0	2	0	1	1	3	0	2
Average	1.8	2.4	3.0	0.2	0.6	3.2	3.0	1.8	2.0	1.0	1.0	0.8	2.6	0.2	0.8
STDEV	0.8	0.9	1.0	0.4	1.3	1.1	1.4	1.6	1.6	1.4	0.7	0.4	1.5	0.4	0.8

S Stressed, *N* Nervous, *H* Happy, *A* Angry, *B* Bored

- HF is associated with PNS (therefore an increase in HF signifies an activation of the PNS and a decrease implies the opposite)
- LF/HF is associated with the balance between SNS and PNS (therefore an increase in LF/HF signifies a dominance of SNS over PNS, while a decrease indicates the opposite)
- HR indicates the number of heart beats in a minute and can be increased by various factors and most prominently mental stress
- SDNN is associated with the general health of the ANS as it reflects all the sympathetic and parasympathetic components

The information is displayed using a sequence of dialog boxes that lead the user through a series of learning steps. The learning material is a multimedia combination of text, images and videos. The user can move back and forth between the dialog boxes to review information previously learned. It is assumed that the user does not have any prior knowledge on the topic and therefore information is presented in an easy to grasp manner. After having learned what the significance of every parameter being measured, the user can move to the next phase.

The second phase is the System Training (ST). The system takes measurements of the user physiological data over a certain time period. This process is expected to run for at least 8 h (not necessarily continuously) during which the user is performing non-stressful tasks (mundane work assignments). The objective is to establish enough benchmark data regarding the expected parameters for a particular subject during non-stressful times. All these

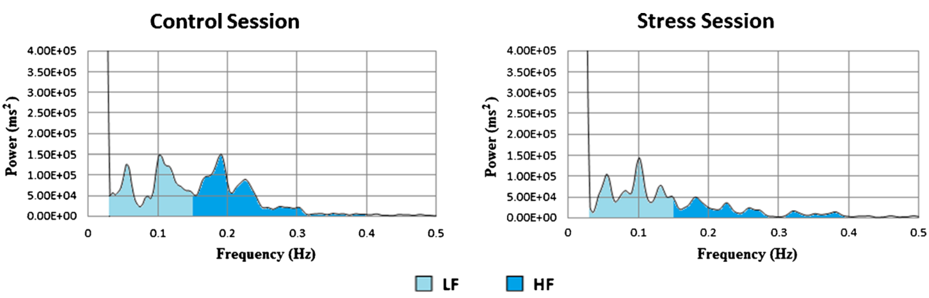

Fig. 12 PSD curves of subject 4 during the control and stress sessions

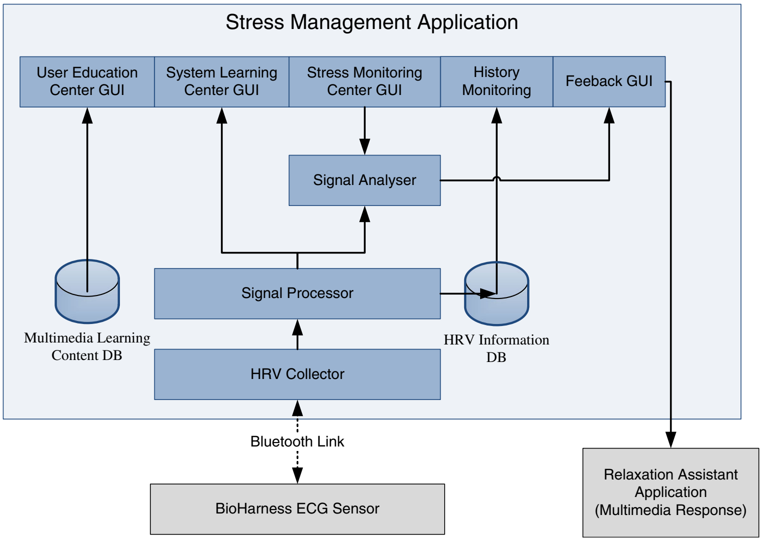

Fig. 13 Stress management application architecture

measurements are saved in the HRV Information DB. This phase does not have to be performed in one session, but can be accumulated over an unlimited amount of sessions in order to gather enough training data.

Figure 15 shows the ST phase GUI. A Color Coded Bar (CCB) is allocated for each parameter (HF, LF/HF, HR and SDNN). Note that the LF parameter has been dropped since it is not known to reflect stress levels on its own. The green color at the center of the CCB symbolizes the mean value of all stored instances of that particular parameter. Colors on the CCB change gradually from green to red to symbolise the distance of a measurement from

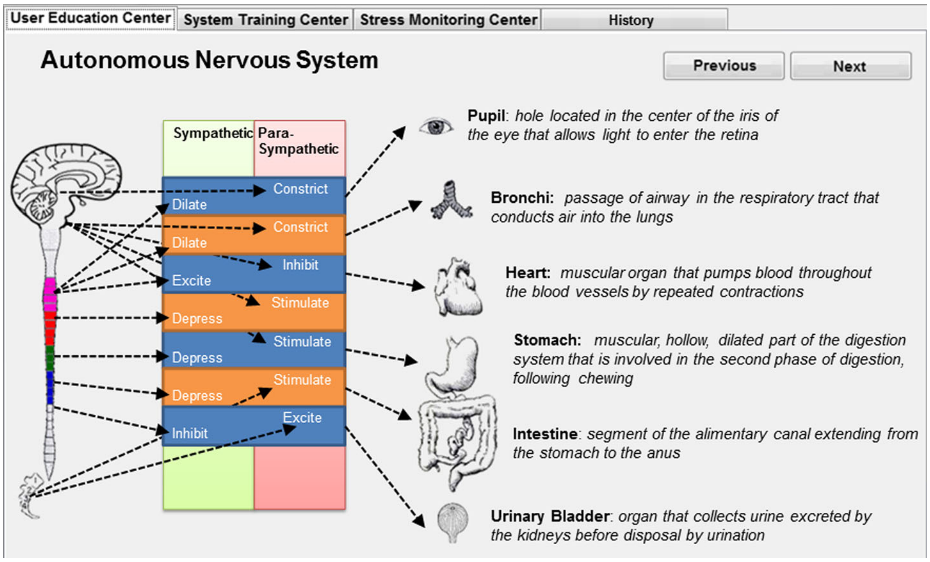

Fig. 14 SMA user education interface

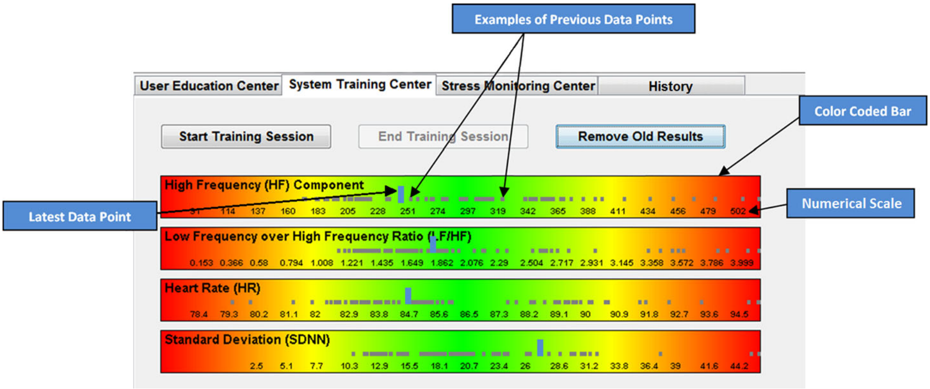

Fig. 15 SMA system training phase interface

the mean. A numerical scale is then superimposed over the bottom of the CCB, with the mean being at the center. The resolution of the numerical scale is calculated in a way to accommodate all previously collected data points (which are displayed as gray dots on the CCB). Every time a new measurement is collected, the CCB is redrawn so that the mean value falls exactly at its center. Every time a new data point is collected, it is displayed graphically as a blue indicator on the CCB.

The third and final phase in the system operation is the Stress Monitoring. This is the biofeedback phase where the user would be warned during stressful periods in order to adjust her or his behavior and therefore gradually learn to better manage stress on the long run. The user is shown the data collected during the training phase as a series of gray dots on the CCB. The system automatically chooses a Normal Values Range (NVR) for each parameter. In Fig. 16, the NVR is shown as the non-darkened part of the color coded bar. The default NVR is selected to comprise all the training data points. The user can modify these ranges at any time using the computer mouse. The idea is that when certain percentage of measurements (50 % was chosen) fall out of range for a preselected period of time (15 min was set), then the person is judged to be under stress. A measurement is judged to be out of range if at least one of the parameters being monitored falls outside of its NVR. The user is also given the choice of disabling any of the parameters so that the system no longer monitors them. The GUI allows users to observe from time to time each parameter in order to see how their daily activities affect

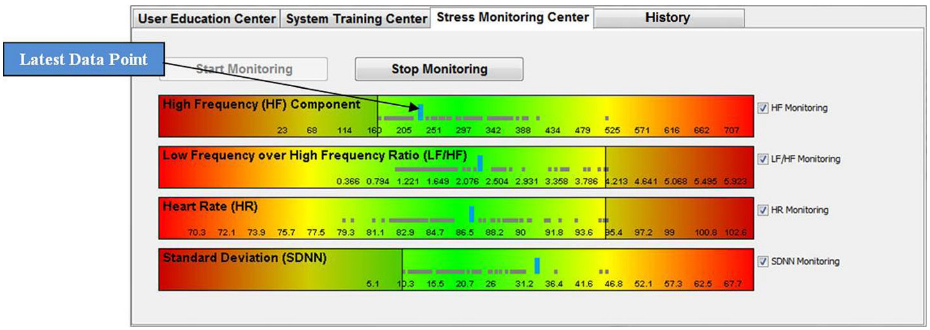

Fig. 16 SMA stress monitoring phase interface

them individually. All the HRV parameters collected during the monitoring activity are stored in the HRV Information DB and appended graphically to the training data. The (SMA) judges a stress situation using the HRV Signal Analyser algorithm presented in Fig. 17.

In addition to the aforementioned functionality that compose the awareness process, the SMA allows, as part of the assistive process, users to review previously measured HRV parameters through the use of automatically generated Comma Delimited Values (CSV) files. The files are generated for a user-defined time period and granularity. The CSV format is readable by many spreadsheet software tools and thus simplifies the process of generating graphs out of the contained information. Nonetheless, in future iterations of SMA, we plan on integrating the graph generation functionality within the application itself and thus reducing the steps involved in reviewing history of measurements.

3.5.1 Relaxation assistant application (multimedia response)

As part of the assistive process, when the SMA judges that the user is under stress, a system tray popup (on a Windows 8 platform) prompts the user whether she or he would like to launch Relaxation Application. If ignored, the popup would disappear on its own in 3 min.

The Relaxation Application randomly loads one of 5 available videos that guide users to perform a deep breathing exercise. The length of the videos ranges from 10 to 16 min. Deep breathing exercises are widely recommended by meditation experts and have been known to help with anxiety and stress [37]. Note that during the deep breathing exercise, the calculation of HF and LF/HF has to be adjusted. During deep breathing, the parasympathetic

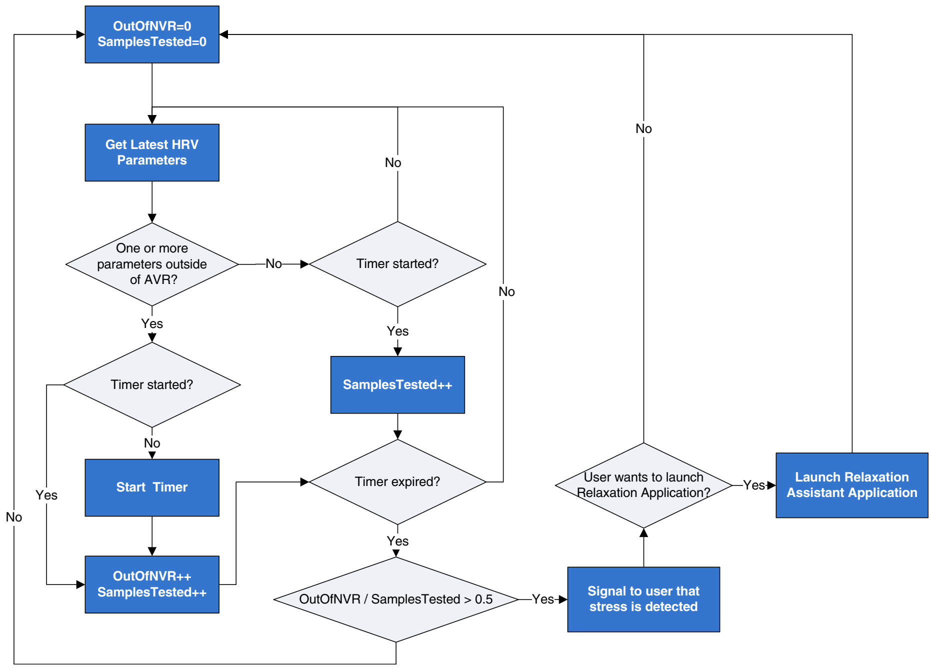

Fig. 17 HRV signal analyser

Table 3 Subjects description

Subject number	Gender	Age (Years)	Weight (Kg)	Duration of use (Days)	Occupation description
1	Female	29	64	16	**Quotes Coordinator:** responsible for presenting quotes for new science start-ups to potential customers.
2	Male	28	85	17	**Graduate Student:** responsible for running lab experiments and evaluating results.
3	Male	26	82	13	**Software Designer:** responsible for writing software modules for a commercial product.

activity shifts into lower frequencies [6]. We therefore used the method proposed in [23] to counter the effects of slowed breathing on the HRV spectrum by taking into account the fundamental respiration frequency (FRF) for the calculation of HF and LF/HF. The FRF is calculated using the respiration rate signal coming from the BioHarness device.

3.5.2 Evaluation

We have evaluated the effectiveness of our stress management program for a period between 13 and 17 days on 3 consenting adult subjects. The subjects were asked to refrain from the following activities for the duration of the experiment: drinking coffee or any other stimulants, consuming alcohol and smoking. A chart of relevant subjects' information is presented in Table 3. All of the subjects spend most of their day sitting in an office chair in front of a desk with a computer screen mounted on top. They perform various tasks on the computer such as viewing and sending emails, reading and writing documents and programming. The SMA, running on an adjacent Surface tablet, would be minimized most of the time, yet they are encouraged to glance at their HRV parameters from time to time. The User learning (UL) task was carried at home outside of work hours. The System Training (ST) phase was performed during the weekend where the subjects took prior permission from their managers to work on favorable and non-stress inducing tasks. This allowed them to choose the tasks they would like to perform without any pressure from their superiors or peers. As for the Stress Monitoring (SM) phase, the measurements were taken during regular work hours. Table 4 shows a summary of subjects' daily use of the SMA. For the length of the monitoring phase of the experiment, users were asked to continuously and subjectively assess their stress levels. They are asked to indicate episodes where they feel the amount of stress they experience can negatively affect their work performance (we assumed this to be the threshold distinguishing between positive and unhealthy stress). Also, whenever the

Table 4 Summary of the daily use of the SMA by the subjects

Subject number	SMA daily use (Hours)																
1	3.0	5.3	4.2	4.1	3.2	5.6	6.1	5.4	5.4	4.2	3.6	3.5	6.2	4.7	5.8	6.0	0.0
3	1.6	4.0	5.0	5.3	1.7	2.9	5.1	7.0	7.2	5.3	4.6	4.6	6.2	4.9	5.4	5.6	1.4
3	2.4	4.0	4.6	3.9	4.3	5.7	4.2	3.9	6.2	6.5	4.3	5.9	0.0	0.0	0.0	0.0	0.0
Days	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Legend:																	
User Learning Phase			System Training Phase					Stress Monitoring Phase					No Daily Use				

Table 5 SMA stress detection results (according to the user subjective assessment)

	Subject 1	Subject 2	Subject 3	Average
Total distinct stress events (identified by user, SMA or both)	9	5	6	6.67
Stress events identified by the user	9	5	5	6.33
Stress events detected by SMA	8	4	6	6.00
Stress events correctly identified by SMA	8	4	5	5.67
Instances incorrectly identified as stress events by SMA	0	0	1	0.33
Stress events missed (not caught) by SMA	1	1	0	0.67
False stress detection rate	0 %	0 %	16.67 %	5.55 %
Stress events detection success rate	88.89 %	80.00 %	100 %	89.63 %

SMA displays a stress warning, they are asked to write down if they agree with the assessment. Table 5 shows a summary of the results based on the subjective user assessment. These results show that 84.07 % of the times, the users agree with the assessment of the SMA. At the end of the experiment, the users filled a questionnaire to rate their experience (see Table 6).

4 Conclusion

As sensory technologies are becoming more cost effective and user friendly, the future of U-Biofeedback is definitely very promising. For instance, the development of miniaturized wireless electrodes makes the task of acquiring ECG data less intrusive and labour intensive. Tiny computers either embedded in clothing or worn by the user in the form of mobile phones can receive data from wireless probes distributed throughout the human body and communicate the results to a remote station via wireless technologies. Furthermore with increasing technological advances in storing and processing a wealth of information captured by the biofeedback system, it is possible to become commonplace for physicians to review patient data gathered from biofeedback devices.

In this paper, we proposed a reference model for U-Biofeedback along with guidelines for such systems. In order to give an insight into the biofeedback analysis and the mind-body loop, we presented a biofeedback stress management case study that makes use of a U-Biofeedback system. In this case study, we presented an HRV based method for mental stress monitoring and have shown how a relaxation response can aid in the stress diffusion process. Our future work includes the improvement of the stress detection algorithm by

Table 6 Questionnaire filled by the subjects at the end of the experiment

	Subject 1	Subject 2	Subject 3
On a scale of 1 to 10 how effective is the SMA as a stress management tool (10 being the most effective?	8	8	9
On a scale of 1 to 10 how efficient was the relaxation manager in diffusing stressful situations (10 being the most efficient)?	6	7	9
On a scale of 1 to 10 how uncomfortable was it to wear the BioHarness device for long periods of time (10 being the most uncomfortable)?	1	3	5

making use of machine learning techniques and the addition of sensors (e.g. skin conductance) to complement the information supplied by the BioHarness device.

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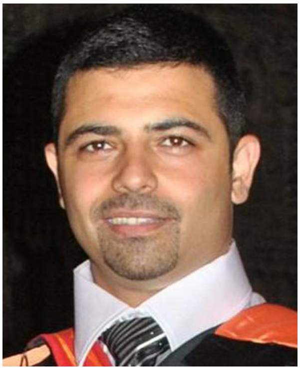

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Abdulmotaleb El Saddik a University Research Chair and Professor in the School of Electrical Engineering and Computer Science at the University of Ottawa, is an internationally-recognized scholar who has made strong contributions to the knowledge and understanding of multimedia computing, communications and applications, particularly in the digitization, communication and security of the sense of touch, or haptics, which is a new medium that is significantly changing the way in which human-to-human and human-computer interactions are performed. He is the director of the Multimedia Communications Research Laboratory (MCRLab) and act as Associate editor of several journals and transactions. Dr. El Saddik has been serving on several technical program committees of numerous IEEE and ACM events. He has authored and co-authored four books and more than 400 publications. He has supervised more than 100 researchers. He is the first Canadian in Computer Science & Engineering to receive the Friedrich Wilhelm Bessel Award from the German Humboldt Foundation. Among his honours are the 2011 Cátedra de Excelencia from Universidad Carlos III de Madrid, Spain and the 2010 I.E. Instrumentation and Measurement Society Technical Award for his outstanding contributions to multimedia computing. He received the Faculty of Engineering's George S. Glinski Award for Excellence in Research (2012) and the IEEE Ottawa Educator Award (2012). He is ACM Distinguished Scientist, Fellow of the Engineering Institute of Canada, Fellow of the Canadian Academy of Engineers and Fellow of IEEE.