Supporting Self-Reflection in Everyday Life

An exploratory review of physiological input methods for the Affective Health system

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This thesis corresponds to 20 weeks of full-time work .

Summary. Today's fast-paced modern life motivates a need for tools and devices that support people in dealing with stress by helping them to control their daily behaviours. There is a variety of emerging applications that track physiological data from the body associated with stress over periods of time by using biosensors. However, most of them remain purely monitoring devices made to diagnose or warn users when they become sressed. We are projecting *Affective Health*, a mobile system designed to enable users to make a connection between the data from their body and their own subjective memories and experience, over the course of daily activities. To facilitate this connection, we propose a representation of the physiological data mapped on three common sense concepts: *physical activity*, *arousal* and *adaptability*. While the first two were previously tested in a similar system developed by the research group, *adaptability*, which represents the ability of the body to cope and recover from stress, had yet to be mapped to consistent physiological input in order to have meaning both in terms of its relation to stress and to end-users.

The intended continuous usage of the system poses challenges in how the physiological data from the body is to be collected. There is a wide range of physiological sensors varying in detection accuracy and degree of discomfort that people are willing to stand. Novel wearable sensor technologies minimize the discomfort by compromising the validity of the measured data.

This thesis contributes an exploratory review of sensors and characteristics of physiological data suited to be measured during the course of everyday life. It is also shown as a proof-of-concept that both *arousal* and *physical activity* can be measured consistently in such unconstrained setting but *adaptability* can only be estimated by assessing sleep quality. Besides supporting sensor input in *Affective Health*, these results provide insights and best-practices when sensing signals from the body in real-time.

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Introduction

This thesis is part of a project at the Swedish Institute of Computer Science (SICS) called *Affective Health*. This project aims to build on a previous project named Affective Diary (Lindström et al. 2006), that produced a *'digital diary where users can scribble their notes as in a conventional paper-based diary, but where we also record bodily memorabilia [...] from body sensor data'*. From the Affective Diary project, we learnt that it is possible for users to identify with and be influenced by the physiological readings [1] collected from the sensors. *Affective Health* has the objective of producing a similar system, but with real-time feedback and possibility of scrolling back to past events. The intent of *Affective Health* is to promote an increased focus on health, helping users to prevent stress and stress related disorders.

1.1 Background

Stress is a natural reaction of the body to changes in the environment. It prepares us to deal with the change, activating all the available resources to confront it and adapt. In itself, it does not carry any negative value as it as helped our ancestors to survive until now, escaping wild animals or hunting for food. The most primitve stress reaction occuring in our bodies is called "fight or flight", when we have to choose between facing a danger or running away from it. Changes in environment, however, for people living in the modern society, occur on a more psychological level and the causes of stress (called stressors) can nowadays be events such as tight work schedules, being stuck in the traffic or marital disagreements. Exposure to these stressors is typically longer than in a simple "fight or flight" situation, giving rise to body reactions that are characterized by lack of adaptation and tension release.

When the stress response lasts for a long period and people are unable to adapt to the requirements of the new environment, the human body starts to be damaged,

[1] Physiological readings are input *"relating to the science of the functions of living organism"* (CancerWEB 1997). They can be readings from any organ in the human body (e.g. heartbeat, body temperature, etc.)

compromising its ability to fight diseases, thus generating medical conditions like depression, anxiety, infertility, ulcers, heart problems and diabetes, among others (e.g. Seeman et al. 1997).

The influence of stress on wellbeing is now widely accepted and has became a public health concern (Cox 1993). Many companies have developed programmes or hired help to educate their employees in stress management (LGE 2007). Activities like yoga and meditation are increasingly common and people start to feel that they need to find tools and strategies to handle stress in order to live a good life.

Until not so long ago, the computer research community was practically oblivious to all this and only recently we start to see a growing interest in creating technologies and applications that can help people deal with this problem in their lives. Biomedical Computing is now a big field and produced a wide range of small biomedical sensors capable of capturing and processing accurately body signals with little human supervision. This enables the use of them not only in hospitals but also in everyday life. Following this, a great number of home-based monitoring systems for hospital patients were developed and are already being put to use (e.g. Exmocare 2007, Kiwok 2008). These systems often focus on presenting the patient's biodata in a raw or unprocessed format for further analysis by a doctor or an expert, thus limiting its use to professional contexts.

Affective Computing (Picard 1997) is a field withing Computer Science which focus on computing related with emotions and affective states. Affective Interaction is an emergent field of study that is similar to Affective Computing but with a fundamental difference in goal (Sundström et al. 2005): instead of inferring user's affective states and build computational models of emotion, Affective Interaction develops applications in which the user can feel emotionally involved by providing mechanisms for communication of affective states. Affective Diary (Lindström et al. 2006) was a research project conducted in this field. It records body signals and present them to the user mapped in two easy to understand concepts: Physical Activity and Arousal. The idea is that end users should easily understand and relate to these accounts of their everyday bodily activities, inviting to introspection.

Following the steps and the success of Affective Diary, *Affective Health* will try to overcome the limitations of the current commercially avaliable health monitoring devices for independent use by non-expert users. In order to achieve this, the raw information from the body signals must be processed and presented in a meaningful way. Adding to Physical Activity and Arousal, the new system might also map a new concept, Adaptability. This concept, described in detail later on this thesis, can now be briefly defined as: 'How well the body adapts to changes in the environment'. It is the belief of this project that this three concepts together, with careful design, can provide a record of events that will help users reflect on their lives and thereby reducing stress.

1.2 Problem

This thesis will aim to give an answer to three questions. The first one is concerned with the new high-level concept that we wish to represent in *Affective Health*: Adaptability. It is not clear if this concept can be mapped by body signals, so the first question is:

'Which physiological signals are related to Adaptability and how can the mapping be done?'

To extract meaning from the complexity of body signals, it is necessary to process them after acquirement, identifying the parts of the signal or the changes that contain meaning. These parts are defined as features. The present thesis will address these problems focusing on the goals of *Affective Health*, so the second question is:

'Which features in biodata capture the meaning of Physical Activity, Arousal and Adaptability?'

Following this problem, another practical problem arises. The previous project, Affective Diary, used biosensors to extract the concepts of Physical Activity and Arousal. The results were very satisfactory but some of the limitations found in this project can be tracked down to an unadvised choice of sensors and use of not validated methods for biodata acquisition. So the third question that will be addressed in this thesis is:

'Which methods of physiological input are reliable and give high quality biodata?'

1.3 Contributions of this thesis

In this thesis, we will explore the current feasibility of mapping Physical Activity, Arousal and Adaptability to biodata, from a technical point of view. The aim is to map these three concepts to a robust and reliable sensor input in an everyday life setting to provide *Affective Health* and future similar applications within Affective Interaction field with a good base for decisions.

The main contribution of this thesis is a supervised review of the state-of-the-art in sensors and extraction methods in physiological data. A configuration of biosensors and features capable of mapping Physical Activity, Arousal and Adaptability will be proposed. These results will be used directly to support decisions in the *Affective Health* project and also in future projects that make use of biosensors, either by justifying sensor acquirement or by providing inspiration for building new biosensors.

1.4 Method

Affective Health is a project being developed in two parallel threads: interface design and sensor implementation. These threads have as a common starting point the three concepts. While the interface design starts from the concepts and tries to represent them to the user, the sensor implementation will provide a sensor layer that captures physiological input from the user and maps it to the concepts, for later representation.

This thesis is the result of one of the first steps in the sensor implementation. To explore the technical constraints of capturing biodata and the feasability of mapping it to the concepts, a literature survey was conducted under the supervision of Professor Kristina Höök and Markus Bylund at SICS. Current practices on biodata analysis were analysed and discussed, as well as the current state-of-the-art in biomedical sensors.

During this exploratory review, we had expert advice from the medical doctors Yrsa Sverrisdottir from Sahlgren University Hospital and Inga Jonsdottir and Gunnar Ahlborg, from Institute of Stress Medicine, in Göteborg. This advice was taken under the form of two separate visits to both the hospital and the Institute, as well as email consultation.

1.5 Limitations

The review and guidelines presented by this thesis can be used theoretically for any application that intends to make use of biomedical sensors. However, this work was undertaken to satisfy the requirements of *Affective Health*: the need to represent Physical Activity, Arousal and Adaptability under specific design conditions. So the results and reflections presented here should be valid in this scope. We believe that this concepts are wide enough not to hinder the scientific usefulness of this work in other contexts as well.

1.6 Outline

On Chapter 2, we provide a background on stress and current practices on stress management as well a general overview of biosensors. The *Affective Health* project and its design requirements are on Chapter 3, concluding with a list of requirements for the physiological input methods. Chapter 4 discusses the three concepts that we aim to represent in the *Affective Health* system. We define of these concepts and review the current biosensors and methods for input. Chapters 5 and 6 present the Results and Discussion.

❖ 2

Background

Before attempting to design a stress management support system, it is important to understand what stress really is about. This Chapter will provide background on stress, a brief medical explanation and its long-term negative effects on our physical health. Also, current statistics on stress in European countries as well as stress management and reduction methods will be presented.

The Chapter will conclude with a short review on technical aspects and uses of biosensors, important for the understanding of the following chapters.

2.1 Stress

The first study on stress is attributed to Selye (1936). In this study he describes several laboratory experiments in which he exposes rats to diverse ”noxious agents” such as cold, surgical injury, spinal shocks, muscular exercise or intoxication with sub lethal drug doses. From this study he concluded that the rats would typically go through three behavior phases: alarm, adaptation and exhaustion. After the initial alarm and body response (which involved severe transformations) several rats would first adapt to the stressor, entering the second phase. As a consequence of a period of time of continuous exposition to the stressor, depending on its severity, their body would succumb and suffer effects equivalent to the first alarm stage, conducting ultimately to death. This interpretation model of stress, based on the response of the organism to the strain, or stressor, was coined General Adaptation Syndrome.

Another model of stress was the one developed later by Folkman et al. (1986) which identifies two processes: cognitive appraisal and coping. When faced with a possibly hazardous encounter with the environment, the person will go through the process of cognitive appraisal, evaluating the possible outcome of this encounter. Coping is defined here as the process of dealing with stress, in which the person changes the environment or her own internal expectations in order for these to match, or for the environment to exceed her expectations.

A recent relevant framework for studying stress is the Demand-Control-Support model (Karasek & Theorell 1990). This model, created with a focus on work-related stress, examines the relationship between the individual and the environment, from the point of view of the individual. Karasek & Theorell propose three factors to define the perception of the work environment: demand, control and support. Demand is the amount of workload placed on the person. Control refers to autonomy; if the individual is able to decide how to complete the work tasks. Support is defined as the amount of assistance that the worker gets from the manager or supervisor. Although the present thesis is not directly concerned with work-related stress, this model is important because it has dominated research in effects of long-term stress in the last years (SALTSA 2006). Individuals with high demand, low control and low support usually experience prolonged periods of stress (Karasek & Theorell 1990).

Having low social support outside of the work setting is also associated with increased stress and disease outcome. Individuals with low socio-economical status are more prone to psychiatric diseases deriving from long-term exposure to stress (Rose 1994).

A stress experience can be measured using three methods: evaluating the stimuli; evaluating the subjective cognitive response (by asking the subject how he feels) or evaluating the physiological bodily responses. The first method can obviously only be applied with humans and can potentially be deceiving because it does not take into account the capabilities of the subject to deal with the stressor. The second measurement method can be very subjective (Ursin & Eriksen 2004). Both are hard to measure in real-time.

In order to understand the third method, the physiological response to stress, it is important to take a look first on how the body is internally regulated.

2.1.1 Body autonomic regulation

The internal enviroment of the body is regulated by two control systems: neuronal and hormonal (Jänig 2003).

The neuronal regulation acts rapidly and is mediated by the Autonomic Nervous System (ANS). ANS is a part of the nervous system composed by a complex net of nerves that are distributed all over the body and control directly the function of most tissues and organs. The ANS is mostly responsible for involuntary and non-conscious functions like regulating the heart rate, blood pressure, respiration. sweating, movement of the bowel, etc. There are two branches of the ANS, illustrated on the Figure 2.1: the Sympathetic and Parasympathetic nervous systems. The Sympathetic system mobilizes energy and resources from the body in situations of arousal whereas the Parasympathetic system is primarily used in situations of rest.

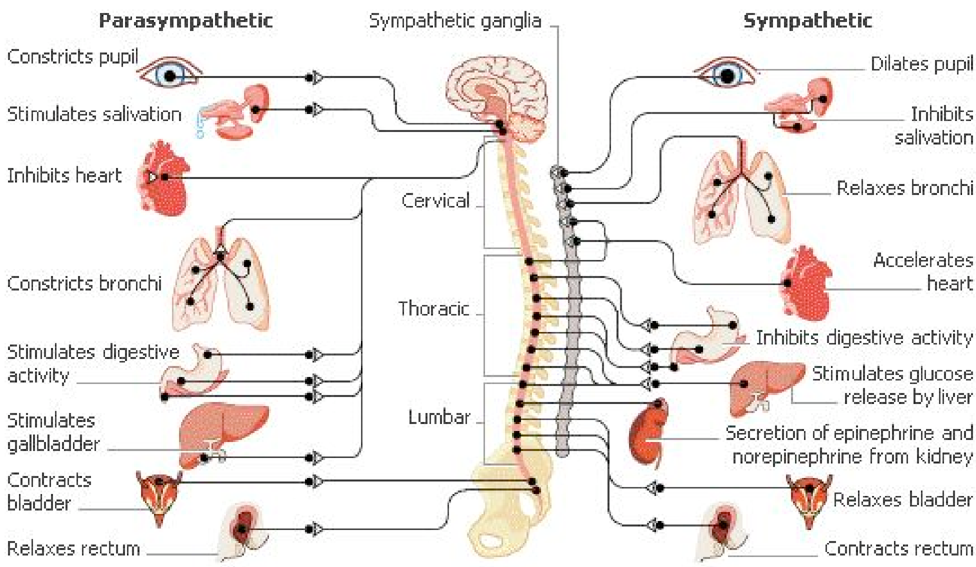


Fig. 2.1. Main functions of the Sympathetic and Parasympathetic nervous systems.

The other regulatory system is the endocrine hormonal system. Hormones are chemical messengers produced in the body by organs called glands and then travel in the blood-stream to other parts of the body, where their action is needed. The purpose of the hormones is to control or regulate the activity of tissues or organs. The hormonal regulation is in general slower than the neuronal regulation (Jänig 2003).

There is one particular set of organs that is responsible for the main regulatory functions of the body and phisiological responses to stress. It is called Hypothalamic-pituitary-adrenal axis (HPA). The HPA is composed by the hypothalamus and two glands called pituitary and adrenal (see Figure 2.2 for an illustration). The hypothalamus is a small part of the brain responsible for coordinating the hormonal system.

The physiological responses to stress involve both the ANS and the endocrine system, in particular the Hypothalamic-pituitary-adrenal axis (HPA). The hypothalamus, though comprising less than 1% of the brain's total volume regulates both the ANS and the release of hormones. Thus, despite its modest size, the hypothalamus controls cardiovascular functions, respiration, temperature regulation and food, water intake, and hence the maintenance of an equilibrium of the internal environment, Both ANS and HPA work in conjunction to mantain the body in an equilibrium situation, also known as homeostasis, a concept created in 1865 by Claude Bernard that can be described as a slow regulatory process that operates on an organism, maintaining it in a stable condition (Cannon 1932).

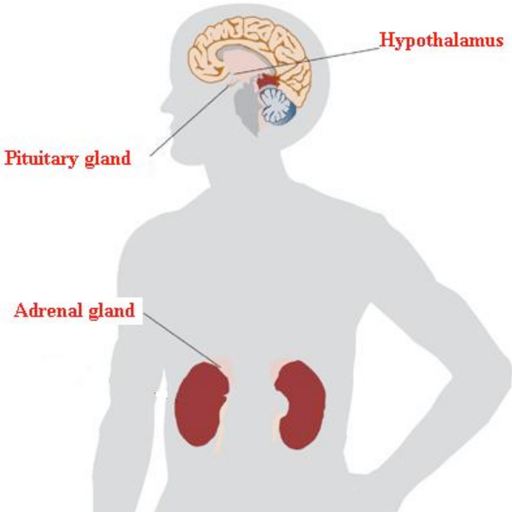


Fig. 2.2. Scheme of the HPA axis. Adapted from (Adinoff et al. 1998)

2.1.2 Allostasis and stress response

Following the development of different theories on stress, a new concept appeared, defined by Sterling & Eyer (1988) as allostasis. It is similar to homeostasis, defined in the previous section, but it works faster. It responds to fast changes in the environment, such as exposure to a pathogenic (e.g. virus or bacteria), or a prolonged “fight or flight” reaction.

Every time there is a stress response, the organism enters a state of arousal and each internal system responds to adapt to the change. This response starts in the brain, with the activation of the Sympathetic system and deactivation of the Parasympathetic system from the ANS occurring in paralel with a release of hormones in the HPA.

There are nerve endings and receptors for the hormones in cells and tissues all over the body so,immediately, the immune defences are strengthened, the heart rate is increased, skin conductivity rises or the pupil diameter widens, among others (Cannon 1914).

As an example, let us imagine a man walking in a forest. He is in a healthy condition and the process of homeostasis is occuring at every second, with his body maintaining a constant internal temperature by sweating and keeping the amount of sugar in the blood in equilibrium. At a certain instant, he spots a snake lying in the middle of the road. His body reacts instantaneously and enters a “fight or flight” state, with all the changes described in the previous paragraph preparing him to react quickly. He can choose to fight the snake or turn around and choose another way. Either one has the potential to solve the conflict but let us say that he chooses to avoid the snake. As soon as the environmnet is considered safe, the allostatic process stops and the body enters in a state of recovery, as exemplified by the Figure 2.3. After this state, the body in a healthy condition should resume the normal functioning and the homeostasis processes continue as before.

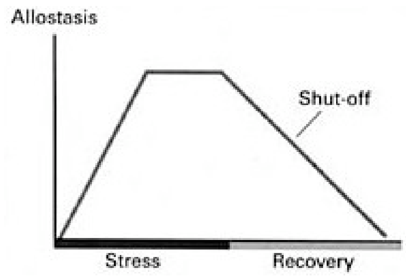


Fig. 2.3. Example of a stress response. Adapted from (McEwen 1998)

This response has short-term benefits as it adapts the organism to the environment. However, it does not come without long-term consequences. Either because of inefficient responses or repeated exposure to stressors, allostasis has a long-term effect on the body called allostatic load (see Figure2.4).

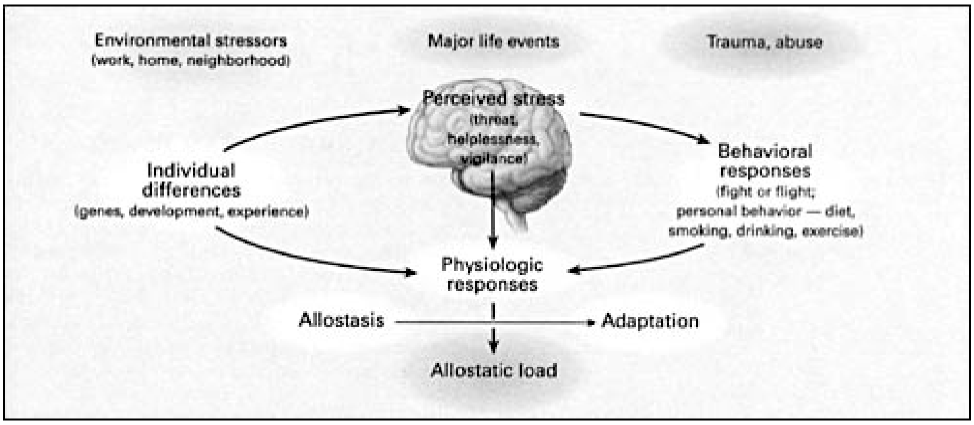


Fig. 2.4. Allostatic load comes from allostasis and is affected by a number of factors like individual differences, behaviour and past experiences. Extracted from (McEwen 1998)

McEwen & Wingfield (2003) define two types of allostatic load:

Type 1 allostatic overload occurs when energy demand exceeds supply, resulting in activation of the emergency life history stage. This serves to direct the animal away from normal life history stages into a survival mode that decreases allostatic load and regains positive energy balance. The normal life cycle can be resumed when the perturbation passes. Type 2 allostatic overload begins when there is sufficient or even excess energy consumption accompanied by social conflict and other types of social dysfunc-

tion. The latter is the case in human society and certain situations affecting animals in captivity. (. . .) If allostatic load is chronically high, then pathologies develop. Type 2 allostatic overload does not trigger an escape response, and can only be counteracted through learning and changes in the social structure.

Figure2.5 shows on the top a normal physiological response, with a period of exposure to a stressor and withdrawal, and 4 conditions that lead to allostatic load.

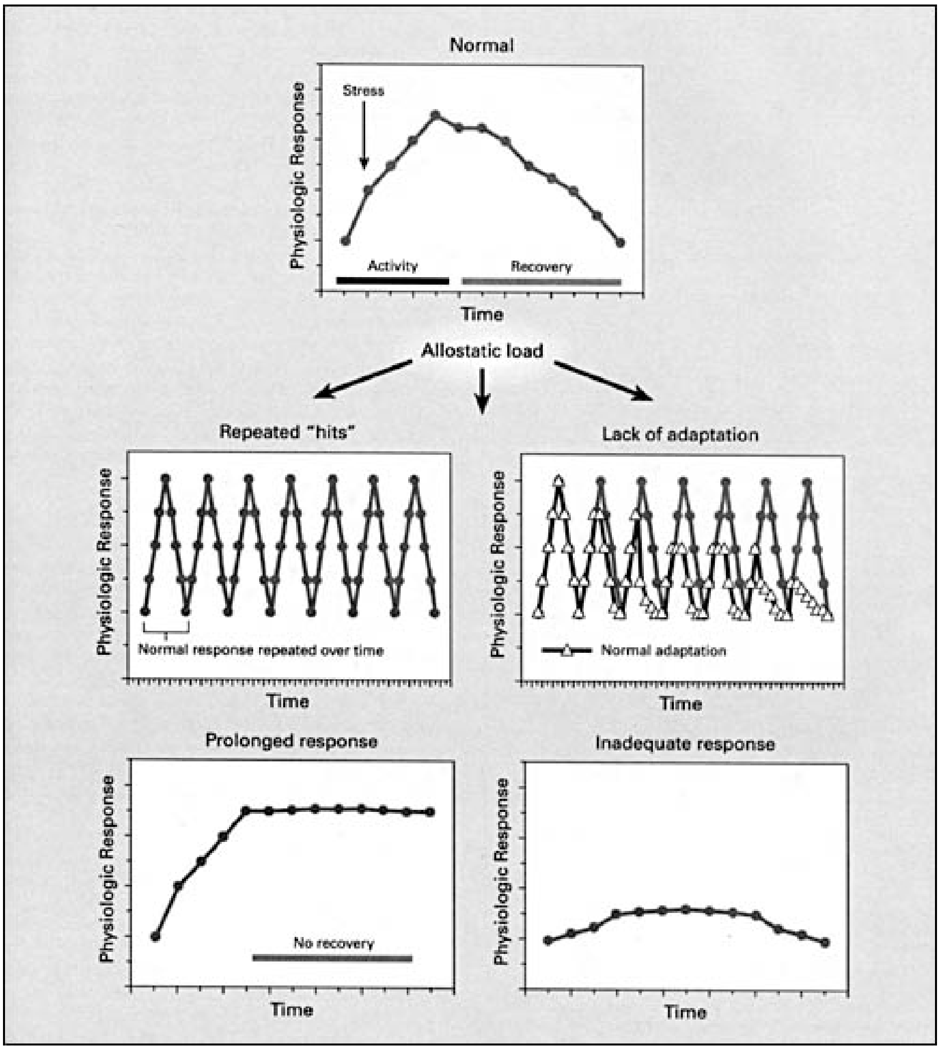


Fig. 2.5. Illustration of a physiological response and 4 situations leading to allostatic load.

The first figure of allostatic load shows a normal psychological response repeated over time with the presence of new stressors. It is the case of having "too much stress" in life.

In the second figure only one stressor is present repeatedly. The graph with triangles denotes a normal response in this case, occurring an habituation of the body and subsequent decrease on the response. The dotted line represents an abnormal response, similar to the one in the first figure, where the body does not adapt to the same stressor and has always the same response. An example of this case is the fear of traveling by plane; some people have strong stress responses on the first time and then adapt, causing less intense responses on the latter times. For other people, the fear remains the same, no matter how many times they are exposed to the stressor. For the latter, the cost of allostatic load is higher.

On the bottom left, on the third figure, a prolonged response is shown with no recovery after withdrawal of the stressor. Finally, the figure on the bottom right shows a dampened physiological response during exposition to a stressor. This attenuated response allows other systems to take compensatory actions and become hyperactive, usually with the cost of allostatic load.

The cumulative damage of allostatic load during our lives can lead to long-term consequences.

2.1.3 Long-term consequences

Various studies point to the fact that allostatic load can lead to permanent changes in immunological, cardiovascular and neuronal systems. Stress has been associated with infections and inflammations, cardiovascular, pulmonary, dermatological and immunitary diseases, atherosclerosis, infertility, diabetes, obesity, psychiatric conditions and progression to cancer (e.g. Seeman et al. 1997, McEwen 1998, McEwen & Wingfield 2003, Kaplan et al. 1991, Yun & Doux 2007) Stress leads also to unealthy behaviours (Everly & Lating 2002) such as smoking and/or low physical activity, which can independently weaken the body and accelerate progress towards diseases (Barengo et al. 2004, Lucini et al. 2005).

Increased cardiovascular risk seems to be related with overactivity of the Sympathetic nervous system (Julius 1993), due to frequent activation in stress responses. It has been shown that stress impairs the homeostatic regulations of the body, particularly the cardiovascular regulation (Mezzacappa et al. 2001, Lucini et al. 2005). The reduced autonomic regulation of the heart makes it more vulnerable to acute stress (i.e. stress happening during short periods of time), where short term rises in heart rate and blood pressure can cause arrythmia and sudden death (Lucini et al. 2005).

The long-term effects of stress were also associated with premature aging, as reported in a pioneer study by Epel et al. (2004). This study was conducted with a group of women who were caring for a child suffering chronic illnesses for several years. Self-reports from these women put them in a high stress category. Epel et al. found that the high stress group of women had suffered changes in the DNA level that prevent cells to multiply and regenerate the body, compared to a control group. These changes are characteristic of aging. The same result was also found by Damjanovic et al. (2007) with highly stressed caregivers of Alzheimer patients. These results point to the fact that long term stress accelerates aging, leaving the body in a naturaly vulnerable state. However, further research is needed in order to determine exactly in which systems of the body does premature aging occurs.

2.1.4 Stress management

The impact of stress, especially work related stress, in everyday life has become a major interest of researchers, companies and governments in the last years. According to SCB (2005) and Marklund et al. (2004), stress related disorders in Sweden have increased substantially since the middle nineties as well as long-term sick leaves. In 2005, 24,4% of the Swedish workers suffered from work-related disorders, with stress and mental strain as one of the most important causes for both men and women (SCB 2005). Table 2.1 illustrates the growth of days lost at work from cardiovascular diseases and unspecified mental disorders as consequence of stress in the middle 80s up to the 90s, in United Kingdom.

Work days lost (million)	**Mental Disorder**		**Diseases of the Cardiovascular System**	
YEAR	Men	Women	Men	Women
1985/86	35.6	20.1	67.6	8.1
1986/87	37.2	20.3	68.0	8.4
1987/88	39.3	23.1	73.6	10.1
1988/89	43.9	26.7	77.3	11.1
1989/90	48.0	31.7	81.4	12.5

Table 2.1. Days lost at work in United Kingdom, as a consequence of stress related disorders. Adapted from (Cox 1993)

Many people start seeing the need to combat stress in an effective way and, in general, two types of stress combat approaches are discussed (Cox 1993, PEROSH 2004):

Individual Approach Focus on reducing the risk of individual exposure to a stressor and management of the consequences of stress for each individual

Organizational Approach Focus on the characteristics of jobs and origins of stressors, with the goal of reducing or eliminating them.

A workshop, held in 2004, of Partnership for European Research in Occupational Safety and Health (PEROSH) analysed how European countries are dealing with the problem. There seems to be an increased focus on the Organizational Approach, with steps taken from a company and governmental point of view to improve work environments and therefore eliminate work related sources of stress. It is still difficult to compare the effectiveness of different programmes, as they differ a lot in methodology and focus. But PEROSH (2004) is one of the first steps on this area, so this is likely to change in the following years.

The Organizational Approach, however, is mostly concerned with work related stress. Though it can work towards a more healthy work environment, dealing with stress in personal life seems to be left out for each individual to handle.

Affective Health is more focused on the Individual Approach. At this level, measures can either be taken towards stress reduction, by identifying specific stressors and minimizing exposure, or stress management, which focus on individual training for dealing with stress.

Two particular techniques of individual stress management are relevant to this thesis: self-reflection and body awareness.

Self-reflection is the act of introspectively analyse oneself. One way to achieve this is through journaling. Keeping a journal or diary does not only keeps us in touch with ourselves, by providing an anchor to everyday life, but it is also a very used tool recovery from traumatic events and in stress management programmes (Anderson & MacCurdy 2000). Houghton (2005) shows an example of how writing a diary can help to identify causes of stress and eliminate them:

> *A general practitioner thought his main source of stress was unrealistic patient demands, but when he did his diary he found that the root of the problem lay in rushing to take the children to school and still trying to be ready to see his first patient at 9 am sharp. He always arrived breathless and frazzled, and by the time he saw his first patient at 9 15 the next two patients had already arrived. While he thought the solution was to give up medicine in order to open a book shop, it turned out to be a simple matter of scheduling his first patient for 9 15 on the days he did the school run.*

Besides journaling, other important aspect of stress management is body awareness. Yoga and meditation are two examples of activities that have the objective of increasing body awareness. Landsman-Dijkstra et al. (2004) describes a 3 day Body Awareness Program. The first 2 days consist on three type of sessions:

- Working with the body, focusing on bodily sensations and feelings;
- Working with the mind, focusing on the thoughts that come with the feelings;
- A creative session, that focuses both on bodily sensations and thoughts.

The last day of the program is filled with “bodywork”, “mindwork” and making a plan of change. This program has been tested with 122 participants with aspecific psychosomatic symptoms [1] and has shown to be effective, not only on short-term but also on the long-term. The program changed their coping strategies with illness and stress in general, resulting in a better quality of life (Landsman-Dijkstra et al. 2004, Landsman-Dijkstra et al. 2006).

2.2 Biomedical sensors

As defined in Harsanyi's (2000) book, a *"sensor is a transducer that converts the measurand (a quantity and a parameter) into a signal carrying information"*. In general, this signal can be electrical, mechanical or optical.

Biomedical sensors, or simply biosensors, are sensors for which the measurand is a biological component, such as a physiological response. The use of biosensors has been increasing in the last years and they are being applied not only to monitor patients in an hospital environment (the typical historical use), but also for patients at home and even healthy people, for disease prevention and training. This democratization of biosensor technology has generated a big market demand, resulting in a revenue, in 2001, of 5.2 billion dollars in this industry (Wilkinson 2002). Also, the need for new and more accurate sensors represents in these days a huge research area.

Biosensors can be classified as intrusive, indwelling or non-intrusive, by the extent on how much they invade the body. Intrusive biosensors are used under the skin, while non-intrusive sensors are used on the skin optically reading information. Indwelling sensors make their measurements from existing body cavities, without altering any anatomical property (Neuman & Liu 1988).

Typical uses of this technology include microsensors and wearables (Lymberis 2005).

2.2.1 Microsensors

According to, Lymberis (2005), during the last 10-15 years microsensor technology has developed come in terms of intelligence, speed, miniaturization, sophistication and new materials at low cost. Microsensors can by used in vitro, helping on the discovery of new drugs (sources) or in vivo [2].

Implantable in-vivo solutions are capable of monitoring glucose levels on diabetics, viruses and bacteria, etc. (Jaffari & Turner 1995). These systems are not being still widely used due to difficulties in finding right biocompatible materials to be used inside the body, power sources and communication (Lymberis 2005)

[1] Psychosomatic symptoms are *"bodily symptoms of psychic, emotional or mental origin"* (CancerWEB 1997). They can be head or muscle aches, dizziness, etc.

[2] In vivo means *"in a living organism"* where as in vitro is defined as *"performed in a glass or plastic vessels in the laboratory"* (CancerWEB 1997)

2.2.2 Wearable sensors

Wearable biosensors are a kind of non-intrusive sensors. Bonato et al. (2006) defines them as:

> *"Biomedical (including biological) wearable sensors/actuators and sensor- based communicative systems that can monitor and/or stimulate, and/or treat, and/or replace biological and physical human functions."*

The largest part of the market demand and research is currently placed on the monitoring type of wearables. Wearable biosensors do not have the problems identified in the microsensors and are already starting to be common. They can be used in multiple domains like remote monitoring of health patients, astronauts or athletes. Their miniaturization offers now the possibility of integration with clothing or accessories such as hats, belts, wrists, shoes or gloves. Although it brings advantages, this miniaturization limits their functionality by posing challenges on power sources, processing power, memory and range of collectible biological data. (Lymberis 2005).

Engin et al. (2005) gives a review of the current trends in wearable biomedical sensors. Two types of wearables are described in particular: smart textiles and photoplethysmographic (PPG) sensors.

PPG sensors are one of the most researched types of sensors on the field of wearables since they promised to revolutionize the way that cardiovascular physiological measures can be assessed. Currently they are capable of measure heart rate, heart rate variability and arterial blood pressure.

Fig. 2.6. Early prototype of a PPG ring

PPG works by sending light against the skin surface and measuring the amount of light that is reflected. At each contraction of the heart, blood is sent through periferal vessels, modifying their volume. The vessels are situated close to the skin, so this alters the amount of reflected light captured by the sensor. The captured light, shown on Figure 2.7, constitutes a signal called Blood Volume Pulse with a invariant, direct current (DC) and a pulsatile or alternating current (AC). By detecting peaks in the AC portion of the signal, it is possible to detect cardiovascular measurements like the heart rate (Asada et al. 2003).

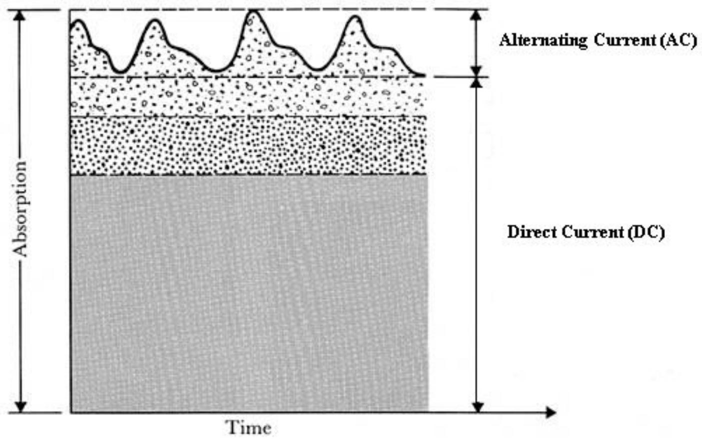


Fig. 2.7. Absortion of light by a PPG sensor. The AC part of the signal gives information about the heartbeat

Textiles also promise to see big development in the following years. Engin et al. (2005) defines smart textiles as *" context-aware textiles which are able to react and adapt to stimulus from their environment by integration of smart materials into its structure"*. These type of wearables can be made by implementing the functionality into strongly integrated, yet non-textile electronic components or by following the paradigm "the fabrics is the computer". Figure 2.8 shows the first wearable motherboard, an example of the latter case developed for use by soldiers in a combat situation, where, embedded in the fabrics, there are optical fibers that detect bullet wounds and special flexible transmission fabrics that can transmit information like heart rate, temperature, etc. from various sensors (Firoozbakhsh et al. 2000).

The current effort in research in biosensors provides us with a wide range of possibilities of getting insight about the internal functioning of our bodies.

Figure 2.9 ilustrates the main signals that can be captured and the usual places where the sensors are placed.

Fig. 2.8. Example of a smart textile called Georgia Tech Wearable Motherboard™

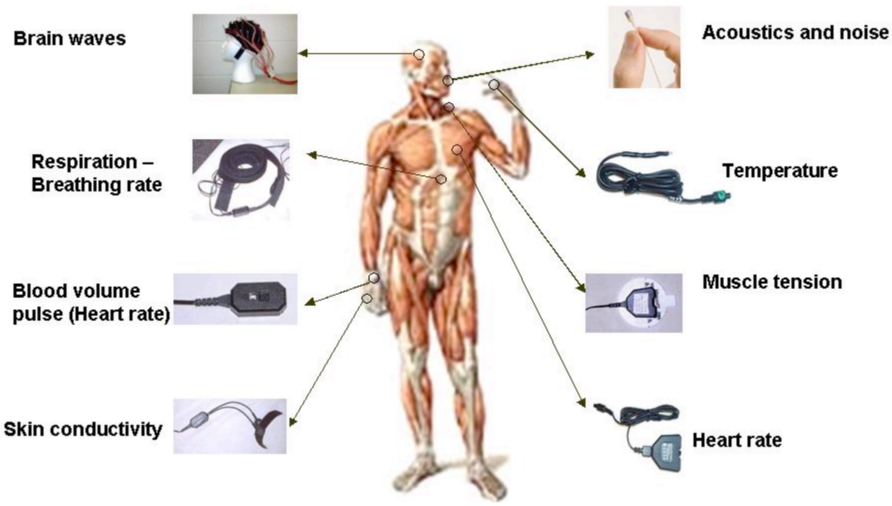


Fig. 2.9. Examples of usual places in the body used to capture signals from wearable sensors. Some of this signals will be discussed along this thesis. Adapted from (Kim 2004)

3

Affective Health

Affective Health aims to encourage self-reflection on life experiences, focusing on stressful events, as well as allowing for biofeedback in real-time. The objectives of the project meet the requirements of the Individual Approach to stress combat, detailed on Section2.1.4: stress reduction and stress management. In the same Section, under stress management, two techniques were described in detail: self-reflection and body awareness. *Affective Health* also aims to make the users more self-aware of their body and the events on their lives. This effect is achieved by the means of a real-time on user's mobile phones. The real-time feedback is shown together with clues from what has been happening in the context. These clues can be materials collected from the mobile phone such as text or multimedia messages, bluetooth presence, photos, sound recordings, etc.

It is not the purpose of this thesis to focus on the design aspects of creating such a representation. However, understanding the design qualities is essential to guide and set constraints in the analysis of biosensors and biodata that follows in the next Chapters.

3.1 Evaluating emotion in Affective Interaction

Since *Affective Health* is a project conducted in the field of Affective Interaction, it is important to know first what is the vision behind the system. Affective Computing (Picard 1997) is a field of research that aims to bring emotions to the computer domain. Briefly, the goal is to capture the user's biodata, facial expressions or body language and translate that input to emotions, based on computational models, in order for computers to take into account the user's emotional state. This approach rarely takes into account social situations and context (Ståhl 2005).

Schachter & Singer (1962) proposed a two-factor theory for evaluating emotion, suggesting that one needs to know two things to interpret an emotion: the physiological arousal from the body and cognition about the context. Another author, Kagan (1984), points out:

> *The term emotion refers to relations among external incentives, thoughts, and changes in internal feelings, as weather is a superordinate term for the changing relations among wind velocity, humidity, temperature, barometric pressure, and form of precipitation. Occasionally, a unique combination of these meteorological qualities creates a storm, a tornado, a blizzard, or a hurricane - events that are analogous to the temporary but intense emotions of fear, joy, excitement, disgust, or anger. But wind, temperature, and humidity vary continually without producing such extreme combinations. Thus meteorologists do not ask what weather means, but determine the relations among the measurable qualities and later name whatever coherences they discover.*

Affective Interaction is similar to Affective Computing in the sense that emotions play a central role. However, instead of trying to create model to guess the emotional state of the user, affect is seen as interaction, where the user can construct the meaning of her own emotions (Boehner et al. 2005) by interacting with the system. In fact, relating this to the observation by Kagan, only the user can be the meteorologist because only her can know the all variables (not only the physiological response but also social context) needed to correctly label an emotion, if that is at all possible.

Boehner et al. describe a set of guidelines for designing systems aiming to support understanding and self-interpretation of the user's own emotions. This set is called Interactional Approach:

- *The interactional approach recognizes affect as a social and cultural product*. Emotions are rooted in the social situation we are in and can only be interpreted if we take that into account
- *The interactional approach relies on and supports interpretive flexibility*. Interpretation of emotion is left for the user
- *The interactional approach avoids trying to formalize the unformalizable*. Emotions are not represented as discrete units of information
- *The interactional approach supports an expanded range of communication acts*. The representation of emotion by the system can very rich. Emotions do not need to represented by clear signs or verbal statements
- *The interactional approach focuses on people using systems to experience and understand emotions*. It is not the purpose of these systems to read or label user's emotions but rather to let the user construct and experience the emotion

The Interactional Approach opens up for the design of systems that allow users to experience an Affective Loop. In her licentiate thesis, Sundström (2005) describes the Affective Loop as an interaction process with three steps:

1. the user first expresses her emotions through some physical interaction involving the body, for example, through gestures or manipulations of an artifact;
2. the system (or another user through the system) then responds through generating affective expression, using for example, colors, animations, and haptics;
3. this in turn affects the user (both mind and body) making the user respond and step-by-step feel more and more involved with the system

The design of *Affective Health* will be user-centered and follow the guidelines stated by Boehner et al., aiming at involving the user in the system by producing an Affective Loop experience.

3.2 Inspirational systems

There is a fair amount of previous developed systems and research on the field of Affective Interaction, health monitoring and intervention. The following ones were selected because they contain some of the qualities that are expected to play a role in *Affective Health*.

3.2.1 Affective Diary

Affective Diary is a project conducted at SICS in cooperation with Microsoft Research which consists on a client on the mobile phone, a digital diary software and biosensors (Lindström et al. 2006). The system works by capturing sensor data from the user and uploading it to the diary through the mobile phone, together with other materials from the phone such as text and multimedia messages, photographs, bluetooth presence, etc. The sensor data captures some of the physiological expressions of human emotions. An ambiguous colorful body shape is then formed from the sensor data and associated with the other collected materials.

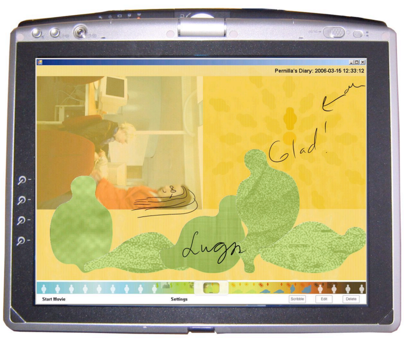


Fig. 3.1. Interface of the Affective Diary

The aim of the diary is to invite reflection on the experiences of the day, making bodily experiences available, while empowering the user to change them and create their own interpretation of the events.

3.2.2 Home Health Horoscope

Completely ambiguous, Home Health Horoscope is a system that uses sensors to measure the wellbeing state of the house, instead of the inhabitants (Gaver et al. 2007). A sensor network is placed around the house in meaningful locals (known a priori by analyzing the habits of the inhabitants) such as the kitchen table, a sofa, etc. The presence or absence of people in these places is analyzed and interpreted by the system which then outputs a horoscope-like ambiguous affirmation such as *"Thinking before you speak and act will keep you out of trouble. The real source of your trouble is a lack of self-control... "*. The horoscopes do not intend to be accurate but to provoke curiosity and reflection. It is also not aimed at inciting behaviour change but rather to stimulate curiosity. In the end, the user's subjective interpretation of the horoscope is the real output of the system.

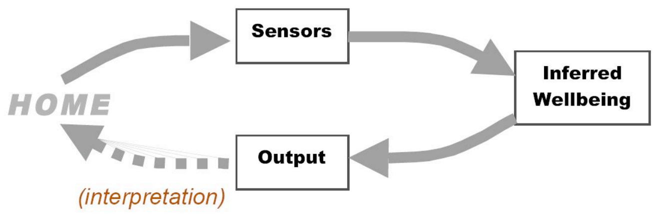


Fig. 3.2. Scheme of the Home Health Horoscope. The ambiguous output of the system needs to be interpreted to make sense.

3.2.3 Exmocare Watch

The watch from Exmocare (2007) is a monitoring commercial system capable of capturing multiple physiological signals at once, from a wrist worn watch. The sensor data can be uploaded to a client software in the computer and shown in a raw form, either in real time or a posteriori. The software also has some algorithms that can be used to infer the emotional state of the user from the sensor data and present it graphically. Other usage of the system is distance monitoring as it is capable of sending pre-defined warnings to a caregiver, in case one or more signals fall below or above a threshold.

Fig. 3.3. Exmocare watch

Exmocare Watch is a pure monitoring system with some extra processing and can be used as a biofeedback device such as heart rate monitors from Polar USA (2007), mostly developed for sports. The capabilities of distance monitoring make it similar to BodyKom a system developed by Kiwok (2008) which is intended for hospital patients staying at home, measuring an ECG signal and sending it via a secure connection to the hospital. Like these, there are many systems that can provide monitoring; some of them even specialized for stress management.

3.2.4 SenseChair

SenseChair was designed for the elderly, offering physical, social and emotional support and encouraging them to remain living independently at their homes (Forlizzi et al. 2005).

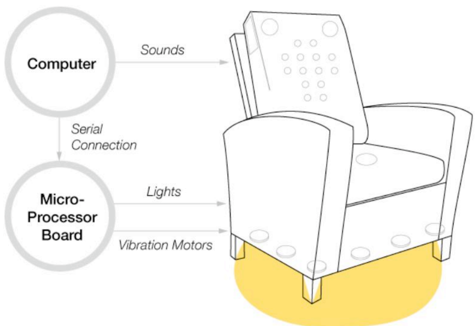


Fig. 3.4. Sense Chair

The chair uses sensors to collect information about the person sitting down. Using sensor data as well as information about the user's behavior and the surrounding area, SenseChair can output ambient display or direct notifications using sounds, lights and vibration. One use-case example is the chair detecting an unergonomic sleeping position and gently waking the user up using low frequency vibration, natural sounds and soft blue lights.

Far from being a monitoring device, SenseChair nevertheless elicits behavior change in the user and supports it in her daily life with the help of naturally ambiguous cues like colour, sound or vibration.

3.2.5 Breakaway sculpture

Breakaway is an ambient display with aesthetic properties that intends to encourage people, whose job requires them to sit for long periods of time, to take breaks more frequently (Jafarinaimi et al. 2005). It is represented by a small anthropomorphic sculpture (represented in Figure 3.5) that is to be placed on a desk where the user sits. The shape of the sculpture, mimicking the human body, is influenced by sensors placed on a chair measuring the amount of time that the user spent sitting: if the user has been sitting for too long, the sculpture assumes a slouching position; if the user gets up and goes for a walk, the sculpture returns to the upright position.

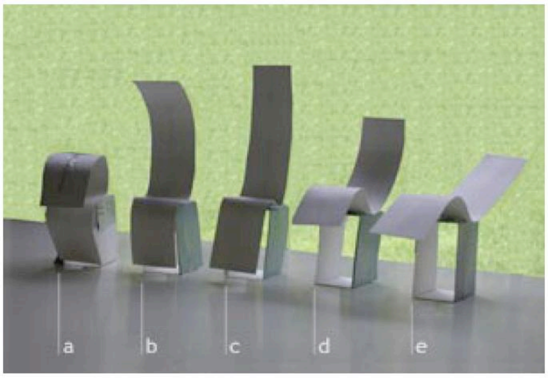


Fig. 3.5. Breakaway sculpture shown in different positions. (a) represents a slouching position and (e) a relaxed position

This system was tested with users and positively evaluated. It uses body language to communicate with the person in order to encourage behavior change.

3.3 Design Qualities

All these systems contain some qualities that we expect to be present in *Affective Health*. Ambiguity of representation is present in all the systems except for the Exmocare Watch. This quality, although can be seen as undesirable by traditional views of human-computer interaction, was looked upon by Gaver et al. (2003) as a *"a* *resource for design that can be used to encourage close personal engagement with systems".* Ambiguity allows for open interpretation of the system and forces the user to get involved in order to decide what is the meaning of the system.

Another design quality, present in Affective Diary, is embodiment. Defined by Dourish (2001) as *"interaction with computer systems that occupy our world, a world of physical and social reality, and that exploit this fact in how they interact with us".* Dourish says that an interaction is embodied not only because there exists physical interaction (like the one occurring when biosensors are measuring physiological data) but rather when that interaction is within a social setting and circumstances that give meaning and value to it.

Furthermore, the representation of biodata in *Affective Health* should be unvalenced. Valence is a dimension used to represent positiveness or negativeness of emotions. Russell (1980) represented emotions in a two-dimensional space with two axes: valence and arousal. Each emotion has a specific value of valence and arousal (e.g. "Excited" has high arousal and positive valence), as shown in Picture 3.6. However, an everyday life setting is too complex to capture all the determinants that allow us to classify an emotion (social determinants, context, mood of the person, etc.). Therefore we opt to represent Physical Activity, Arousal and Adaptability in a complete unvalanced way using a design that should allow the users to make their own valence interpretation based on their everyday understanding.

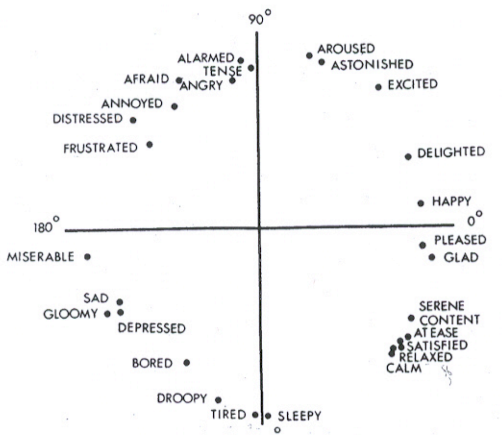


Fig. 3.6. Russell's model of emotion, where which emotion is represented along the axes of valence and arousal.

SenseChair and Breakaway aim to encourage behaviour changes toward health. Affective Diary and, in a certain sense, Home Health Horoscope encourage self-reflection; where the first does it by presenting user's own biodata with context clues, the latter presents ambiguous horoscopes. Affective Diary also provides the possibility to look back in time and reflect on events that happened a long time ago. Although these are not design qualities, they are relevant functionalities for the design problem at hand.

Thus, we are designing for the user to relate to an ambiguous and embodied representation of her body status. The sense of embodiment is achieved by combining as many clues as possible from the social context with the biodata representation. If this happens, a kind of Affective Loop may then be achieved, creating a strong affective relationship with the system. This involvement with the system and increased body awareness may lead to reflection and subsequently to behaviour change. This is the main difference between *Affective Health* and conventional biofeedback applications and can be the key to the success of this system.

3.4 Requirements on the physiological input methods

From Exmocare Watch and similar simple biomonitoring systems we take the qualities of long-term reliable sensor data and the use of wireless unobtrusive sensors. *Affective Health* should be able to integrate into everyday life with minimum maintenance. As research in implantable sensors is far from being able to produce sensors with these characteristics (Lymberis 2005), it becomes clear that the choice must rely on Wearable Sensors.

From this, we can enumerate a set of requirements on the methods of input that will be part of *Affective Health*:

1. The method should rely on wearable sensors;
2. The method should use lightweight and extremely non-invasive sensors that allow for a comfortable use;
3. The sensors used in the method should be unobtrusive when it comes to appearance, or highly customizable;
4. The method should have a reliable output;
5. The sensors used in the method should be robust and durable and require minimal or no maintenance;

The third requisite narrows the choice of sensors to the ones that are small enough to be almost invisible or integrated into clothing or accessories. The fourth requisite, concerning reliability, is of crucial importance since we do not intend to make a laboratory study or use sensors in a controlled setting. Therefore they should be able to cope with wear and tear of everyday life and still be able to have a reliable output. Feature selection on physiological data will also follow the same principle; features that are too sensitive to errors from sensors or that can behave unpredictably in similar conditions should be discarded.

A design choice was also made before starting the literature review in biosensors: smart textiles would not be considered. The reason for this decision is twofold: *(1)* this kind of solutions is still in a research phase when it comes to monitoring physiological signals (Engin et al. 2005); *(2)* textiles would require a great amount of maintenance because they would need to be washed with special care. For this reason, smart textiles go against requirement 5 and do not qualify for long-term continuous everyday life usage.

Furthermore, the choice of the sensors will be limited to the commercial availability or technical feasibility and also take into account the amount of trusted scientific background supporting the validity of the measurand of the sensor.

4

Mapping the Concepts

The next step in our process will be to map the biodata to concepts that end users should be able to understand - layman's terms. The reason for using high-level concepts in *Affective Health* is that the system is intended to be used by users without any medical or technical knowledge. The following concepts will be analysed:

Physical Activity represents how much and how one person moves
Arousal is a measure of physiological response to stress and exercise
Adaptability represents the person's capacity to adapt to changes in environment

Physical Activity and Arousal come directly from a previously developed system, Affective Diary. The use of Physical Activity in *Affective Health* is justified by research showing that exercise is a good way to relief stress, as well as many benefits for the heart and overall state of the body (King et al. 1989, Barengo et al. 2004, U.S. Department of Health and Human Services 1996). Knowing how much one moves during the day can be useful to assess lifestyle and motivate a change toward more physical exercise and a healthier life. Another reason is that having a report of Physical Activity during the day improves recall of when events happened and thereby facilitates self-reflection.

Arousal is a concept directly related to stress. When faced with a stressor, an organism reacts by inducing an aroused physiological response, preparing it to deal with the situation. So Arousal can be used by the user to indentify stressors and analyse her body response in situations of stress. Besides this, it is also possible to use representation of Arousal in real-time to help users to relax.

The concept of Adaptability was taken from medical background on stress (see Section 2.1). An excess of allostatic load caused by stress disrupts the normal process of homeostasis (adaptation) and leads to diseases. There is a loss of Adaptability when homeostasis is compromised or the allostatic response is impaired, meaning that the body has less autonomic regulation and is less able to cope with stress (Lucini et al. 2005).

A discussion based on literature is included for each one of the concepts in separate Sections, focusing on the type of biosensors needed and the technical aspects of the biodata acquisition. These discussions aim to select the best array of sensors for the needs of *Affective Health*, filtering the less adequate solutions.

Filtering was made simultaneously by:

1. Selection of physiological signals (such as heart rate or skin temperature) and features (such as count, mean or slope) , based on their power to map to Physical Activity, Arousal and Adaptability;
2. Selection of measurement techniques based on their technical characteristics and compliance to the considerations and requirements defined on the Section above.

Because of the large variety of sensors and research available in this area, the filtering was made in two steps: first we look at the literature panorama and select only the solutions that are most likely to satisfy the requirements; second, we analyse in detail these solutions and compare them.

4.1 Physical Activity

The usual definition of Physical Activity is given by Caspersen et al. (1985) which describes it as *"as any bodily movement produced by skeletal muscles that results in energy expenditure"* [1]. For the purposes of this thesis, we will lax this definition to any bodily movement, even if there was not any significant or measurable energy expenditure. The reason for this is that we are not only interested in measuring exercise but also low intensity movements and body postures that can help the user remember and reflect on her life, when looking into her bodily data representation in retrospective.

Two types of features are available in general to monitor physical activity in daily life: relative movement and steps. These map directly to sensor solutions: accelerometers and pedometers. As modern pedometers usually consist internally of accelerometers, it matters, before looking with more detail into these solutions, to make clear this distinction: accelerometers are defined as devices that have as output relative movement; pedometers simply output a number of steps.

4.1.1 Relative Movement

This feature represents the amount of movement the user does relative to herself and it is usually accessed by accelerometers. Accelerometers are capable of measuring

[1] Energy expenditure can be defined as the amount of energy, measured in calories, that a person uses

not only the quantity but also the intensity, frequency and duration of physical activity. They can be classified by uniaxial, biaxial and triaxial, depending on the number of movement planes that can capture. A uniaxial accelerometer measures movement in 1 plane, a biaxial can measure acceleration in 2 planes and a triaxial accelerometer measures in 3 planes, by combining the measurements of 3 different accelerometers disposed 90 degrees from one another. In general, triaxial accelerometers work better to measure normal day-to-day activity (Plasqui & Westerterp 1999).

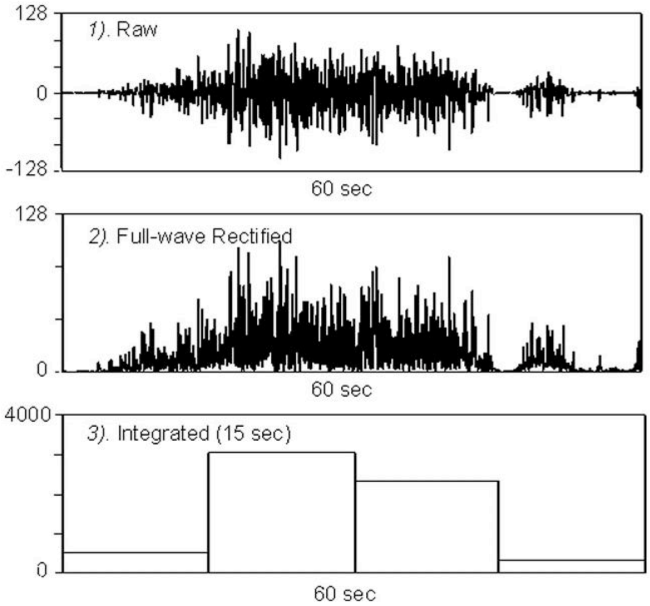


Fig. 4.1. Post processing of accelerometer. 1) Raw counts; 2)Rectified counts; 3) Epochs. Extracted from (Chen & Basset 2005)

The output of an accelerometer is usually expressed as a dimensionless unit called "counts". This unit needs post-processing in order to account for Physical Activity. Figure 4.1 shows two possible stages of this processing. The first illustration shows a 60 second window of bidirectional raw output (including negative values for movement), sampled at a fixed frequency (depending on the model of the accelerometer) and after going through a conversion from analog to a digital signal: "raw counts". In the second illustration, the signal has gone through a full-wave rectification, in which the negative part of the signal has been converted to positive. The third and last illustration represents an integration of the signal over 15 second windows, creating an alternative output unit called epochs. Epochs, which represent an average of movement during a specified time interval, can be processed efficiently by computer algorithms (Chen & Basset 2005).

Fig. 4.2. Actigraph, an example of an accelerometer.

The small size of current accelerometers (see Figure 4.2) makes possible to position them at virtually any part of the human body. The positioning is conditioned by the lifestyle of the person and the type of movement that we want to record. Measuring movement in children, young adults or elders can be very different. The preferred type of physical activity for a sedentary adult or elder is walking (Tudor-Locke & Myers 2001). Studies suggest that an accelerometer positioned on the waist (Berlin et al. 2006) or lower-back (Bouten et al. 1997), close to the center of gravity, is the best for such activity. This positioning, however usually fails to record accurately activities like cycling, swimming or fast running (Chen & Basset 2005, Bouten et al. 1997), as well as any movement occurring in the upper part of the body (arm movement, for example). Other possible positions include the wrist or ankle. To derive body posture, some solutions combine accelerometers in different body parts, mainly chest and thighs (Chen & Basset 2005).

4.1.2 Steps

Pedometers have been widely used as monitors of physical activity. They record steps, a simple measure of ambulatory (walking) activity. Although early-days mechanical pedometers lacked in accuracy , the new digital ones are now capable of satisfactory results (Tudor-Locke 2002). A digital pedometer is constructed based on accelerometers: the acceleration signal is processed by an algorithm that detects patterns of acceleration that correspond to steps. Although a step detection algorithm could be implemented in the *Affective Health* client running on the mobile phone, based on the output of an accelerometer, it is still valid to explore the direct extraction of steps from sensors as signal processing in mobile devices can be very expensive in CPU and battery lifetime.

A modern pedometer can give reliable results, with error below 5% (Vincent & Sidman 2003), in counting steps for people with a normal gait who walk at least at 0.9m/s, underestimating steps for lower walking speeds or irregular gait (Berlin et al. 2006). The Step Activity Monitor is an advanced pedometer composed internally of a triaxial accelerometer that has a reliability of 99% even with people with disabilities and irregular gaits (Coleman et al. 1999). The accuracy of a regular pedometer, however, varies with the brand and model. (Schneider et al. 2004, Crouter et al. 2003, Schneider et al. 2003, Melanson et al. 2004, Bassett et al. 1996)

(a) Pedometer (b) Use of pedometer

Fig. 4.3. Pedometer and usage of pedometer on the waist

The position of a pedometer should be the lower part of the body or the waist (Berlin et al. 2006), as shown in Figure 4.3(b).

As they simply record the number of steps, movement occurring only in the upper part of the body or seated physical activity is not recorded. Furthermore, a pedometer cannot record the intensity of the movement, making impossible to distinguish if a person is running or walking (Berlin et al. 2006). Furthermore, it is not possible to know the direction and orientation of the movement.

4.1.3 Evaluation

Pedometers have been used with success in behaviour change programmes, promoting physical activity (Tudor-Locke 2002). Also, they do not require post processing because the output is a simple integer representing the number of steps. This is specially important when considering that this processing will be done by a mobile device, with limited power, processing and memory resources.

As behaviour change is one of the main objectives of *Affective Health*, pedometers with their simple design seem to be likely candidates.

It is clear, however, that the counts or epochs derived from accelerometers contain much more information than simply the amount of steps, from the pedometer. Even if ambulatory physical activity is the most common type of activity, a user is more likely to relate to the representation of her bodily data with an accelerometer. With a tri-axial accelerometer to measure inclination or combining data from accelerometers placed in different positions, it is also possible to derive body posture (Hansson et al. 2001, Chen & Basset 2005), knowing when a person is standing or lying down, and very low intensity movement like the one occurring when driving a car or going up in an elevator. This can be valuable input for the design as it provides more clues about the context, improving the possibilities for users to make sense of their own data. That, in turn, enables a sense of embodiment and a potential for self-reflection.

Accelerometers have another important advantage. As motion artifacts are one of the most common source of errors in ambulatory use biosensors, they can be very useful for eliminating these artifacts. Several solutions exist that make use of accelerometers to detect and attenuate the effects of movement in the signal of other biosensors (e.g. Westeyn et al. 2006, Asada et al. 2004).

Both methods of assessing Physical Activity comply with all the requirements defined in Section 3.4, as shown in Figure 4.4.

Relative Movement

1. Wearable sensors ✓
2. Lightweight and non-invasive sensors that allow for comfortable use ✓
3. Visually unobtrusive sensors ✓
4. Reliable output ✓
5. Durable and robust sensors requiring minimal or no maintenance ✓

Steps

1. Wearable sensors ✓
2. Lightweight and non-invasive sensors that allow for comfortable use ✓
3. Visually unobtrusive sensors ✓
4. Reliable output ✓
5. Durable and robust sensors requiring minimal or no maintenance ✓

Fig. 4.4. Sensor requirement compliance in Physical Activity input methods

4.2 Arousal

Stress response is the response of the organism to a stressor, might it be physical or psychological, and it is characterized by an increase of activity in the Sympathetic system and decrease in the Parasympathetic (a detailed explanation was given on Section 2.1.1). Arousal is a measure of this response. Similar bodily reactions occur in physical exercise, so this feature can also be associated with this activity. As arousal is a reaction occurring in the whole body, there is a variety of measurable body signals reflecting physiological changes (Chanel et al. 2005, McEwen 1998, Wagner et al. 2005):

- Hormones released by the HPA axis and activation of the ANS;
- Electroencephalogram (EEG), measuring the brain waves;

- Electrooculography (EOG), measuring the pupil diameter change;
- Electromyography (EMG), a technique that measures levels of contraction in the muscles, specially in facial muscles, in the case of arousal;
- Respiration rate;
- Skin Temperature;
- Cardiovascular activity with a number of possible indices, including heart rate, heart rate variability (HRV) and blood pressure and
- Electrodermal activity, changes in the skin conductance of electricity.

From these, the only ones that are hard to be measured non-invasively are the hormones, so we discard them. EEG, EOG, EMG and respiration rate are good candidates but the apparatus needed to correctly acquire these signals goes against the sensor requirements 2 and 3, defined on Section 3.4. In particular, respiration rate can also be estimated by looking into cardiovascular activity, as will be explained in the following sections.

Skin temperature can be used to discriminate arousal. During a “fight or flight” situation, the activity of the Sympathetic nervous system redirects the blood circulation from the periphery of the body to the interior, delivering more oxygen to the heart and other internal organs. This reduces the skin temperature, as result of less blood circulation in the surface. When the person is in a relaxed state, the opposite happens: the blood flows through the skin and rises the temperature. However, besides a large inter-individual variability (Freedman et al. 1987, McGrady & Roberts 1992), the usage of a skin temperature sensor to measure arousal in an everyday life setting has also the problem that, due to the constant homeostatic regulation of the body, the ambient temperature, breeze and clothing affect the measurement. If the environment is cold, the body will naturally adapt to the external environment by trying to maintain the internal temperature and pull the blood away from the periphery, which may cause a drop in skin temperature identical to the one happening in a stress response (Wainapel & Fast 2003). Furthermore, it has been found that skin temperature has different responses for emotions with similar arousal level (Oatley 1992). As an example, fear is associated with lower skin temperature and anger associated with high skin temperature. For these reasons, we excluded skin temperature since it is an ambiguous physiological reaction when it comes to represent Arousal.

Thus the ones that will be analysed in detail are the Electrodermal Activity and Cardiovascular Response.

4.2.1 Electrodermal Activity

The human skin has its own electrical activity. When a constant voltage direct current (DC) is applied in two points of the skin, the result is a current flow that changes over time. This phenomenon is explained by a variation on the skin conductance. Venables & Christie (1980), Fowles (1986) and Schmidt & Walach (2000) constitute comprehensive reviews of current practices on Electrodermal Activity (EDA) measurement.

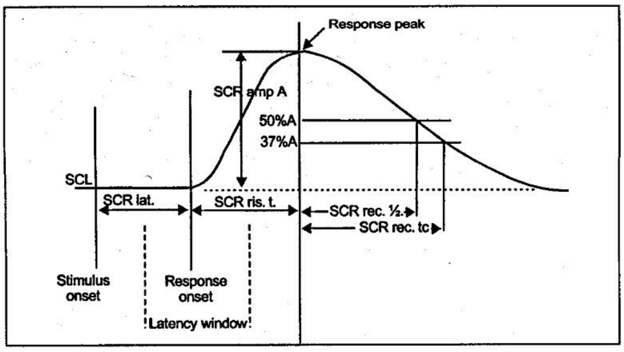


Fig. 4.5. Skin conductivity response. *(SCL = Skin conductivity level; SCR = Skin conductivity response)*. The graph shows different stages of the SCR, such as the rising time and return to baseline. A SCR typically lasts a few seconds. Extracted from (Schmidt & Walach 2000)

Skin conductance is measured in Siemens or mho (Micromho), and it can be divided in two distinct components: *tonic* and *phasic*. The *tonic* component changes slowly overtime and is related with the overall arousal level and natural day-to-night variations [2]. The *phasic* component rides on top of the *tonic* and causes peaks on the signal when a person is startled, feeling pain, sustaining breathing, etc. (see Figure 4.5). These peaks, called skin conductance responses (SCR) [3] have been used widely as a measure of instantaneous arousal because the conductance of the skin changes rapidly as a consequence of a dilatation in the eccrine sweat glands, directly activated by the Sympathetic system. Apart from the responses that result from external stimuli, SCRs may occur spontaneously. Because of this, it is usually hard to determine what caused a particular SCR. Inter-individual differences can also pose problems when evaluating arousal based on SCR.

Figure 4.6 shows graphs of SCR from two different subjects exposed to similar repeated stimuli. It is visible in the top graph that the SCRs repeat themselves, occurring no habituation to the stimulus, whereas in the bottom graph, the subject

[2] A study conducted by Hota et al. (1999) has shown that the tonic component of the skin conductance rises during the day

[3] Skin conductance responses are the inverse of galvanic skin responses (GSR) which measure changes in the electrical resistance of the skin. According to (Lykken & Venables 1971), the GSR term should no longer be used because it does not describe the measurement process adequately

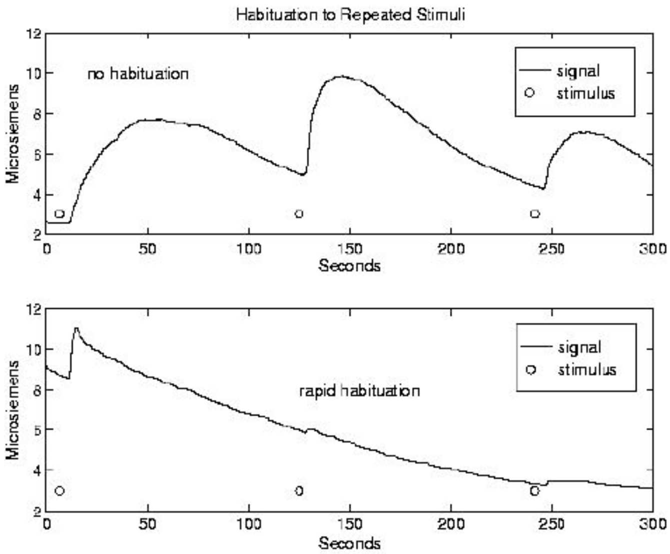


Fig. 4.6. Differences in skin conductivity response between individuals exposed to the same stimuli. Extracted from (Healey & Picard 1998)

only suffers the first SCR and the next stimuli do not provoke any change on the skin conductivity. Besides this, the *tonic* component of the skin conductance is influenced by ambiental variables like temperature (which can rise the overall sweat level, caused by homeostatic regulation) and humidity. These interferences can rise the *tonic* level because a moisturized skin has naturally a higher skin conductance.

Fake SCRs may also be caused by artifacts caused by movement, interferences with other electronic devices or differences in contact between electrodes and skin. One way to circumvent these is by post-processing the signal and eliminating all the very high-frequency components by applying a filter. ActionGSR, from Westeyn et al. (2006), uses accelerometers to correct the skin conductance signal and eliminate the artifacts produced by movement.

The usual places to place the two electrodes destined to measure the conductance of the skin are the forehead, palms of the hands and feet as these are the locations in the body with the highest concentration of eccrine sweat glands. Figure 4.7 illustrates two possible sensor configurations for measurement of skin conductance.

4.2.2 Cardiovascular response

The role of the Autonomic Nervous System on cardiovascular control is well-known and documented (Jalife & Michaels 1994, Grassi et al. 1998). Parasympathetic system acts upon the heart directly through a nerve called N. vagus, slowing it down,

Fig. 4.7. Example of skin conductivity sensors in the hand and in the foot. Extracted from (Picard & Scheirer 2001) and (Picard & Healey 1997)

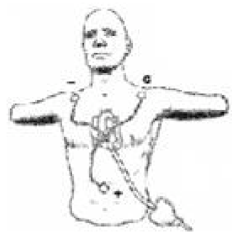
and the Sympathetic branch of ANS accelerates heart beat through different neural nerves. These influences are exerted continuously to maintain homeostasis.

One particular phenomenon, relevant to the understanding of the next Sections, is the fact that fluctuations on of the heart beat follow the respiration rate. As a person breathes in, the the heart rate accelerates. Expiration is accompanied by deceleration in the heart. This phenomenon, known as respiratory sinus arrhythmia (RSA), is explained purely by the Parasympathetic modulation, slowing down the heart by exerting control through the vagal nerve during expiration and accelerating it by withdrawal of parasympathetic influence. During a stress response, the RSA is no longer observable since there is a predominance in activity of the Sympathetic system.

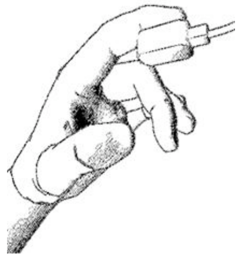
Knowing this, we will look in detail into sensor measurement of heart rate, heart rate variability and blood pressure, which are regulated both by the autonomic and endocrine systems and have been found to be good measures of arousal.

The most used method for measuring the electrical activity of the heart, considered the “gold standard”, is the Electrocardiogram (ECG). Introduced by Willem Einthoven in 1893, ECG monitors the heart through the placement of up to 12 electrodes in several parts of the body such as arms, chest and legs. These electrodes measure the electrical activity of the heart as it contracts and relaxes and its accuracy is close to 100%. A small and portable device capable of recording ECG is the Holter monitor. Even if they have shown to have good results (Zimetbaum & Josephson 1999), all the ambulatory electrocardiography devices produced so far are still too cumbersome and would not qualify for comfortable continuous use and integration into everyday life, as shown in Figure 4.8(a).

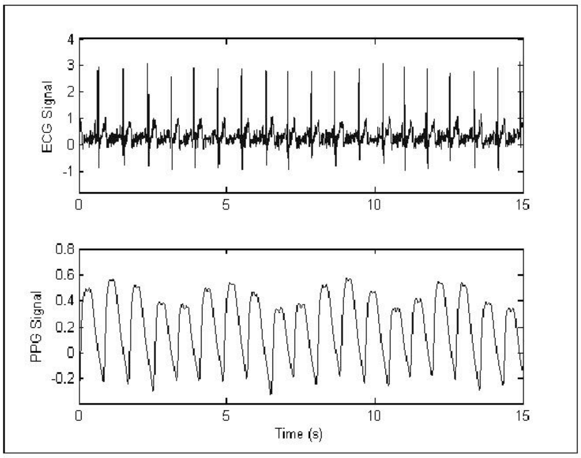
PPG sensors (described in Section 2.2), however, correlate well with ECG and can be worn on a ring or a wrist watch. Although PPG is sensible to light changes, temperature and motion artifacts, techniques have been developed with the use of accelerometery and filtering to attenuate the errors (Asada et al. 2004), making PPG technology robust enough for continuous monitoring.



(a) Holter monitor



(b) PPG sensor on the finger



(c) Signal captured simultaneously by a ECG monitor and a PPG sensor

Fig. 4.8. Possible usage of PPG and Holter monitors and output of both sensors

Assessing arterial blood pressure [4] from PPG sensors is also possible. Before the existence of PPG, the most used non-invasive method for measuring blood pressure is called "oscillometric method", developed by (Erlanger 1904). It involves an inflating cuff around the arm and an electronic pressure sensor detecting the blood flow. This method does not require expertise and can be used at home. The use of an inflatable cuff does not qualify this method for continuous ambulatory use. Recent techniques allow measuring blood pressure without the use of a cuff (Andriyashchenko et al. 1995). These techniques will be explored in detail later in this Chapter.

We will now explore the extraction of features from three physiological signals: arterial blood pressure, heart rate and heart rate variability.

[4] Arterial blood pressure is the *"The force that the circulating blood exerts on the walls of the arteries"* (CancerWEB 1997), where the blood circulates coming from the heart. It is commonly referred simply as blood pressure.

Arterial blood pressure

Blood pressure measurement is divided into systolic and diastolic. Systolic blood pressure is the pressure during the contraction of the heart. Diastolic blood pressure is the pressure during the relaxation phase. These are shown and explained in Figure 4.9. The same figure (4.9(b)) refers also the mean blood pressure, which is a mean calculated during one heart cycle (contraction and relaxation).

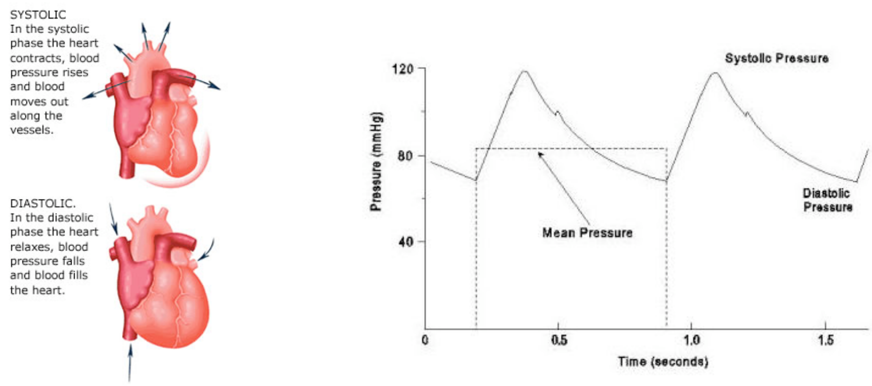


Fig. 4.9. Variation of blood pressure as the heart contracts and relaxes

Blood pressure is measured in mmHg (millimeters of mercury), a unit of pressure. It has been shown to rise during aroused states due to the activity of the Sympathetic system (Bernardi et al. 2000).

Sorvoja (2006) provides a review of practices on non-invasive blood pressure measurement and gives emphasis to three techniques: Tonometry, Pulse Transit Time (PTT) and Volume Clamp.

Tonometry measures blood pressure by applying external pressure on the skin above the artery. As the artery contracts and expands due to the passage of the blood, the sensor will measure the pressure applied on the skin and give a reading of blood pressure (see Figure 4.10 for an usage example of a tonometric sensor in the wrist).

Fig. 4.10. Demonstration of the tonometric method to assess blood pressure

A tonometric sensor can be easily integrated into a wrist watch. Salo et al. (2007) proposed a design of a small, portable and low-power consumption tonometric sensor. However, the construction of this sensor is still in process and there was no validation of this new design by independent studies found in literature.

One other technique described is PTT. Pulse Transit Time is the time it takes the pulse pressure waveform to propagate through a length of the arterial tree and it is inversely proportional to the blood pressure. Basically, if the blood pressure is higher, the blood takes less time to propagate into the arteries. This technique can use PPG to measure the changes in blood volume in 2 places, typically the wrist and fingertip. Briefly, the PPG sensors measure the exact time when the blood volume peak (caused by a heartbeat) occurs; the time difference between peaks in the wrist and in the fingertip represents the PTT, the time that the blood took to reach the fingertip from the wrist (see Figure 4.11).

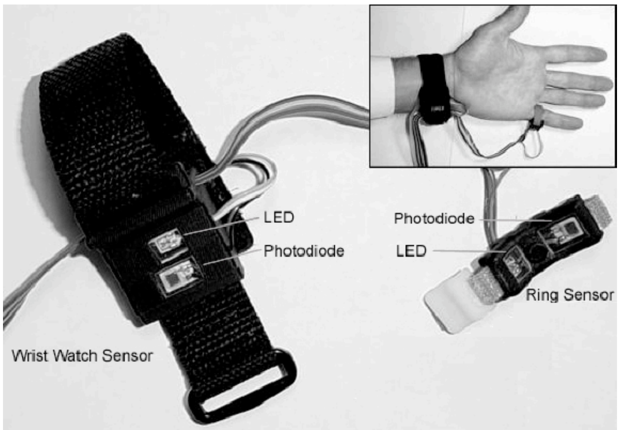


Fig. 4.11. Wearable sensor for measuring blood pressure through PPT method. It is composed of two PPG sensors.

PTT is the technique that has seen more development in recent years. Andriyashchenko et al. (1995) compared PTT with tonometry for long-term measurement and concluded that PTT was less intrusive since it does not need to apply external pressure and is less prone to errors since tonometry requires that the sensor is positioned exactly on top of the artery. This makes PTT more attractive for long-term monitoring. Hung et al. (2004) constructed a wireless measurement device that uses a PPG ring communicating via bluetooth to a mobile device, with a good accuracy.

However, as promising as it looks, PTT seems to be yet confined to research and lacks studies validating its use in an everyday life setting. The last technique described in this Section, Volume Clamp, has seen commercial application. Volume Clamp works by combining a PPG sensor and a small pressure cuff in the finger.

Briefly, the pressure cuff inflates to the same pressure of the artery. This pressurization of the cuff is controlled by the readings of the PPG sensor. Finapres^{TM}is the first commercial application based on a prototype by Boehmer (1987). Finapres has been validated by more than 150 studies and reviews and its accuracy is widely recognized (Sorvoja 2006). Portapres^{TM}, from Finapres Medical Systems, is a portable blood pressure monitor represented on Figure 4.12 that uses 2 PPG sensors to achieve better signal quality.

Fig. 4.12. Usage of Portapres. The sensors in the wrist and fingers communicate with the belt which has data storage capacity and a power source

Before attempting to determine an arousal level from blood pressure, the baseline for each individual must be determined. The standard procedure is for the person to stay relaxed for 5 minutes and move as little as possible (American Heart Association 2005). Once a baseline is determined, the arousal level can be determined by measuring short-term rises. Nothing was found in literature concerning methods for determining arousal levels from blood pressure but various studies agree that there is a general rise in both systolic and diastolic blood pressure during situations of emotional arousal (e.g. Bernardi et al. 2000, Gerin et al. 2006).

Heart rate

Heart rate is measured in beats per minute (bpm). In a stress response, the heart is one of the first organs to react, with an increase in the bpm determined by a withdrawal of Parasympathetic influence and increased influence of the Sympathetic system. Extracting the heart rate from the PPG sensor is a matter of determining exactly in which moment the ventricular contraction occurs (that is when the blood is pumped out of the heart). This causes a peak in the PPG signal similar to the ones observed in Figure 4.8(c) due to the fact that the blood volume in the arteries increases in this moment.

Once the heart rate is determined, measurement of arousal is made by detecting changes from the baseline. Since the heart rate baseline has a large inter-individual variation, it is necessary to calculate the resting heart rate (rHR) for each person. To best time to do it is in the morning, just after waking up from a good night of sleep. A number of factors can influence this measurement, such as the current stress level or the quality of sleep. Due to methodological constraints, a simplified baseline determination is usually done in laboratory setting after a period of 5 to 15 minutes of relaxation (e.g. Vuksanovi & Gal 2007, Mezzacappa et al. 2001, Lackschewitza et al. 2008).

There are not many cues on medical literature on how to correctly assess the arousal level from heart rate, most studies are more concerned in finding correlations between arousal and physiological responses so they simply measure changes in heart rate. Affective Computing literature provides some methods to assess arousal level, varying in complexity. Liu (2004) uses a simple algorithm with an specified threshold value to detect a stress response. More complex methods involve direct emotion classification using Machine Learning algorithms such as decision trees and neural networks (Picard 1997). We will not analyse those these further since they are mostly focused on extracting a concretely labeled emotion from physiological input, instead of an unvalenced index of arousal.

One simple method that could be used, taken from expert advice [5], is measuring the maximum heart rate (HRmax) for an individual and, from that, calculate training zones (illustrated in Figure 4.13)using percentages of HRmax as it is usually done by sport coaches and athletes to guide the training.

These zones could map directly to arousal levels. HRmax can be calculated in two ways: *(1)*Direct measurement in an exercise test, where the body is pushed to maximum strain;*(2)* Calculation using HRmax formulae.

The most common formula used to assess HRmax is:

$$HRmax = 220 - age \tag{4.1}$$

For example, if a person is 30 years old, then her HRmax according to this formula is 190bpm. This formula is attributed to Fox et al. (1971), who estimated it from a dataset obtained in other studies.

Robergs & Landwehr's (2002) review on 43 formulae used to calculate HRmax shows that formula 4.1 has in fact an error of 7 to 11 bpm. This finding is also supported by Silva et al.'s (2007) study on elder women, where an error of 7.4 bpm was found in the same formula when comparing predicted values against real values of HRmax, obtained in an exercise test. Robergs & Landwehr's (2002) review

[5] This advice was taken from the doctor Inga Jonsdottir and supported by doctors Yrsa Sverrisdottir and Gunnar Ahlborg, who guided the medical investigation in this thesis

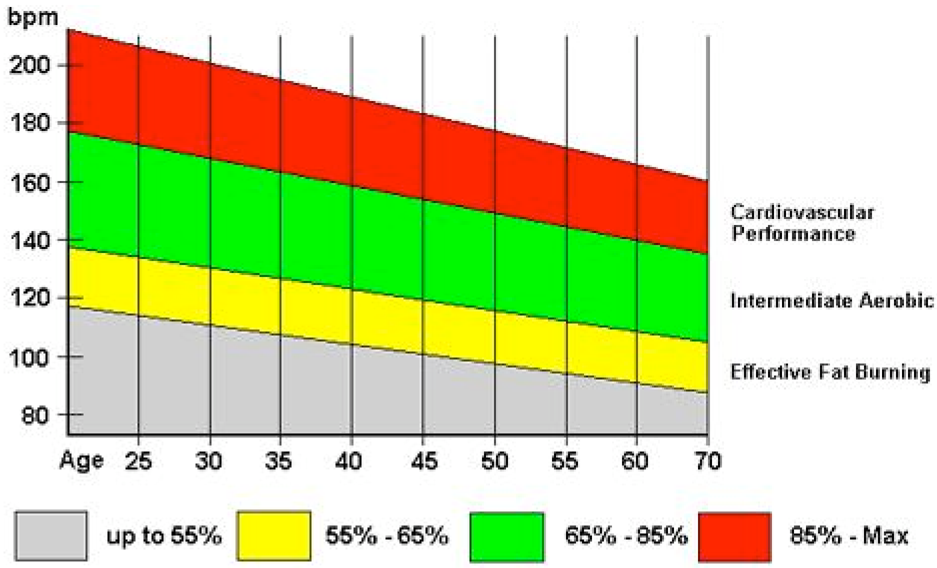


Fig. 4.13. Training Zones for exercise estimated from the formula *HRmax = 220 - age*

concludes that there is currently no acceptable formula and points to the fact that, to calculate a correct HRmax, an ideal formula should take into account more than just age; it should also consider physical fitness as well as mode of exercise [6] , as HRmax can be different depending on the type of activity. HRmax could also be possibly different for emotional arousal, but there are currently no studies published on this matter. From the reviewed formulae, the one with smaller error was published by Inbar et al. (1994):

$$HRmax = 205.8 - 0.685(age) \tag{4.2}$$

This formula has an error of 6.4 bpm, which was considered unacceptable for scientific and clinical purposes (Robergs & Landwehr 2002) but might still be acceptable for the *Affective Health* system, as it is not intended to make a diagnostic tool but rather to give clues about the overall state of the body.

Heart rate variability

Heart rate variability is defined as the natural occurring variation in time between two consecutive peaks in the ECG or PPG signals. The method for obtaining it from PPG sensors is similar to heart rate, described in the previous section. According to Chang et al. (2007), caution should be used when extracting HRV from a PPG signal,

[6] A mode of exercise is a type of exercise. Modes of exercise can be cycling, running, weight training, among others.

as differences were found when comparing the HRV results extracted from ECG and PPG recordings.

Each interval between two consecutive peaks is called normal-to-normal (NN) interval. HRV can be represented as a time series of NN intervals (all the analysis methods further described will assume this).

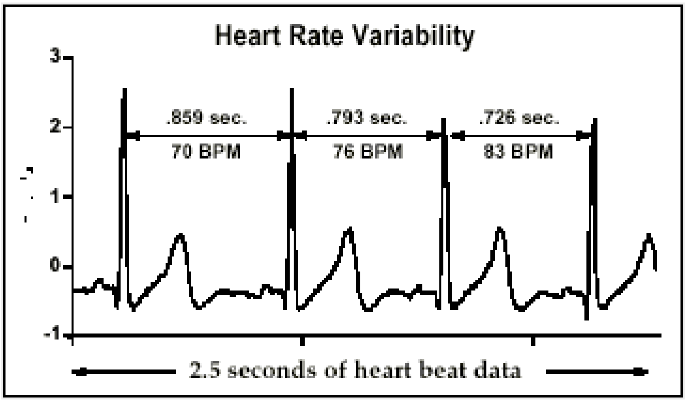


Fig. 4.14. Heart rate variability shown as the variation of the interval between two heartbeats. It can be represented in seconds or in beats-per-minute

Measures of HRV have been shown to correlate inversely with heart rate (Ungi et al. 1995, Mandanmohan et al. 2005), making HRV at least as reliable as heart rate to detect arousal. HRV contains more information than HR, which makes it possible to discriminate between Sympathetic and Parasympathetic components of the ANS influence on the heart. There are several possible methods used when analysing HRV. The comprehensive review from the The Task Force of the European Society of Cardiology (Electrophysiology 1996) divides these methods in three categories, explained later in detail:

Time Domain methods are the simplest category of methods. This category is further subdivided in statistical and geometrical methods

Frequency Domain methods which are obtained from analysing how the variance of the NN intervals is distributed as a function of the frequency

Nonlinear methods uncover the nonlinear phenomena involved in the genesis of HRV like the influence, on the heart, of complex homeostatic interactions between different systems in the human body

The Task Force standardized the measurement of HRV, recommending 5 minute recordings to analyse short-term variations and 24 hour recordings to measure long-term trends. Both Time Domain and Frequency Domain methods can be used for short-term recordings but when recording in long-term, Time Domain is preferred.

No recommendations are done regarding Nonlinear methods. Measure of arousal is typically made in short-term recordings (Electrophysiology 1996).

Methods of Time Domain are typically averages, variations, histograms or geometrical methods like the calculation of density distribution of the NN intervals. Table 4.1 describes the methods recommended by (Electrophysiology 1996) to study HRV in the time domain.

Variable	**Units**	**Description**
SDNN	milliseconds	Standard deviation of all NN intervals
SDANN	milliseconds	Standard deviation of the averages of NN intervals in all 5-minute segments of the entire recording
rMSSD	milliseconds	The square root of the mean of the sum of the squares of differences between adjacent NN intervals
HRV Triangular Index	no unit	Total number of all NN intervals divided by the height of the histogram of all NN intervals measured on a discrete scale

Table 4.1. Time domain methods recommended by Task Force of the European Society of Cardiology

Ten studies were selected from literature to illustrate the role of HRV analysis in assessing physiological stress responses to different kinds of stressors. These are summarized in Table 4.2. We are now going through the results from these studies one by one.

A study by Montebugnoli et al. (2004) with 25 health men and women found that *SDNN* was a highly sensitive indicator of stress during dental extractions, becoming lower during the extraction period. This index of HRV reflected changes during arousal more accurately than heart rate (also measured), making it a better indicator on arousal in this study. Another study (Lackschewitza et al. 2008) performed with hyperactive patients in a laboratory setting during a Trier Social Stress Test [7], also found *SDNN* to be discriminative between stressful and relaxed situations. *SDNN* is capable to measure longer periods of exposure to a stressor as shown in a study by Ushiyama et al. (2008) where this method was applied in 24 patients before and during the recovery time from a non cardiac medical surgery. *SDNN* de-

[7] Trier Social Stress Test is a tool created by Kirschbaum et al. (1993) for inducing stress in laboratory conditions. It contains periods of anticipatory stress, public speech and mental arithmetic task.

Study	**Stressor**	**HRV feature and behaviour**
Montebugnoli et al. (2004)	Dental extraction	*SDNN* reduced (more sensitive than heart rate)
Lackschewitza et al. (2008)	Trier Social Stress Test	*SDNN* reduced, *rMSSD* reduced; *LF* higher; *HF* reduced
Ushiyama et al. (2008)	Surgery	*SDNN*reduced and rises with recovery; *HRV Triangular Index* reduced and rises with recovery
Mezzacappa et al. (2001)	Mental Stress	*rMSSD* reduced
Komatsu et al. (2007)	Interaction with an Agent	*HF*power reduced; *LF* power rise
Castro et al. (2008)	Arithmetic Stress	*HF*power reduced; *LF* power rise
Moriguchi et al. (1992)	Arithmetic Stress	*HF*power reduced; *LF*power rise
Bernardi et al. (2000)	Reading, free talking, mental stress	*LF* power increased with mental stress and talking
Vuksanovi & Gal (2007)	Mathematical task with vocalization	*HF* rises with half of the subjects; *HF* reduced for the rest; *short-term scaling component* and *SampEn* associated with *HF* rise;*LLE* associated with *HF* fall
Terkelsen et al. (2005)	Mental stress and pain	Pain rises *LF* and causes no change in *SDNN* and *HF*; mental stress during pain causes no change

Table 4.2. Summary of ten studies analysed concerning HRV and stress responses

creased significantly before the surgery and recovered gradually during the 7 day postoperative period. *HRV Triangular Index*, usually used as a measure of overall HRV, was also calculated in this study with similar correlation with recovery (lower before the operation and higher after 7 days of recovery). Ushiyama et al.'s (2008) study goes further by analysing the differences, on these indexes of HRV, in the last day of recovery between patients that had a normal recuperation and patients with postoperative complications; the ones who recovered normally had a significantly higher *HRV Triangular Index*. Another variable of the Time Domain, *rMSSD*, was found in different studies (e.g. Lackschewitza et al. 2008, Mezzacappa et al. 2001) to become lower during periods of exposure to a stressor and to rise during relaxation periods. This variable has been seen as a direct measure of Parasympathetic influence on the heart (Electrophysiology 1996, Mezzacappa et al. 2001). No studies were found in literature relating *SDANN* to arousal level.

Any time series can be seen as a composition of sines and cosines with distinct frequencies. As we are assuming a time series representation of HRV, it is possible also to analyse the signal using Frequency Domain methods. Frequency Domain variables are obtained by means of power spectral density (PSD) analysis, usually done in HRV with the application of an algorithm called Fast Fourier Transform (FFT).

FFT transforms the signal into sinusoidal oscillations with distinct frequencies and amplitudes. For each oscilation associated with a certain frequency, the amplitude determines its contribution (power) to the signal (Seely & Macklem 2004).

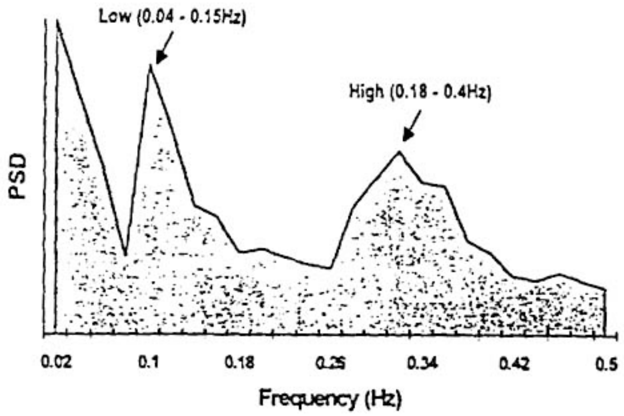


Fig. 4.15. Power spectral density distribution of HRV. Two frequency bands are distinguished: low frequency and high frequency.

The result, shown in Figure 4.15, is a power distribution in frequency of the HRV signal. Two distinct frequency bands in the power distribution are identified with peaks in power. The *high-frequency (HF)* (0.18-0.4Hz) band is commonly associated with Parasympathetic activity and the *low-frequency (LF)* band (0.04-0.15Hz) is mediated by both Sympathetic and Parasympathetic nervous systems (Akselrod et al. 1981, Pomeranz et al. 1985), though the exact meaning is not yet determined. There are two other bands identified as *very-low frequency (VLF)* and *ultra-low frequency (ULF)* in the review from Electrophysiology (1996); however, as the physiological explanation for these bands is not yet established on short-term analysis (the one necessary for measurement of stress responses) we will ignore them in this Section for simplicity.

From the *LF* and *HF* bands, it is possible to estimate autonomic regulation of the heart. *HF* has been found to be synchronous with respiration (Bernardi et al. 2000) and a good measure of RSA (the acceleration and deceleration of the heart rate following respiration, explained in the beginning of this Section).

Komatsu et al. made a study (Komatsu et al. 2007) employing frequency methods to monitor HRV in subjects during a planned stressful interaction with an artificial agent. They found that, when the interaction was reported stressful by the subjects, the *HF* would be lower than the *LF* power, denoting a loss of RSA and Parasympathetic activity. Lower *HF* power and higher *LF* power during aroused states is also reported by many studies (e.g. Castro et al. 2008, Moriguchi et al. 1992, Lackschewitza et al. 2008). However, just looking at the power of these two bands can be deceiving as reported in a study by Bernardi et al. (2000), where it was found that talking could affect the whole spectrum because it causes faster breathing and thus a big shift on the spectrum to the *LF* part. This was referred as well in (Vuksanovi & Gal 2007), where subjects were asked to perform a mathematical task with vocalization. In this study it was also found that the *HF* response to stress has inter-individual differences: in some of the people the power rises and in others the *HF* power is lower. Besides this, Terkelsen et al. (2005) reported lack of change in the power spectrum of HRV in pain when the subject is in mental stress, while still causing a rise in heart rate.

Finally, Nonlinear analysis of HRV employ methods from nonlinear dynamics. Nonlinear dynamics, as defined in CancerWEB (1997), is the study of systems who react nonlinearly to initial conditions or perturbing stimuli. Biological systems usually display nonlinear dynamics and chaos [8] behaviour. Variation in heart rate also exhibit this behaviour (Seely & Macklem 2004, Goldberger et al. 2002, Peng et al. 1995) . There is great number of methods in this category but the Task Force (Electrophysiology 1996) concluded that research is still needed before these methods can be safely used in physiological studies and clinical settings. More recent investigation associates these indexes with progression to heart diseases (as predictors) and aging (e.g. Perkiomaki et al. 2000, Schumann et al. 2002). A study from Vuksanovi & Gal (2007) found that 3 indexes were correlated with stress response: *Sample Entropy (SampEn)*, a nonlinear index of entropy [9] ; *Largest Lyapunov exponent (LLE)*, an index that measures amount of chaos (i.e. sensibility to initial conditions); and *short-term scaling component*. Unfortunately the behaviour of this indexes was different between groups of individuals and it was not possible to establish a baseline.

To map these features to an arousal level, the baseline for each one would have to be determined in the same way that was described for heart rate. Extracting arousal levels from HRV would depend on which feature to use. If we use features from the Time Domain, then the individual maximum for each feature can be determined from an exercise test, where the heart is pushed to the limit and, from that, calculate arousal level zones. For Frequency methods, the ratio *LF/HF* could be used since it seems to map to arousal level in most of the studies. There was not enough evidence in the literature supporting the use of nonlinear analysis of HRV to map to arousal.

[8] Chaos is defined as an extreme sensitivity to initial conditions. Chaotic systems often seem random, but this is due to the interference from the initial conditions

[9] Entropy is defined in the dictionary (CancerWEB 1997) as *"The amount of disorder in a system"*. It measures the randomness in a system.

4.2.3 Evaluation

All of the features analysed constitute validated measures of Arousal. EDA in particular is very sensible to subtle changes in arousal and provides a measure of the activity of the sympathetic system.

Measuring cardiovascular parameters differs in complexity. Heart rate and arterial blood pressure are the simplest. On the other side, HRV can discriminate between different components of the ANS, containing more information about physiological arousal. Besides that, it was shown in the study by Montebugnoli et al. (2004) to be more sensitive to changes in arousal than heart rate. There are more features in HRV than the ones that were analysed in this Section (Electrophysiology 1996). The selection of features to analyse further was based on recommendations of the Task Force of the European Society of Cardiology, their representation in literature and proven correlation with arousal. In particular, features from the Time Domain, like *SDNN* or *rMSSD* seem to be very good indicators of arousal. *rMSSD* was also shown to be a good direct indicator of parasympathetic activity in one everyday life setting (Goedhart et al. 2007) when compared to others like *HF* from frequency analysis. Frequency domain indexes, when used outside of a specific setting, behave sometimes in unpredictable ways (Bernardi et al. 2000, Vuksanovi & Gal 2007). Further research might be needed to know exactly how the complex interplay between *HF* and *LF* works and what is the exact meaning of these bands.

From this analysis, we are left with four possible features: skin conductance responses, blood pressure, heart rate and HRV in Time Domain. Figure 4.16 shows the requirement compliance of the input methods related with Arousal.

The only ambulatory blood pressure sensor that as seen application outside of a laboratory setting, Portapres, also does not comply with requirements 2 and 3 because it needs three points of measurement (wrist and two fingertips) with wires connecting them, which obstructs the free use of hands.

Heart rate and HRV can be measured from one PPG sensor in the wrist or in a ring. Both method and features comply with all the requirements enunciated in Section 3.4. However, even the simplest Time Domain methods of HRV analysis are more sensitive to measurement errors than heart rate. This happens because heart rate is determined as an average of peaks in the PPG signal and HRV is characterized by all the inter-beat intervals. Chang et al. (2007) reports differences in indexes of HRV analysis in signals, from the same subject, collected simultaneously from ECG and PPG sensors. Even if the difference was not considered statistically significant, there were cases where it reached almost 20%. These facts make HRV indexes less strong compared to heart rate when it comes to satisfying requirement 4.

Heart rate has been shown to correlate significantly with skin conductance. Figure 4.17 shows an example of that, where heart rate was calculated from an ECG

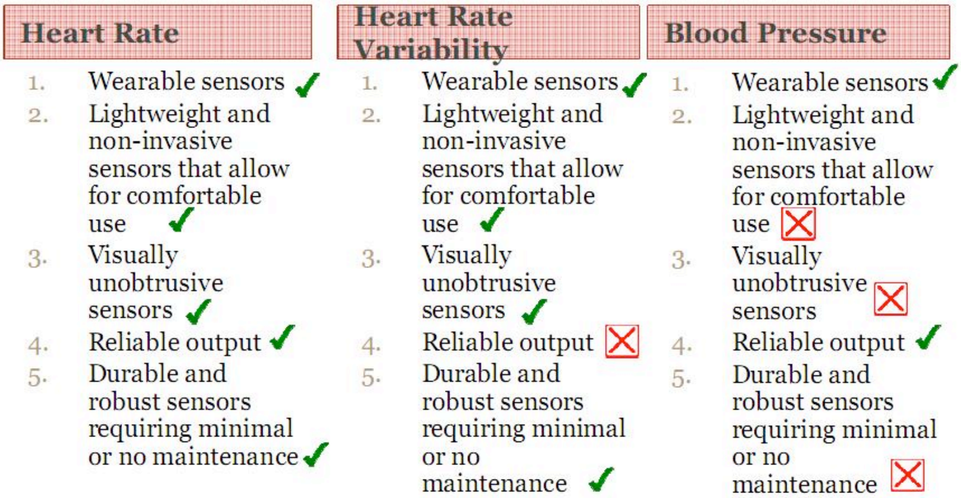


Fig. 4.16. Sensor requirement compliance in Arousal cardiovascular input methods

signal by selecting peaks in 15 second intervals where the heart accelerates and then running an average in each interval (Malmstrom et al. 1965).

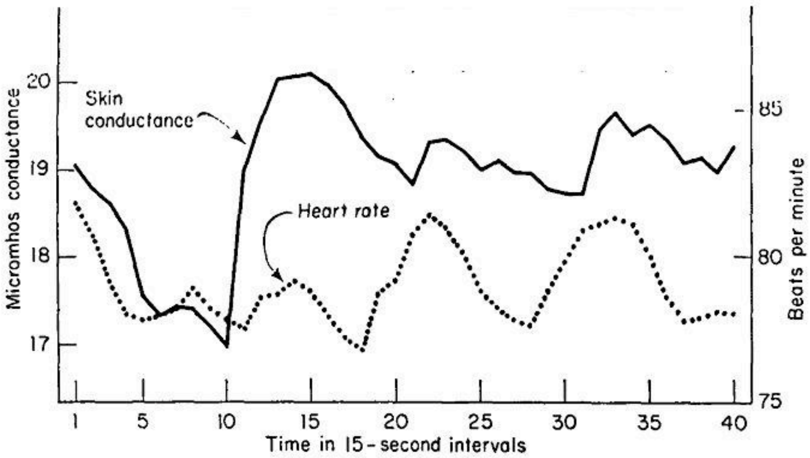


Fig. 4.17. Heart rate correlation with skin conductivity after applying Malmstrom et al.'s (1965) method

The apparatus needed to correctly extract skin conductivity need to be placed, on the body, where most of the emotional sweat (caused by eccrine glands) occurs. This places, typically the forehead, palms and soles of the feet, require obtrusive and possibly uncomfortable sensors. Research in Affective Computing produced artifacts that minimize this discomfort, like a thin glove (Picard & Scheirer 2001). However, wearing a glove in everyday life is unlike to comply with the requirements 2 and 3 (see Figure 4.18) . Others, like Exmocare (2007), integrated a skin conductance sensor into a watch, measuring from the wrist. Unfortunately there was no validation of skin conductance measurement in the wrist (or any other part except for the three previously referred) found in literature.

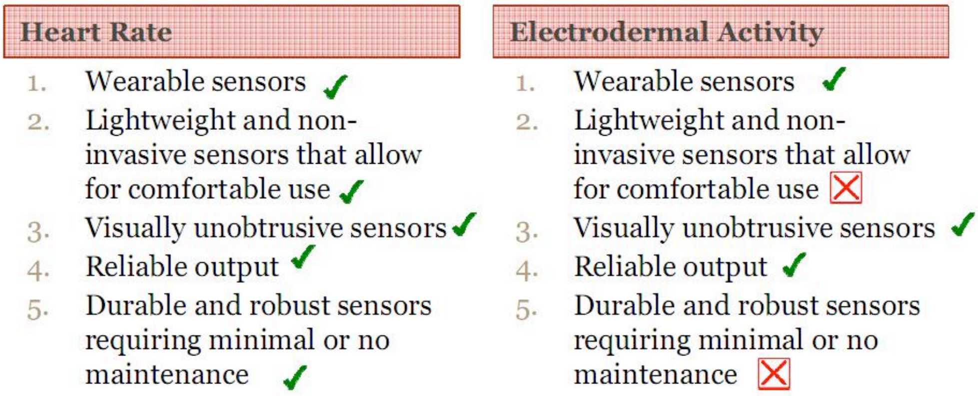


Fig. 4.18. Sensor requirement compliance in heart rate and electrodermal activity to measure Arousal

4.3 Adaptability

The concept of Adaptability, defined before as "capacity to adapt to changes in environment", has been put forward as an hypothesis in the *Affective Health* project. Since there is currently no monitoring system that represents this concept or any other similar one, we will explore in this Section the feasibility of mapping it to collectible physiological data.

The human body has an incredible potential for adaptation. Homeostasis is the process responsible for the adaptations that happen over a long time period. When the organism needs to reply fast, such as in the presence of a stressor, a different process occurs, in parallel with homeostasis: allostasis. Allostasis usually comes with allostatic load, a negative consequence for the organism that can impair homeostasis and leave the body more vulnerable to diseases. These two processes were explained in detail in Sections 2.1.2 and 2.1.3.

Allostatic load appears in the literature almost independent of age. In fact, as age progresses, the majority of older adults experiences two or more chronic conditions (e.g. hypertension) and allostatic load has been an increasingly used model to explain this fact (Singer et al. 2005). Some people are able to age more healthier than others and this fact appears to be associated with healthy habits (e.g. not smoking, exercise) and less exposure to stress. Nielsen et al. (2007) review current evidence of allostatic load on literature and notice the large inter-individual differences when it comes to healthy aging and response to stressors, based on personality, gender, social and cultural environments.

The investigation on how to measure allostatic load on acute stress responses and discovery of biomarkers of accumulated damage from stress is currently on a early stage, but with an increasing number of studies being published on the subject (Loucksa et al. 2008). A biomarker can simply be a physiological index (e.g. blood pressure) that can measure the effects of allostatic load. Figure 4.19 shows what would be the "perfect" biomarker (allostatic load, given as an example of a biomarker, can be estimated by a physiological index).

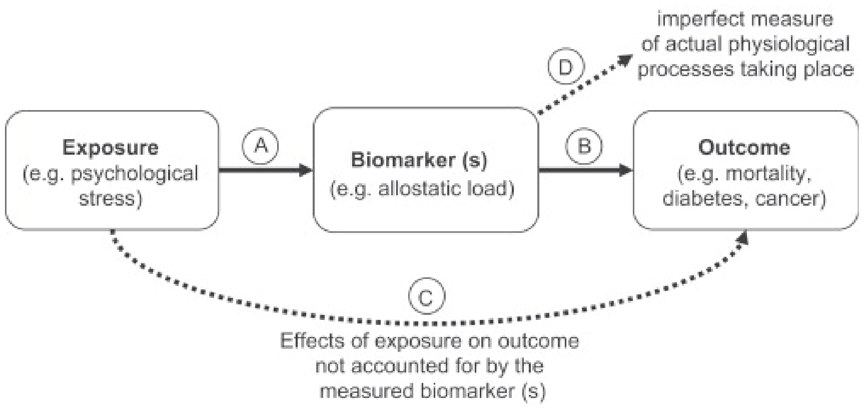


Fig. 4.19. Imperfection of biomarkers of allostatic load. Extracted from (Loucksa et al. 2008)

The perfect biomarker would predict entirely the outcome, shown by paths A and B in Figure 4.19, that can be a predisposition to diseases. However, the current reality is that we still do not have a perfect biomarker that can capture all the aspects of exposure to stress (path C). In addition, all the biomarkers that can be captured by current technology are merely approximations of the internal processes of the body (path D).

Knowing this, if we consider mapping Adaptability to a marker of allostatic load, we should not aim to get a true value with clinical use potential, since the sensing technologies used in the research of allostatic load are still far away from being implementable in a wearable sensor (e.g. currently one the best biomarkers discovered so far is the number of cells of the immune system (Loucksa et al. 2008), measurable only by microsensors in a laboratory setting). Instead, the investigation will be driven by a "best-effort" goal.

In a study conducted by Seeman et al. (1997), it was found that degeneration by allostatic load in ten physiological variables related with the activity of the ANS and HPA could predict cardiovascular risk and mortality in a 2.5 year follow up. Most of the data used in this study cannot be measured non-invasively as the variables used were mainly related with concentration in the blood of several hormones related with autonomic regulation. Cardiovascular markers were, however, in the list of predictors.

Measurable cardiovascular markers that account for the cumulative damage of allostatic load from stress were already explored in this thesis, associated with Arousal (in Section 4.2): heart rate, HRV and arterial blood pressure (Lucini et al. 2005, Brady & Matthews 2006). Lucini et al. found that individuals being exposed for a long time to stress are characterized by having higher blood pressure and a predominant sympathetic activity (assessed by heart rate of HRV analysis). High blood pressure, not only is directly associated with stress, but also appears as a major physiological marker of increased cardiovascular risk (Alberti et al. 2005).

Besides cardiovascular markers, one other important marker that is affected by exposure to stress is sleep quality. Low sleep quality is both a marker of the consequences of stress (Morin et al. 2003, Winwood & Lushington 2006) and a generator of allostatic load, since the body cannot recover during sleep (Cauter et al. 1997, Ekstedt et al. 2003).

Sleep and cardiovascular markers will be analysed during this Section, testing if their validity and measurement techniques are qualifying enough to be included in *Affective Health*.

4.3.1 Cardiovascular markers

Besides arterial blood pressure and increased sympathetic activity, we can explore one other possible marker: nonlinear indexes of HRV.

Nonlinear analysis of many biological systems reveals a complex behaviour characterized by multiple interconnected feedback loops. In presence of disease or aging (both characterized by accumulated allostatic load), these loops breakdown and the systems usually reveal a less complex behaviour. For example, EEG signals have less entropy in presence of anaesthesia and respiratory variability as well as the entropy of the concentration of growth hormone in the blood, both decline with age (Seely & Macklem 2004).

Many studies associate loss of complexity in HRV (given by different indexes) with loss of health and aging (e.g. Schumann et al. 2002, Bojorges-Valdez et al. 2007, Goldberger et al. 2002, Peng et al. 1995, Seely & Macklem 2004). However, none of the articles reviewed in literature found a direct and independent correlation between nonlinear analysis of HRV and long term exposure to stress.

Arterial blood pressure

Blood pressure measurement was analysed previously in Section 4.2.2. In particular, it has been noted that the available methods of measurement did not comply with the requirements defined for *Affective Health*. However, the amount of evidence in literature supporting the use of this cardiovascular marker for measuring allostatic load deserves further analysis. In this section we will only explore the utility of measuring blood pressure for Adaptability.

According to American Heart Association (2005), *"Blood pressure is a powerful, consistent, and independent risk factor for cardiovascular disease and renal disease"*, with more than a half of the United States population having average values of blood pressure above the normal range (systolic blood pressure of 120 to 139 mm Hg or diastolic blood pressure of 80 to 89 mm Hg). American Heart Association point to three potential measures of blood pressure that are associated with increased risk: average level, diurnal variation and short-term variability. Average level is the most known and more related with allostatic load but it has also been referred that subjects whose blood pressure value does not go down during the night are at most risk than those who do, even if their average is the same. So diurnal variations should also be taken into account. Short-term variability appears defined in literature in many ways. One type of variability is the reactivity to stressors, and that will be explored in the Section devoted to reactivity, later in this Chapter.

American Heart Association (2005) defined standard normal average values for ambulatory (everyday life) blood pressure recording. These values are higher than the normal values usually defined for blood pressure, when the measurement is made by a doctor and the subject is relaxed, because they have to account for normal arousal and physical activity that happens during the day. They are expressed in the Table 4.3.

	Optimal	Normal	Abnormal
Daytime	<130/80	<135/85	>140/90
Nighttime	<115/65	<120/70	>125/75
24-Hour	<125/75	<130/80	>135/85

Table 4.3. Table of normal average ambulatory values (in *mm Hg*) of blood pressure during different time spans. The two values appearing in each cell are the systolic and diastolic blood pressures, separated by a '/'. Extracted from (American Heart Association 2005).

The association between blood pressure and long exposure to stress can be found in several studies (e.g. O'Connor et al. 2001, Lucini et al. 2005). Guimont et al. (2006) analysed the progression of blood pressure of 6719 white-collar workers (men and women) during 7.5 years, compared with job strain. They have found that having a high demand job with low social support (which is associated with stress) is correlated with significant, but modest, increases in systolic blood pressure. Lucini et al. also had similar results with a smaller group of subjects (126) who reported symptoms of chronic stress. The measurements of blood pressure in both these studies have been done in an laboratory setting.

Other studies (Schnall et al. 1998, Vrijkotte et al. 2000, Landsbergis et al. 2003) performed in an ambulatory setting also found a significant increase of approximately 4 mm Hg in average systolic blood pressure for people that self-reported long-term exposure to stress. Diastolic blood pressure was also affected in all of them, but less significantly. Moreover, these changes are also present at night, denoting that the increased blood pressure is not only a consequence of arousal and physical activity during the day, but a chronic state directly associated with long-term exposure to stress and an incapacity to relax.

Sympathetic predominance

Julius (1993) reviewed literature evidence on hypertension (i.e. a chronic condition defined as having a blood pressure $>140/90$) and points to the fact that developing a chronically high blood pressure later in life is predictable by having an earlier increased activity of the Sympathetic nervous system. This is fundamented by longitudinal studies where healthy subjects with higher heart rate have a higher probability of developing, over the course of the years, hypertension or associated symptoms. A presumed hyperactivity of the Sympathetic nervous system may be explained by frequent activation during responses to stressors (Julius 1993).

This is also independently confirmed by some of the studies previously analysed when exploring blood pressure, also measuring other markers associated with the activity of the Sympathetic and Parasympathetic nervous systems. Lucini et al. (2005) found that, besides an increased blood pressure, chronically stressed people have higher *LF* power and lower *HF* power on the Frequency Domain analysis of HRV. As explained before, the *HF* appears to be associated with the Parasympathetic system and the *LF* band has both Sympathetic and Parasympathetic influences. The findings that a decreased Parasympathetic activity is associated with chronic stress are supported also by other studies (e.g. Thayer & Sternberg 2006) Lucini et al. did not report a higher heart rate for people suffering from chronic stress.

Vrijkotte et al. (2000) found an higher heart rate and lower influence of the Parasympathetic influence on the heart assessed by an index of the Time Domain analysis of HRV: *rMSSD*. These measurements were taken in an everyday life setting during the course of three days. Figure 4.20 shows the variation of these variables over the course of days.

Heart rate recovers almost totally in the stressed group and controls, but *rMSSD* can be used to distinguish groups even during sleep. Vrijkotte et al. go further by

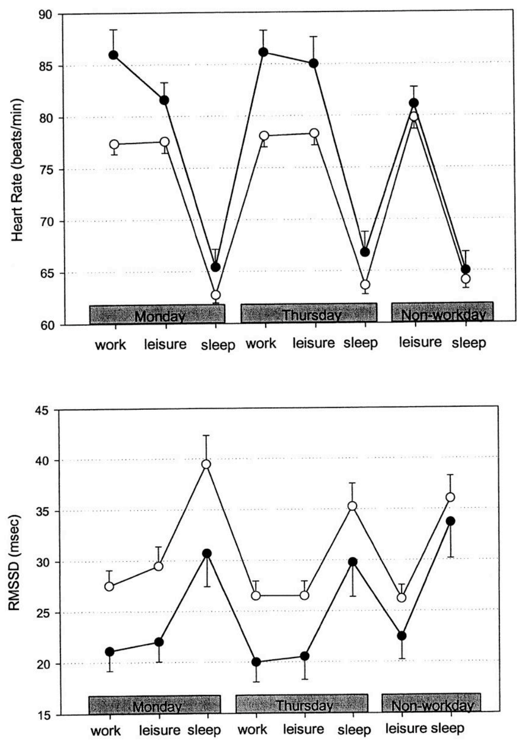


Fig. 4.20. Changes in heart rate and rMSSD during the course of three days for a high stressed group and a group of controls. The line with black dots represent the high stressed group and the line with white dots represent the controls. Adapted from (Vrijkotte et al. 2000)

proposing the average value of *rMSSD* during sleep as a probability predictor for mild hypertension, a state that occurs before hypertension. However, it has been noticed that there are not still many studies regarding cardiovascular recuperation during sleep as a direct consequence of stress, so this matter requires more extensive studying (Myllymöki 2006).

Increased reactivity of cardiovascular indexes (heart rate, HRV and blood pressure) to stress and delayed recovery to baseline also is related with sympathetic predominance. It has been shown that people who have been exposed to long periods of stress react more vigorously to stressors (e.g. Lepore et al. 1997), exhibiting an exaggerated physiological response. Vrijkotte et al. also refers this association in the same reported study. In a study with adolescents, Matthews et al. (2003) concludes that blood pressure reactivity predicts future blood pressure average in adolescents, with the high-reactive subjects developing high blood pressure later in life. However, there is also evidence in literature showing that cardiovascular reactivity in controlled settings depends on the kind of stressor (Nealey-Moore et al. 2007) and personality of the individual (Ivancevich 1987). One meta-review (Gump & Matthews 1999) analysed 19 studies related with reactivity and recovery in subjects with background stressors and concluded that more than half of studies concerning reactivity show, in fact, increased cardiovascular response to acute stressors in people exposed in the past to a lot of stress. However, a still substantial minority of studies also show a decreased cardiovascular reactivity for certain people exposed to certain stressors.

Delayed cardiovascular recovery from an exposure to acute stress (short-term exposure, such as getting scared of something) seems to be also associated with increased risk, as noted by Schuler & O'Brien (1997) in a meta-review of related studies. Schuler & O'Brien referred also that the recovery usually depends on the physical fitness and race of the subject. Gump & Matthews refers that chronic stress is associated with delayed recovery of blood pressure (also confirmed by recent studies: Stewart & France 2001, Steptoe & Marmot 2005) but not with delayed recovery of heart rate.

4.3.2 Sleep

Disturbed sleep has been suggested as one of the main mechanisms reflecting the consequences of long-term stress (Dahlgren 2006, Winwood & Lushington 2006). Figure 4.21 shows the visible correlation between reported sleep problems and diseases caused by work-related stress in Sweden, with data from SCB (2005). Poor sleep also causes physiological arousal, which in itself is a cause of more allostatic load (Dahlgren 2006).

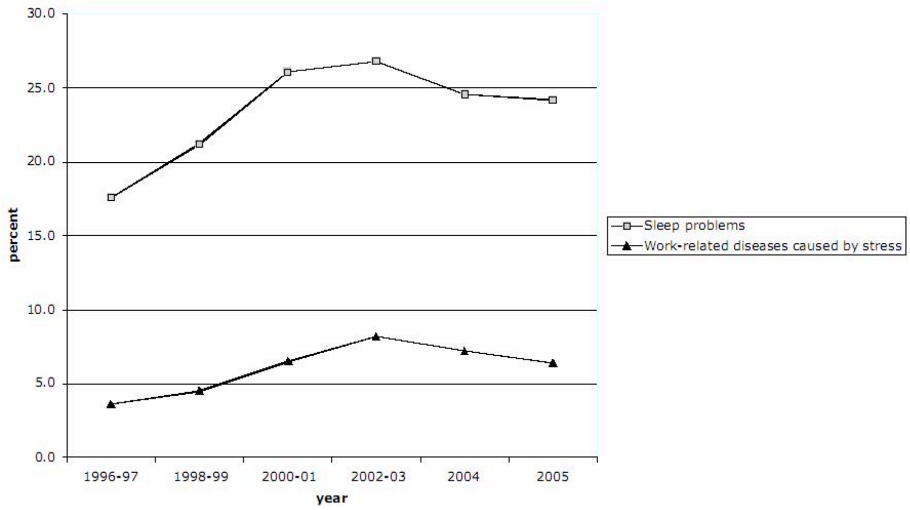


Fig. 4.21. Relationship between stress and sleep related problems in Sweden. Extracted from Dahlgren (2006)

Clinical assessment of sleep is usually done by a method called polysomnography, which measures brain waves, muscle tension and eye movement (Tryon 2004). With a polysomnograph, it is possible to detect sleep stages and physiological activity during sleep. This method, however, is expensive and time demanding (Dahlgren 2006) and does not qualify for continuous sleep measurement in an everyday life setting. It is also possible to measure sleep by identifying periods of activity and rest with a wrist worn accelerometer (Tryon 2004, Jean-Louis et al. 2001). Tryon showed that accelerometery and polysomnography have high correlations: 0.72 to 0.98 for total sleep period, 0.56 to 0.91 for sleep efficiency[10] and 0.49 to 0.87 for beginning of waking up after sleep. Figure 4.22 shows a typical output from an accelerometer during wake and sleep times.

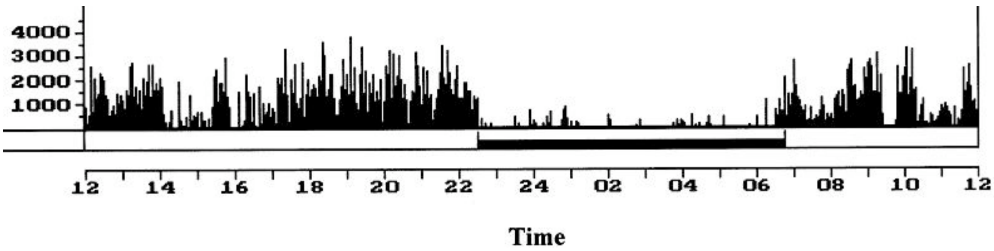


Fig. 4.22. Graph of physical activity a 24 hour period. Adapted from (Jean-Louis et al. 2001)

As it may be difficult to detect sleep time automatically (because the output of an accelerometer for periods of very low physical activity are similar to sleep periods), Tryon proposes that the sensors have “lights-off” and “lights-on” buttons in order to help the estimation of sleep time. The buttons should be pressed by the user when she goes to sleep and when she wakes up. Even if this might result in a overestimation of sleep period, the method is normally used in sleep assessment studies (e.g. Garnier & Benefice 2006) and has been shown to improve substantially the reliability of the method (Tryon 2004).

Besides the determination of sleep time and sleep efficiency, one other method used to assess sleep is measuring sleep fragmentation. Fragmentation is defined by short-term increases in arousal during sleep time. Ekstedt et al. (2003) measured brain waves during sleep to detect arousal and found that subjects that exhibited more than 8 rises in arousal during deep sleep stages have increased blood pressure and other markers of allostatic load by chronic stress. It has been shown that HRV analysis during sleep can detect sleep fragmentation periods, by assessing Sympathetic and Parasympathetic activities (Sforza et al. 2007). The authors propose frequency analysis to derive features like *LF* and *HF*. During sleep fragmentation pe-

[10] Sleep efficiency is defined as the ratio of total sleep time to time in bed.

riods, *LF* is higher than *HF*. Slight increases in heart rate and blood pressure could be also observed. Other authors (e.g. Sforzaa et al. 2004, Hayward 2004) have also found short-term increases in heart rate and blood pressure during fragmentation periods.

4.3.3 Evaluation

The most validated method for assessing the cumulative damage of allostatic load is the measurement of blood pressure. From the analysis carried on in Section 4.2 (Arousal) it was concluded that the only sufficiently validated biosensor capable of measuring blood pressure in an everyday life setting without causing much discomfort, Portapres, still does not comply with the requirements 2 and 3 defined in this thesis for the input methods since obstructs the use of the hands.

Analysing the health implications of having a high blood pressure, however, provided background to justify other cardiovascular markers like having a pronounced Sympathetic drive to the heart. A predominant Sympathetic activity seems to be correlated with future high blood pressure (Julius 1993), which could mean that a feature related with low Parasympathetic or high Sympathetic tone is an earlier predictor of future cardiovascular risk. Features produced from HRV analysis seem to have this quality and have been shown to be related with long-term exposure to stress (Vrijkotte et al. 2000, Lucini et al. 2005). Frequency analysis indexes of HRV (like *LF* and *HF* powers) seem however to be strongly influenced by respiration, talking and body postures (e.g. Vuksanovi & Gal 2007, Electrophysiology 1996). Features from the Time Domain analysis of HRV are very sensitive to errors from sensors, especially when it is done in a large amount of data (Seely & Macklem 2004), and PPG sensors, though have been shown to be sufficiently good to derive heart rate, may not be good enough to provide high quality data needed for HRV analysis in an ambulatory setting (Chang et al. 2007). So HRV analysis is against the requirement 4, concerning reliability. This has been already pointed out in the Arousal section, but this statement is stronger when it concerns Adaptability, because a large amount of data is needed to derive meaningful features like the average of *rMSSD* during the night period in the study by Vrijkotte et al. (2000).Alternatively, a chronically high heart rate can be used to assess continuous predominance of Sympathetic influence on the heart.

Increased reactivity and delayed recovery from acute stress are not sufficiently supported in the literature, as pointed out by Gump & Matthews (1999) and Schuler & O'Brien (1997). This is true also for long-term recovery, like the one happening during the night after a stressful day at work (Myllymöki 2006).

The relationship of poor sleep and chronic stress has a strong background in the literature (e.g. Morin et al. 2003, Winwood & Lushington 2006, Dahlgren 2006).

Sleep quality and total sleep time can be measured by an accelerometer in the wrist, which complies with all the requirements. One other feature related to sleep measurement is fragmentation, which can be assessed by short-term increases in heart rate. Heart rate can also be measured with total compliance with the requirements by PPG ring or a PPG wrist sensor.

5

Results

The analysis carried on in the previous Chapter provided various methods of input and possible features with the potential to map to the concepts of Physical Activity, Arousal and Adaptability. The analysis was mostly based on literature but some solutions were filtered because of non compliance with the requirements defined in Section 3.4. Therefore, the results presented here are an integration of the evaluations made before. Table 5.1 resumes the biosensors and features in physiological data that were found to have sufficient support in literature while satisfying the requirements of *Affective Health*.

	Sensor	**Feature**
Physical Activity	Accelerometer	*Counts / Epochs*
	Pedometer	*Steps*
Arousal	PPG	*Heart rate* *HRV Time Domain*
Adaptability	Accelerometer PPG	*Sleep time* *Sleep quality* *Sleep fragmentation* *Heart rate*

Table 5.1. Resume of the input methods that satisfy the requirements of *Affective Health*

Two methods of input were given as alternatives for Physical Activity: accelerometry and pedometry. As accelerometers can also be used to assess sleep quality for Adaptability, it is natural to choose accelerometers as well for Physical Activity, as this will reduce the size and weight of the sensor array and improve comfort (requirements 2 and 3). Furthermore, accelerometers can be used to reduce errors derived from movement in the PPG signal (Asada et al. 2004) and can also be configured to measure steps as well (Ying et al. 2007), thus making accelerometry a more flexible and reliable solution.

As for Arousal, two different features are presented that can be derived from PPG sensors. Heart rate and HRV features have been shown to have a negative correlation (Ungi et al. 1995, Mandanmohan et al. 2005) and, in particular, HRV features seem to be more sensitive to acute stress responses (Montebugnoli et al. 2004). HRV is also sensitive to body postures and simple movements like a tilt in the head (Electrophysiology 1996). This extra sensitivity might overestimate Arousal for an everyday life setting. Thus heart rate appears as a more stable feature. Heart rate has also the advantage of having a standardized method for baseline calculation and an easy mapping to arousal levels, by calculating the maximum heart rate for each user.

Adaptability cannot be so clearly mapped to biodata. One "best-effort" measurement that can be done is sleep assessment, done by means of the features: sleep time, sleep quality and sleep fragmentation. This requires that the sensors are comfortable enough to be used during sleep. Besides this, having an increased heart rate throughout the day can be a marker of Sympathetic predominance, so this should also be taken into account. Figure 5.1 presents a proposal for a biosensor configuration to be used in *Affective Health*.

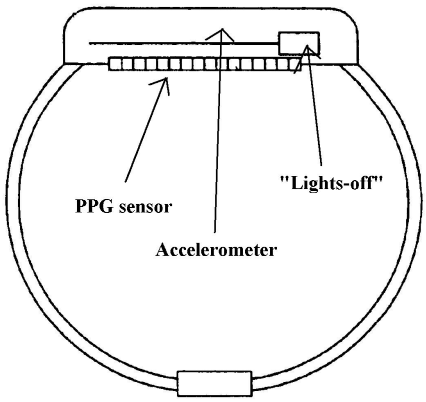


Fig. 5.1. Scheme of a proposed wrist sensor with a PPG sensor capable of measuring Blood Volume Pulse, a triaxial accelerometer and a "lights off" switch.

The sensor package can be used comfortably in the wrist which has literature support regarding correct sensor positioning both for the accelerometer (Garnier & Benefice 2006, Jean-Louis et al. 2001) and PPG (Poon & Zhang 2005, Sorvoja 2006). PPG sensors are usually preferably used in the finger as a ring because the skin is thinner, improving the quality of the signal (Engin et al. 2005). But there was no evidence found for correct measurement of Physical Activity and sleep related measurements from the finger. So, to keep the sensor array as compact as possible, the PPG sensor is positioned in the wrist. The “lights-off” button, recommended by Tryon (2004), is used to help estimate sleep time and improve estimation of Adaptability.

It should be noticed that only one accelerometer in the wrist cannot derive body posture, thus providing less input for design, when it concerns Physical Activity.

6

Discussion

In a reflection about Affective Wearables, Picard & Healey (1997) concluded that there is a need for novel biosensor design that is both accurate and unobtrusive for continuous use. It also refers that *"a difficult challenge of affective computing research is to determine which features of the sensor information should be considered salient, both to reduce the amount of data that is stored and transmitted, and to improve the analysis of the data"*. The present thesis gives a possible answer to these questions with a compact and minimalistic sensor configuration and a set of features that map to three concepts that are easy to understand and supported by medical background on stress.

When designing a wearable device aimed to be used by healthy people, the issues of comfort and unobtrusiveness are critical. People with cardiac problems might accept to carry an heavy ECG monitor during 24 hours but healthy users are unlikely to burden themselves. Also, users are unlikely to bother too much with correct sensor placement and calibration, which, combined with an unpredictable everyday life setting, may result in very noisy sensor data. These considerations are important to understand the restrictive requirements imposed on *Affective Health's* physiological input methods.

Many questions, however, were left unanswered. We left power source and communication requisites out of the scope of this thesis as we were mostly concerned with the biodata and the methods themselves, more than the sensors. It is clear however that a sensor configuration for *Affective Health* must include some sort of real-time wireless communication in order to transmit the physiological features to a mobile device, where they can be visualized. It must also have lower power requirements, as it is intended to be used continuously. These questions are left for future work. Of course, future studies must also support the exploratory review in this thesis with empirical data from a similar sensor configuration, with users in an everyday life setting.

Concerning Adaptability and its mapping to biodata, this literature review demonstrated an urgent need for future research in both the areas of Physiology/Medicine and Electronics. There is a need for better sensors that can measure blood pressure in an everyday life setting with minimal discomfort. This is especially important when considering that hypertension affects thousands of people in the world and its symptoms are not always expressed (American Heart Association 2005), though it can still lead to cardiovascular diseases and diabetes. Further research is also needed to uncover the significance of cardiovascular markers of accumulated allostatic load like HRV analysis or cardiovascular reactivity/recovery. This can give support for non-invasive measurement and give rise to new biofeedback devices that help people prevent diseases, instead of curing.

It is likely that, in the near future, wearable textile solutions become better and leave the research community to enter people's homes, thus permitting new kinds of physiological input methods. Until then, we hope that the results here presented will serve to support self-reflection during the course of everyday life.

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