INSTITUTO SUPERIOR TÉCNICO
Universidade Técnica de Lisboa

Mobile Acquisition Platform for Sleep Assessment

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Dissertation for obtaining the Master's Degree in

Biomedical Engineering

Jury

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November 2010

Acknowledgments

I would like to thank both my supervisors, Prof. João Sanches from IST and Prof.ª Teresa Paiva from FMUL. Prof. João Sanches for his ideas, suggestions, explanations and motivation, always in an enthusiastic way. To Prof.ª Teresa Paiva for her insight on the sleep subject, in particular concerning the opinions in the development of sleep and dream diaries. Additionally, I also would like to thank Prof. Rodrigo Ventura for the occasional Python enlightenment.

Prof. João Sanches always encouraged team work with common objectives, something that gave the opportunity to meet Alexandre Domingues. Thank you Alex for the hours spent trying to bend the difficulties, for the work you developed, for the suggestions, for the constant availability.

I would like to show my gratitude to my family. To my mother, for all the random kisses in the forehead, for always listening. To my father, for all the precious advices in this particular work, but most importantly, in life. Thank you both for always believing in me, for showing me your unconditional support, your care, your love. To my grandmother, who was always worried that I worked too hard, who always encouraged me to experience life and to enjoy the time with my friends. To my sister, who always looks on the bright side of life, calling me her favorite nerd each time I referred this thesis.

Also, it is an honor for me to thank my Biomedical colleagues, for I am part of the best class I could have ever expected. Thank you for all the academic companionship, but also for the laughs and leisure times. I am so fond of our friendships. In particular, for the last months of intensive work, I thank both Zé and Manel for the continuous support, either in the form of permanent English discussions, scientific insight or, most important, kind words and a shoulder when needed.

Finally, I would like to thank my friends from Alverca, who have known me the longest. I appreciate our differences, which enrich each and every one of these friendships. I deeply appreciate the support you have given me throughout the years.

This thesis is dedicated to my family and to my friends. You helped me win each and every battle. You helped me win this particular war.

Abstract

Sleep disorders affect a large percentage of the population all over the world and are often associated with other pathologies. Therefore, an early and accurate diagnosis is determinant to provide adequate treatment. While polysomnography (PSG) is the preferred tool in this type of diagnosis, the exam is expensive, uncomfortable for the patient and usually it must be performed in clinical facilities, thus it is not adequate for long time monitoring exams.

The scope of this thesis is to provide a highly portable system, an alternative to existing sleep assessment tools, supported by a physiological monitoring belt and a mobile phone connected via Bluetooth®. The *Mobile Acquisition Platform for Sleep Assessment* (MAPSA) is an easy-to-use and interactive system, which monitors several physiological signals, namely electrocardiogram, breathing rhythm, skin temperature and actigraphy. Moreover, it stores relevant sleep related information, through sleep and dream e-diaries. Although this system acquires a much more limited set of physiological data, it does not significantly interfere with the normal routine of the patient, which allows long time monitoring exams and the diagnosis of other types of disorders not easily detectable by the PSG.

Illustrative examples are provided on how to use the tool and what outputs are to be expected, so as to explain the possibilities this platform may bring in the diagnosis of sleep disorders, but also in other fields such as heart rate variability biofeedback. The MAPSA takes advantage of a light hardware and user-friendly interface, which should aid sleep physicians in their daily practice.

Keywords

Sleep disorders, Physiological Monitoring Belt, Mobile Phone, Sleep e-Diary, Dream e-Diary.

Resumo

Os distúrbios de sono afectam uma elevada percentagem da população mundial, estando frequentemente associados a outras patologias, o que sublinha a importância de diagnósticos precoces e correctos. Embora a polissonografia (PSG) seja o método de eleição neste tipo de diagnóstico, é um exame dispendioso, incómodo para o paciente e geralmente realizado em instalações clínicas, pelo que não é adequado para registos prolongados.

O objectivo desta tese é criar um sistema extremamente portátil, uma alternativa aos exames de diagnóstico existentes, baseada numa cinta cardíaca e num telemóvel, ligados por Bluetooth®. Esta plataforma de aquisição móvel para diagnóstico de distúrbios de sono, designada MAPSA (*Mobile Acquisition Platform for Sleep Assessment*), é um sistema de utilização simples e intuitiva, que monitoriza algumas variáveis fisiológicas como o electrocardiograma, respiração, temperatura ou actigrafia. Adicionalmente, regista informação relacionada com o sono, através de diários de sono e de sonho. Ainda que este sistema adquira um conjunto de dados muito mais limitado, não interfere significativamente na rotina do paciente, o que permite a realização de registos prolongados e o diagnóstico de distúrbios não tão facilmente detectados pela PSG.

Ilustram-se exemplos de utilização e dos resultados que a plataforma devolve, mostrando as possibilidades que esta pode trazer tanto no diagnóstico de distúrbios de sono como noutros contextos - *biofeedback* na variabilidade cardíaca. A MAPSA utiliza componentes acessíveis e uma interface simples, vantagens relevantes na prática diária de especialistas do sono.

Palavras Chave

Distúrbios de sono, Cinta Cardíaca, Telemóvel, Diário de Sono, Dirário de Sonho.

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List of Abbreviations [1]

ACK	ACKnowledge
API	Application Programming Interface
BF	Breathing Frequency
bpm	Beats per Minute
CBT	Core Body Temperature
CENC	Centro de Electroencefalografia e Neurologia Clínica
CSV	Comma Separated Values
DB	Database
DSPS	Delayed Sleep Phase Syndrome
DeD	Dream electronic Diary
ECG	Electrocardiogram
EDS	Excessive Daytime Sleepiness
EEG	Electroencephalogram
EOG	Electrooculogram
GSM	Global System for Mobile Communications
GPS	Global Positioning System
GUI	Graphical User Interface
HRV	Heart Rate Variability
Hz	Hertz, how many times per second
MAPSA	Mobile Acquisition Platform for Sleep Assessment
ms	Milliseconds
NREM	Non-Rapid Eye Movement
OS	Operative System
OSAS	Obstructive Sleep Apnea Syndrome
PLMD	Periodic Limb Movement Disorder
PLMS	Periodic Limb Movements of Sleep
PRC	Phase Response Curve
PSG	Polysomnography
PVH	Paraventricular Hypothalamic Nucleus
PyS60	Python for S60
RAM	Random-Access Memory
REM	Rapid Eye Movement
RLS	Restless Leg Syndrome
SeD	Sleep electronic Diary
SPP	Serial Port Profile
SWS	Slow Wave Sleep
SWSD	Shift Work Sleep Disorder
UI	User Interface
USB	Universal Serial Bus
VMU	Velocity Measuring Unit
WASO	Wake time After Sleep Onset
WLAN	Wireless Local Area Network

[1] Note: This list is in alphabetic order

List of Symbols

VO_{2max}	maximal oxygen consumption
HR_{max}	maximum Heart Rate
HR_{rest}	resting Heart Rate
f_{inst}	instantaneous frequency
f_s	Sampling Frequency
N	Number of Samples

1
Introduction

Contents

Sleep has persisted as an essential physiological function throughout all mammalian evolution, with some experiments showing that animals are not able to survive without it [60]. Furthermore, sleep interferes with many biological processes, namely immune system function [47], metabolism [63], gene expression [12] and capabilities such as learning or memorizing [21].

Nonetheless, sleep deprivation has become pervasive in society and with particular relevance in the developed countries, where a significant number of people reports less than seven hours of sleep most nights. Truth is sleep is undervalued, and that is probably because the functions of sleep are not yet clear for the generality of the population. In fact, at best people accept that they have to sleep, while at worst they perceive sleep as an illness that should have a cure [20].

This type of mentality, as well as economical pressure, is what brought in recent years a global society of 24/7, twenty-four hours, seven days a week. With this culture, an outnumber of sleep disorders, as well as sleep disorders related pathologies critically arose, namely diabetes, obesity, depression and cardiovascular diseases [10]. These pathologies are associated with reduced quality of life, increased morbidity and higher mortality risk, thus representing a significant economic and social burden to society [40]. Therefore, it is imperative to diagnose sleep disorders early and accurately.

While there are several diagnostic methods available in sleep laboratories, it is clear that *polysomnography* (PSG) represents the benchmark for diagnosing this type of illnesses. PSG is a multi-parametric test that extensively evaluates the bio-physiological changes that take place in the human body while the person is asleep. This exam is supported by highly complex hardware and, thus, is typically executed in a sleep laboratory with a permanent attendance technician [16].

1.1 Objectives and Motivation

Despite the widespread use of polysomnography, its expensive cost and very complex hardware difficult long time monitoring exams. Furthermore, such an exam disrupts the quotidian routines of the patient, hindering certain interesting evaluations. Additionally, some of the most common sleep disorders do not require as much data as the PSG provides, being actually diagnosable with lighter systems [32]. Examples of such diseases are narcolepsy, *Periodic Limb Movement Disorder* (PLMD), *Restless Leg Syndrome* (RLS), *Delayed Sleep Phase Syndrome* (DSPS), *Shift Work Sleep Disorder* (SWSD) and *Obstructive Sleep Apnea Syndrome* (OSAS). All the aforementioned diseases can be diagnosed recurring to combinations of actigraphy, temperature, ECG and sleep diaries [4].

This issue motivated this thesis, which is to develop a highly portable system to assist in the diagnosis of sleep disorders, hereby defined as *Mobile Acquisition Platform for Sleep Assessment* (MAPSA). This is groundbreaking in the sense that it allows long time monitoring of both several physiological variables and relevant user input data, thus assisting in the diagnosis of other types of sleep disorders not easily detectable by the PSG. The MAPSA consists of essentially two devices, a physiological acquisition belt and a mobile phone. While, unsurprisingly, the belt handles the physiological data, the mobile phone provides the user interface as well as the acquisition, processing and transmitting of the data to a physician.

Cardiac belts are devices designed to be worn around the thorax, below the chest area, and to monitor some physiological activity. Some years ago, such devices were a tool only available for high performance athletes. Moreover, traditionally belts were paired with specific fitness watches, being very limited in both battery and transmission range capabilities and only monitoring the cardiac rhythm. Conversely, modern cardiac belts were redefined as physiological monitoring systems. Indeed, considering the Zephyr® BioHarness Bluetooth, the subject wears a smart fabric chest strap which includes sensors to monitor ECG signals and respiration rate, while attached to the strap is a module which contains an infra-red skin temperature sensor and a 3-axis accelerometer for monitoring both attitude (subject posture) and activity (acceleration). In addition, data is transmitted over a ten meter range using Bluetooth® technology to a suitable device, traditionally a personal computer [69].

A mobile phone stands as the second physical part of the monitoring system. Nowadays, mobile phones are a very attractive application platform, as most of them endue a lot of interesting characteristics, namely significant computing power, long battery life, many built-in sensors and wireless connectivity capabilities, such as Wi-Fi and Bluetooth® technologies. Plus, such mobile phones are becoming more and more a common tool among the general population [2].

The goal of the mobile phone application required by the MAPSA system is to offer a user-friendly interface which grants the user the possibility of registering a set of quotidian events usually listed in extensive and not very intuitive questionnaires. At the same time, the application should maintain the necessary connection between the physiological belt and the mobile phone, via Bluetooth®, monitoring the subject's medical data accessed by the belt and displaying relevant information. In addition, both the physiological and user-input data ought to be transmitted to the physician's personal computer, in which the complete set of data collected is properly displayed, providing the possibility of an immediate cross analysis.

While there are several *Operative Systems* (OS) for mobile phones available in the market, the Symbian mobile OS is widely spread, reaching low-cost devices, but still possessing a broad range of options and a user-friendly approach [23]. Thus, after the conceptual definition of the *Mobile Acquisition Platform for Sleep Assessment*, the mobile application will be developed using *Python for Symbian 60* (PyS60). This platform was chosen because it is officially supported by Nokia®, hence providing access to most available phone functions [2]. Additionally, PyS60 ensures the possibility of creating both the physiological data monitoring and the user-input interfaces, with the major advantage of being open source software.

On the other hand, the computer *Graphical User Interface* (GUI) available for the physician to analyze the data will be developed in traditional *Python*, which allows the simultaneous display not only of multiple physiological signals but also of the quotidian events that both sleep and dream diaries comprise. *Python* is a high level programming language, which emphasizes on code readability, and also open source software. The system was developed in both Portuguese and English versions.

A sleep diary is a registry of a person's quotidian activities, such as sleeping, meals and workouts. For sleep disturbs diagnosis purposes, a sleep diary is usually maintained over a period of several weeks and is self-recorded by the patient [53]. Although conventionally sleep diaries were recorded in specific paper spreadsheets, in recent years specific electronic tools were developed, such as database software or online services. Examples of these portable tools are the *NASA Airlog* [61], or the *Sleep electronic-Diary* (SeD), a sleep journal implemented in mobile phones for sleep assessment [26]. These tools have as very important added value - more accurate time registries. Furthermore, studies have shown better patient compliance with electronic diaries, as an alternative to paper diaries [68]

Similarly, a dream diary is a journal in which dream experiences are recorded. Though nightly dreams recorded immediately after waking up, are the most important type of entries, personal reflections or waking dream experiences are also valuable for the study of dreams, psychology or, ultimately, sleep disorders evaluation [62]. As for the aforementioned sleep diaries, traditional dream journals were written reports, or, in this particular case, drawings or paintings. Nevertheless, recording devices and Internet websites brought the possibility of creating a digital dream diary. For medical purposes, a proper and objective scaling of type and intensity of dreams is vital. Additionally, the possibility of an automatic transcription of audio recorded dreams is very interesting, as the analysis of audio files by a medical technician would be extremely time consuming.

In this thesis, not only a *Sleep electronic-Diary* (SeD) is proposed, but also a *Dream electronic-Diary* (DeD). Both journals highly benefit from the fact that a mobile phone is being used as a register platform in portability, time accuracy and also user-friendliness. Plus, the type of events foreseen by these diaries represents a major added value to the physiological data collected by the cardiac belt, again in the diagnosis of sleep disorders.

To sum up, the *Mobile Acquisition Platform for Sleep Assessment* (MAPSA) is here presented as a highly portable physiological monitoring and user-interactive platform, supported by both a physiological monitoring belt and a mobile phone. Such system was conceived with special focus on the aid of sleep disorders diagnosis, but is also presented as a tool with wider purposes, namely HRV biofeedback.

1.2 Original Contributions

This thesis presents original contributions to knowledge, which have been published or submitted:

- A mobile acquisition platform for sleep disturbances assessment, established recurring to a physiological data belt and a mobile phone, submitted and accepted as an extended abstract for the RecPad 2010 national conference in Vila Real.
- A *Dream electronic-Diary* (DeD) Portuguese patent, in which an audio description of dreams using the mobile phone and an automatic transcription of dreams using an external speech recognition platform is proposed; this patent was submitted to Galtec-IST.

1.3 Thesis Scope

This thesis is structured as follows. Chapter 2 contextualizes the proposed platform, providing both a physiological and technological background on the sleep disorders area. Sleep as a physiological process is described, as well as sleep disorders and sleep assessment tools. On the other hand, a state of the art on the devices supporting this system - physiological monitoring belts and mobile phones, is also presented.

Chapter 3 begins by clearly defining the existing lacks in the sleep diagnosis field, which justify the focus on the development of the *Mobile Acquisition Platform for Sleep Assessment*. Following, this chapter presents the conceptual model of the idealized tool, as well as the necessary computational implementation.

The following chapter contains an extended overview of the utilization of the developed system and the features it provides as outputs, supported by necessary illustrative pictures. Furthermore, this chapter presents several adequate applications of the MAPSA system inside the sleep context, as well as on a wider scope, with heart rate variability biofeedback.

Finally, chapter 5 gathers the topics discussed along this thesis, depicting its main conclusions and strengths. Also, further research and development of the *Mobile Acquisition Platform for Sleep Assessment* is discussed, in an attempt to account for the wide possibilities that can arise from this present work.

2

Physiological and Technological Background

Contents

Chapter 2 presents both a physiological and technological background on sleep and, particularly, on sleep disorders. Such background intends to frame and help in the understanding of the objectives and motivation of this thesis. To that purpose, evidence is provided on the need of innovative and much more portable sleep assessment platforms. That fact is reinforced by the current number of patients suffering from sleep disorders and, additionally, by the outgrowing number of people not yet diagnosed.

The present chapter is organized in six sections. In the first one, sleep is defined as a physiological function, with the explanation of its stages and regulation. Section two presents some of the most common sleep disorders, as well as their implications in the patient's quotidian life. In the following section, sleep assessment diagnose exams are detailed, with special focus in polysomnography. Section four introduces heart rate variability biofeedback, a possible particular application of this system. Physiological monitoring belts are presented as an alternative portable diagnosis tool in section five. Finally, the approach to mobile phones as a technological platform with medical interest is done in section six.

2.1 Neurophysiology of Sleep

Sleep is a reversible behavioral state of perceptual disengagement from and unresponsiveness to the environment [11]. During the 1960's, a great volume of new information regarding what happens during sleep arose, and since then the definition of two separate states under the rubric of sleep has been conventioned - *Non-Rapid Eye Movement* (NREM) and *Rapid Eye Movement* (REM) sleep, which alternate cyclically across a sleep episode [52].

2.1.1 Physiological Functions in Sleep

Evidence suggests that sleep is generated by two widely opposing mechanisms: the homeostatic drive for sleep and the circadian system that regulates wakefulness. The circadian clock, characteristic of mammals, has an approximate duration of twenty-four hours, related to the light and dark pattern of each day. Such system anticipates the differing demands along the day, preceding changing conditions with the necessary adjust in almost every physiological parameter, thus naturally including sleep. For instance, in anticipation of sleep, body temperature drops and blood pressure decreases, while sleep propensity rises. On the other hand, before dawn, the metabolism is accelerated in anticipation of the increased activity associated with wakefulness. Located in the anterior hypothalamus, the *suprachiasmatic nuclei* (SCN) is a paired cluster of twenty-thousand neurons, which coordinate both circadian rhythms and homeostatic processes that consolidate sleep [20].

Variables such as *Core Body Temperature* (CBT), blood pressure, sleep-wake cycle, alertness and hormone secretion are considered to be circadian rhythms, thus measured for sleep assessment purposes. Melatonin, in particular, is an important sleep indicator in both nocturnal and diurnal species [58], with specific controlling pathways represented in Figure 2.1. The timing of melatonin secretion by the pineal gland is controlled by SCN projections to the *Paraventricular Hypothalamic Nucleus* (PVH). Efferents pass from the SCN to the *Superior Cervical Gland* (SCG) in the spinal cord, while postsynaptic sympathetic neurons enervate the pineal gland. Melatonin receptors on SCN neurons are then activated by the circulating melatonin from the pineal gland or from orally administrated melatonin [36].

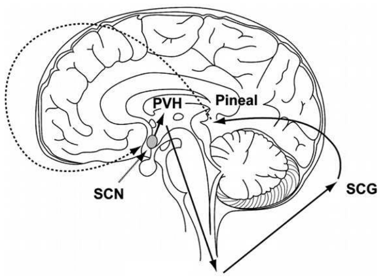

Figure 2.1: Pathways controlling melatonin secretion (adapted from [44]).

The relationship between the homeostatic drive for sleep and the circadian system that regulates wakefulness is shown in Fig. 2.2. The onset of melatonin production occurs with the decrease in SCN neuron firing rate in the evening. This stimulates sympathetic activity resulting in melatonin production and release. Conversely, in the SCN, melatonin inhibits the firing of SCN neurons, which should further diminish circadian drive for arousal. Therefore, the relationship between the two initially mentioned mechanisms is regulated by a regulatory feedback [44].

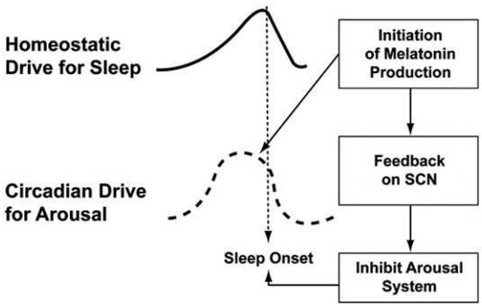

Figure 2.2: The function of melatonin in facilitating sleep onset (adapted from [44]).

The phase of a circadian rhythm reflects where the peak and the trough of a certain parameter occur within the 24 h. For most organisms, which include mammals, the primary phase-shifting stimulus is light, a fact that has been known for decades. The relationship between the phase shifts in the organism and the circadian timing of the stimulus is called the *Phase Response Curve* (PRC) [31].

It is empirical knowledge that sleep interferes with many biological processes, such as immune system function, metabolism, gene expression and learning/memorizing capability [20]. Such interactions are briefly explained in the following paragraphs.

Both the architecture of sleep and sleep-wake behavior are highly conditioned by microbial products and cytokines. On the other hand, sleep processes are associated with metabolism, specifically the production and/or release of certain immune factors, namely cytokines. Overall, there is evidence that disrupted or reduced sleep impairs the immune system while, at the same time, immune responses triggered by infection can alter sleep patterns [20].

As strong suggestion that sleep is vital for the immune system, sleep-deprived rats die of septicemia after a few days [17], while only one night of sleep deprivation in humans can lower the activity of natural killer cells by 28% [25]. At the same time, loss of sleep impairs many other aspects of the immune system, as circulating immune complexes, secondary antibody responses and antigen uptake. For instance, pro-inflammatory cytokines increase the proportion of *Slow Wave Sleep* (SWS), whereas anti-inflammatory cytokines inhibit NREM sleep. The relationship between cytokines and NREM sleep is modulated by growth hormone-releasing hormone, prolactin and *Vasoactive Intestinal Peptide* (VIP) [47]. Another example might be given through leptin, a hormone released by adipocytes which provides information about energy status to regulatory centers in the brain. The decrease in leptin levels is concomitant with an elevation of sympathovagal balance, a concept which reflects the autonomic state resulting from the sympathetic and parasympathetic influences. Furthermore, chronic partial sleep loss is associated with decreased glucose tolerance, decreased leptin levels and adverse cardiovascular effects, consequences consistent with a solid link between sleep duration and obesity [63].

One of the most relevant links between the immune system, sleep and psychological stress is cortisol. In fact, the synergy of sleep disruption and sustained psychological stress results in increased cortisol concentrations in the blood. One night of lost sleep can raise cortisol concentrations up to 50% by the following evening [37]. Whilst high levels of cortisol suppress the immune system, excessively tired people are more susceptible to illness, which is why nightshift workers are more likely to suffer from diseases such as cancer [14].

Recent gene expression studies have allowed researchers to understand the benefits that sleep may bring at a cellular level. Indeed, genome-wide screening of brain gene expression performed in rats and extrapolated to humans highly suggests such relationship, with significant alterations in gene expression in the cortex observed according to behavioral state [12].

The strong relationship between sleep and memory has been shown in outnumbered studies [21] [66] [74]. Moreover, a beneficial influence of long SWS periods on declarative memory formation has been supported in recent years, whereas there is no consistent benefit of this memory from periods of REM sleep. Underlying this influence are mechanisms such as the reactivation of newly acquired memory representations in hippocampal networks, which stimulates a transfer and integration of these representations into neocortical networks. In addition, both spindle activity and slow oscillation-related EEG coherence increase during early sleep following intense declarative learning in humans, two factors that, when together, express neocortical reprocessing of the learned material and are thus consistent with the aforementioned model. Furthermore, sleep seems to diminish cholinergic activation and cortisol feedback to the hippocampus during SWS [21].

In the diagram presented in Figure 2.3 all the aforementioned factors are related, while some not referenced are added. For instance, stress encourages the use of alcohol, which, in turn, can lead to obesity and insomnia. Another example is given by obesity induced stress or by insomnia, which promotes the use of sedatives at night and stimulants during the day.

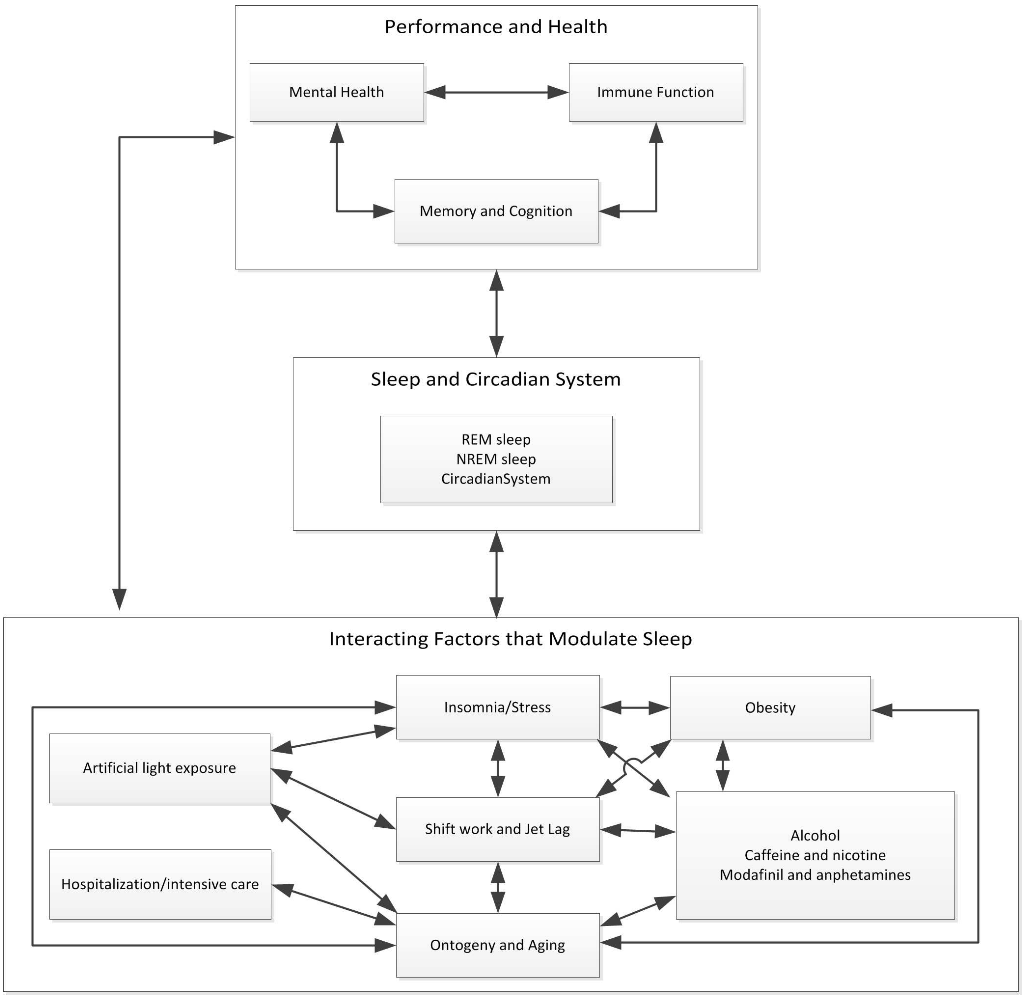

Figure 2.3: Interactions that modulate sleep, health and performance (adapted from [20]).

All these interactions are modulated by age, while increasing age promotes the likelihood of hospitalization, which is often accompanied by abnormal light exposure that promotes insomnia or stress. Ultimately, all three sets of factors modulate each other either directly or indirectly, via sleep and circadian system. For example, immune responses directly affect sleep arousal states, which, in turn, modulate various sleep interacting factors and, therefore, entail feedback effects on both performance/health and sleep [20].

2.1.2 Sleep Stages

Non-Rapid Eye Movement (NREM) sleep is characterized by unconsciousness and increased parasympathetic tone, which is expressed by a fall in blood pressure and slowing in respiration. Four overlapping stages, numbered from 1-4, are generally considered for clinical purposes, divisions associated with *electroencephalography* (EEG). Progressive stages mirror increasing ”depth” of sleep and, consequently, arousal thresholds. Stages 3 and 4 are characterized by a majority of slow EEG waves and thus are commonly referred to as *Slow Wave Sleep* (SWS) [64].

Conversely, *Rapid Eye Movement* (REM) sleep is characterized by an activated EEG, episodic surges of rapid eye movements and muscle atonia, which are associated with an increase in both respiratory and heart rate. As sleep progresses, REM sleep episodes become longer, typically reaching their longest duration in early morning. Normal adults spend 20% to 25% of total sleep time in REM [67].

The differences between wakefulness, REM and NREM sleep are summarized in 2.1. Moreover, the EEG pattern of wakefulness consists of low alpha activity (13-30 Hz), which is replaced with low-voltage mixed frequency theta waves (4-8 Hz) in stage 1 of NREM sleep. On the other hand, slow asynchronous eye movements are seen on the *electrooculogram* (EOG) in the beginning of such stage, which disappear in a few minutes. Naturally, muscle activity is highest during wakefulness and diminishes with sleep. Relatively to ”deep” sleep, stages 3 and 4 of NREM, delta waves account for 20% to 50% of EEG activity during the first and greater than 50% during the last.

Table 2.1: Sleep stages and physiological activity (adapted from [67]).

Parameter	Wakefulness	NREM sleep	REM sleep
EEG	Fast, low voltage	Slow, high voltage	Fast, low voltage
Eye movement	Vision related	Slow, infrequent	Rapid
Muscle tone	++[1]	+	0
LDT/PPT[2]	+	0	++
LC/DR/TMN	++	+	0

Conversely, the cortical EEG pattern of sleep is characterized by low voltage and fast alpha frequencies (8-13 Hz). This pattern is also characteristic of states of relaxed wakefulness with eyes closed and is referred to as *desynchronized* or *activated*, the last relating to an active mind, similar to wakefulness, but in this case associated with dreams [39].

The connection between REM sleep and dreaming was first suggested in 1953 [5], in a study

[1] ++, rapid firing rate (or increasing muscle tone); +, slower firing rate (or less muscle tone); 0, little or no firing (atonia).

[2] *Abbreviations:* DR, *dorsal raphe nucleus*; LC, *locus coeruleus*; LDT, *laterodorsal tegmental nuclei*; PPT, *pedunculopontine tegmental nuclei*; TMN, *tuberomammillary nucleus*.

that reported the relationship of this particular type of eye activity with vivid dreams usually involving visual imagery. The combination of this type of eye activity with specific low-voltage mixed-frequency EEG patterns is the biological basis for explaining the dream process. Although such relationship was consolidated by recent research [24], sleep specialists from different areas still disagree on whether REM dream sleep is qualitatively different from NREM dream sleep. The psychological function of dreaming remains uncertain to the present day. Freud saw dreaming as a disguised attempt to fulfill an infantile wish in the service of maintaining the continuity of sleep, and many equally dubious functions have been attributed to dreaming such as an attempt to solve emotional problems [36].

Usually, sleep starts with a ”shallow” stage 1 of NREM sleep, ”deepening” to NREM sleep stages 2, 3 and 4, which precede the first brief episode of REM sleep in approximately 90 minutes. From then on, NREM and REM sleep continue to alternate in what are called NREM-REM cycles, each lasting about 90 minutes, in a typical total of four to six cycles per major sleep episode. The ratio of NREM sleep to REM sleep, though, varies during the course of the night, with slow wave sleep being prominent in the first third and REM sleep prominent in the last third of the night [36].

Although sleep duration in adults is framed by a Gaussian distribution with average sleeping duration of 7.0-9.0 hours [30], the timing, duration and internal structure of sleep are factors that tend to fluctuate amongst healthy individuals, and essentially according to age. In fact, while infants and elderly have frequent interruptions of sleep, adults of intermediate age, in general, have one consolidated sleep episode per day (Figure 2.4), exception made to cultures in which it is frequent to divide sleep into a mid-afternoon nap and a shortened night sleep [18]. In Fig. 2.4 an hypnogram is depicted, which shows the four stages of overnight NREM sleep and wakefulness for young adult men, with the stages of REM sleep as solid bars.

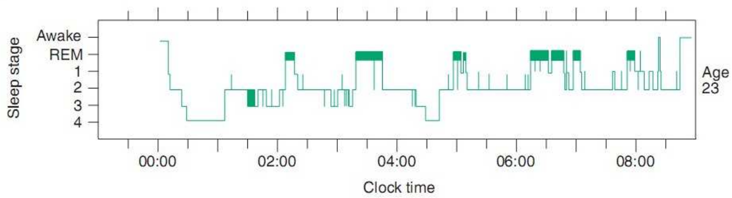

Figure 2.4: Hypnogram for representative young adult men and elderly (source: [18]).

On balance, the strongest and most consistent factor affecting the pattern of sleep stages across the night is age (Fig. 2.5). In newborn infants, the age-related differences in sleep are, as expected, severely marked. In fact, for the first year of life, the transition from wake to sleep is often accomplished through REM sleep, which is called *active sleep*. Although the cyclical alternation of NREM-REM sleep is present from birth, its duration is approximately 50 to 60 minutes in the newborn, compared with the 90 minutes for adults referenced before. Furthermore, infants only gradually acquire a consolidated nocturnal sleep cycle, with fully developed EEG patterns of

NREM sleep stages emerging over the first 2 to 6 months of life. Only when brain structure and function achieve a level that can support high-voltage slow wave EEG activity NREM stages 3 and 4 become prominent [51].

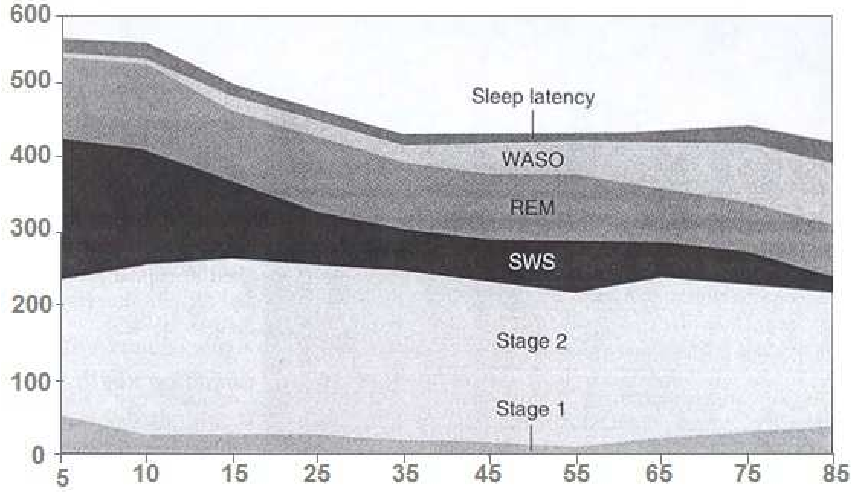

Figure 2.5: Changes in sleep with age (source: [51]).

On the other hand, SWS is maximal in young children and highly decreases with age. Furthermore, SWS changes qualitatively and quantitatively throughout life, with youngsters being nearly impossible to wake up in the SWS of the night's first sleep cycle. By 60 years of age, SWS may no longer be present, particularly in men. REM sleep as a percentage of total sleep is preserved into old age. Nonetheless, exception must be made to cases of diminished intellectual functioning, in which the amount of REM sleep at night declines markedly.

To conclude this discussion, arousals must also be referred. Arousals during sleep increase markedly with age. In fact, extended wake episodes of which the individual is aware and can report, as well as both brief and unremembered arousals, increase with aging. The first is related to the WASO parameter, *wake time after sleep onset*. The later, on the other hand, is often associated with masked sleep disturbances, such as PLMD and OSAS, conditions more prevalent in later life [11].

2.2 Sleep Disorders

As the name suggests, sleep disorders are medical conditions associated with alteration in sleep patterns, thus interfering with normal physical, mental and emotional functioning. Although this is a somehow simple definition, the difficulty in distinguishing between normal and abnormal sleep is reflected in the evolution of the classifications and definitions of symptomatology [36]. Nevertheless, the *American Psychiatric Association* has published a manual in which a valid attempt to classify sleep disorders has been made, with a distinction in dyssomnias and parassomnias. The first is a broad category of sleep disorders characterized by either hypersomnolence or insomnia, further sub-categorized in intrinsic, extrinsic and disturbances of circadian rhythm. Conversely, parassomnias are sleep disorders that involve abnormal and unnatural movements, behaviors, emotions, perceptions or dreams [9].

A significant number of medical conditions are associated with disruptions in sleep, namely asthma and cardiac ischemia, in which sleep-associated symptoms are often the presenting or most bothersome complaint [18]. Nevertheless, the following paragraphs only intend to describe some of the diseases directly connected to sleep.

2.2.1 Narcolepsy

Narcolepsy is a dyssomnia, a condition characterized by *Excessive Daytime Sleepiness* (EDS). Narcolepsy patients experience extreme fatigue and show tendency to fall asleep at inappropriate times as at work or at school. A special feature is that though most people only experience REM sleep until after 90 minutes, narcoleptics experience it within 10 minutes. Narcolepsy is a neurological disorder, not caused by any mental or psychological conditions. In fact, this disease is related to specific biologic factors in the brain, when combined with a set off from the environment, such as a virus [36]. Narcolepsy affects about 1 in 4000 Americans and seems to have a genetic basis [18].

2.2.2 Obstructive Sleep Apnea Syndrome (OSAS)

Daytime somnolence, as well as disturbed nocturnal sleep, is often related to respiratory malfunctions during sleep. Although an outnumber of patients are yet to be diagnosed, with estimates pointing to 80% - 90% of undiagnosed patients, many individuals suffer from reduction or cessation of breathing for 10 to 150 seconds, from thirty to several hundred times every night during sleep, without being aware of it [18]. As the name suggests, OSAS is due to an occlusion in the airway, which is significantly smaller in the case of apnea patients (Fig. 2.6). This condition is most common among overweight men and in the elderly. Diagnosis of this disease is particularly relevant for various reasons. On one hand, people who suffer from OSAS are at higher risk of sleep-related motor vehicle accidents, hypertension and other serious cardiovascular complications. On the other hand, effective treatments for OSAS are known [36].

2.2.3 Restless Leg Syndrome (RLS)

Patients suffering from this sensory-motor condition report an uncontrollable urge to move the legs or, sometimes, the upper extremities. Moving such body parts modulates the discomfort sensation, thus providing temporary relief. Diagnosis of RLS is generally achieved through a good medical history and physical examination, thus not necessarily involving polysomnography (PSG). The prevalence of RLS is 1% to 5% among young to middle-age adults and 10% to 20%

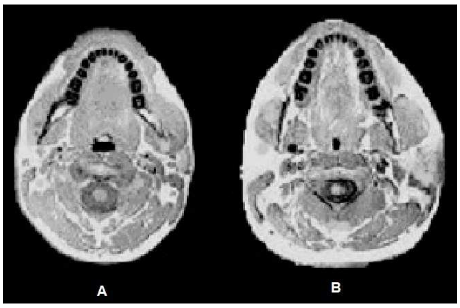

Figure 2.6: Axial MR image of (A) a normal subject and (b) a patient with OSAS (source: [36]).

among adults with over 60 years of age. Although evidence shows that RLS has higher prevalence amongst family members of the patient, with three separate loci identified, the specific gene is yet to be identified [18].

2.2.4 Periodic Limb Movement Disorder (PLMD)

Periodic Limb Movements of Sleep (PLMS) is the principal objective finding in 17% of patients with insomnia and 11% of those with excessive daytime somnolence. Though sometimes is only an incidental finding, there are many cases in which PLMS is the cause of disturbed sleep and, therefore, called PLMD. This condition occurs in a broad variety of sleep disorders and is often associated with frequent arousals and an increased number of sleep-stage transitions [18].

2.2.5 Shift Work Sleep Disorder (SWSD)

In an European study that included Portuguese adults, more than one out of five workers are estimated to work at night, either on a permanent or rotating schedule [6]. Additionally, many people opt to remain awake at night to meet deadlines, drive long distances or simply to participate in recreational activities. Either way, the result is sleep loss and misalignment of the circadian rhythms characteristic to the body.

When night workers have a much greater than average difficulty in remaining awake at work and at sleeping during the day they are diagnosed with chronic and severe SWSD. Professionals such as doctors, vehicle operators or air traffic controllers are some of the groups of people most susceptible to this condition. In fact, although the circadian system tries to adapt itself to the changing schedules, studies indicate that it usually fails in a long term basis, resulting in sleep deprivation, increased length of time awake prior to work and misalignment of circadian phase. All the aforementioned factors, when combined, have as consequences decreased alertness and performance, relevant safety hazards that can result in fatal work accidents. In the long run, shift workers have a higher prevalence of cancer and cardiac, gastrointestinal and reproductive disorders [18].

2.2.6 Delayed Sleep Phase Syndrome (DSPS)

DSPS is another circadian rhythm disruption related condition, with patients reporting sleep onset and wake time intractably later than desired. Polysomnography of DSPS patients is normal respecting every parameter except for delayed sleep onset. Like SWSD, this condition may arise from individuals willingly choosing to remain awake at late hours, for work, school or social reasons, with DSPS patients tending to be young adults. Therefore, DSPS is a self-induced condition, which can persist for years, between attempts to reestablish normal bedtime hours and relapses [18]. Even so, Exogenous melatonin taken in the evening coordinated with light therapy upon awakening is the standard treatment for DSPS, for it shows some interesting results [8].

2.3 Sleep Assessment Tools

The first step to the diagnosis of a certain sleep disorder by a physician is always the analysis of the patient's history and clinical findings, based on which the physician makes a preliminary diagnosis [29]. Naturally, for an accurate diagnosis, further evaluation is often required, which can range from subjective assessment, such as specific questionnaires and sleep diaries, to more thorough exams such as actigraphy or polysomnography.

Although there are several sleep assessment techniques available in a sleep laboratory, polysomnography (PSG) is clearly the gold standard for diagnosing sleep disorders. However, there are alternatives to such an exam, as prolonged actigraphy or self-reported by the patient sleep or dream diaries. In Table 2.2, some sleep disturbs symptoms are related to the associated diagnosing tools commonly used. PSG is not always required, validating the use of other, not as expensive, sleep assessment tools.

Table 2.2: Evaluation of the patient with excessive daytime somnolence complaints (adapted from [18]).

Findings on History and Physical Examination	Diagnosis Evaluation	Diagnosis
Obesity, snoring, hypertension	Polysomnography with respiratory monitoring	OSAS
Restless legs, disturbed sleep, predisposing medical condition (e.g., iron deficiency or renal failure)	Assessment for predisposing medical conditions	RLS
Disturbed sleep, predisposing medical conditions (e.g., asthma) and/or predisposing medical therapies	Sleep-wake diary recording	Insomnias

Referring specifically to OSAS, considering the high number of undiagnosed patients, a simple method is needed, to avoid the referral of all the patients to specialist centers for expensive, labor-intensive and time-consuming polysomnography. OSAS can accurately be diagnosed from history, physical examination or observation during sleep [16].

2.3.1 Polysomnography (PSG)

Polysomnography (PSG) represents, with no doubt, the benchmark for diagnosing sleep disorders. This exam is indicated in the following diagnoses: sleep related breathing disorders, narcolepsy, parassomnias, sleep related seizure disorders, RLS, PLMD, depression with insomnia and circadian rhythm disorders [33].

PSG is a multi-parametric test that thoroughly evaluates the bio-physiological changes that occur in the human body while the person is asleep. Although it is usually performed at night, some sleep laboratories accommodate shift workers and adapt the test schedule to a convenient time. This exam monitors, namely, EEG, EOG, ECG, respiratory airflow, chin muscle tone, oxygen saturation and movements of legs, chest and upper abdominal walls [72].

To measure all the aforementioned parameters, PSG naturally requires highly complex hardware, as illustrated by Fig. 2.7. In fact, PSG is performed with a minimum of twelve channels, corresponding to a minimum of twenty-two wire attachments to the patient, which explains why this exam is typically executed in a sleep laboratory, with a permanent attendance technician [16]. However, comprehensive sleep studies can also be carried out at home, in what is called a *in-home PSG*. This type of PSG monitors ECG, EEG, EMG, EOG, respiratory airflow, respiratory effort, pulse and oxymetry. Periodic leg movement's measurement can be accomplished, though being an optional feature. This type of PSG is not supervised by a technician [56].

Figure 2.7: Subject adequately equipped undergoing PSG (source [72]).

Nowadays, computer based systems facilitate the data storage, visualization and interpretation, thus sleep disorders diagnosis. The main parameters presented by the PSG are the following: total sleep time, wake time, total recording time; sleep efficiency (total sleep time/total recording time); latency for sleep onset (time required for sleep initiation), latency for REM sleep and other stages; duration (in minutes) and proportion of total-sleep-time sleep stages (knowing that proportions vary according to age and sex); frequency of apneas and hypopneas per hour of sleep (apnea-hypopnea index); saturation values and events of oxyhemoglobin desaturation; total number and index of micro-arousals per hour of sleep and their relationship with breathing events or lower limb movements; cardiac rhythm and frequency [72].

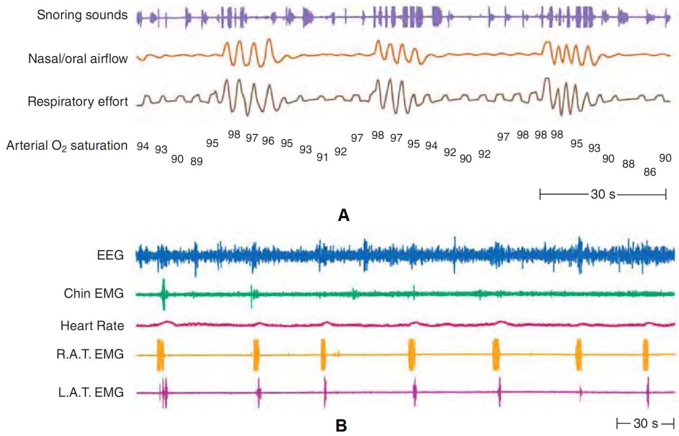

Figure 2.8: Polysomnographic recordings of a subject with (A) obstructive apnea and (B) PLMS [18].

Abbreviations: R.A.T. stands for *Right Anterior Tibialis*, while L.A.T. is for *Left Anterior Tibialis*.

A partial sample result of a PSG is presented in Fig. 2.8. In the upper panel, corresponding to a patient with obstructive apnea, the snoring and reduction of air flow is associated with decreased oxygen saturation. On the other hand, in the polysomnography of a PLMS patient the changes in the EEG and heart rate acceleration point the periodic limb movements [18].

2.3.2 Questionnaires, Sleep and Dream Diaries

Several questionnaires are appropriate for routine clinical diagnosis, for monitoring the response to the treatments initiated, for epidemiological studies and for clinical research. However, the majority of such questionnaires are international, with few of them validated in Portuguese to this day, which leads to misinterpretations caused by cultural differences, which influence the specificity and sensitivity of these methods.

In particular, there are questionnaires that assess sleep in general aspects, focusing on sleep latency, sleep quality, behavioral aspects, nighttime awakenings and daytime sleepiness. Examples of sleep focused questionnaires are the *Sleep Disorders Questionnaire* (featuring both quantitative and qualitative evaluation questions), the *Pittsburgh Sleep Quality Index* (evaluating the quality of sleep in the preceding month, providing and index of severity and nature of the disorder), the *Mini-sleep Questionnaire* (assessing the frequency of complaints), the *Basic Nordic Sleep Questionnaire* (analyzing the most common complaints in terms of both frequency and intensity in the last three months, with quantitative specification) and the *self-reporting sleep questionnaire* (of use for psychopharmacological research) citeTogueiro2005. Furthermore, often sleep laboratories design a sleep questionnaire adapted to their practice and patients. *Centro de Electroencefalografia e Neurologia Clínica* (CENC), in particular, has its own sleep assessment questionnaire in Portuguese, based on [46] and [45].

In the context of sleep disturbs, completion by the patient of a daily sleep-work-drug journal for at least 2 weeks can decisively help the physician better understand the nature of the complaints. Such a journal should include work times and sleep times (including daytime naps and nocturnal awakenings) as well as drug and alcohol use, including caffeine and hypnotics [18]. This self-reporting questionnaires are commonly referred to as sleep diaries [53].

Sleep diaries are usually specific prescribed spreadsheets fill in by hand. However, in recent years, the development of new technologies brought specific electronic tools, such as database software or online services. Furthermore, specific portable devices were developed, such as the *NASA Airlog* [61]. Recently, a new and already patented idea arose: mobile phone integrated sleep diaries[26], designated *Sleep electronic-Diary* (SeD). These convey the initial sleep assessment procedure to a new level, adding new features such as reminders for adding entries and considerably increasing the accuracy of the activities scheduling.

On the other hand, a dream diary is a journal in which dream experiences are recorded. In such diaries, the patient reports nightly dreams immediately after waking up, personal reflections or waking dream experiences. Though nightly dreams are the most relevant entries, the subsequent are also valuable for the study of dreams, psychology or, ultimately, sleep disorders [62]. Dream journals are memory consolidation tools, recommended as a mean to achieve more lucid and vivid dreams, preserving usually forgotten details.

Traditional dream journals were also written reports, or, in this particular case, drawings or paintings. Nevertheless, recording devices and Internet websites brought the possibility of creating digital dream diaries. Dream diaries in this sense are uncommonly used as medical tools, since they involve a very complex analysis procedure, excessively time consuming. In fact, for medical purposes, a proper and objective scaling of type and intensity of dreams is vital. This assessments, when used, are presented in a similar aspect to sleep diaries, specific spreadsheets for patient's self-reporting [46].

Sleep diaries alone and, additionally, the association between sleep and dream diaries can be invaluable as complementary diagnosing tools for sleep disorders. In fact, such tools might be particularly useful when combined with PSG exams or other lighter and less quotidian intrusive diagnosing techniques, such as actigraphy.

2.3.3 Actigraphy

Actigraphy evaluates the sleep-wake cycle by recording the motor activity over an extended period of time, generally over twenty-four hours and up to several weeks. The device that records the limb movements is called an actigraph (Fig 2.9), a motion-sensing device similar to a watch which incorporates a single or tri-axial accelerometer and measures and records the magnitude of the acceleration suffered. Additionally, some actigraphs also monitor light intensity.

Actigraphs have been used for sleep assessment for over twenty years, for an actigraph is a low-cost device that can accurately distinguish between sleep and wakefulness and, therefore,

Figure 2.9: Actigraph *SOMNOwatch plus* ®.

represents a valid alternative to polysomnography in some disorders [27]. However, methodological issues are yet to be systematically addressed in clinical research and practice [4].

2.3.4 Oximetry

Oximetry is used as a solo exam in some sleep assessments, that allows the monitoring of the oxygenation of a patient's hemoglobin. Oximeters are widely available in the market and are a convenient method for providing a fast diagnose. However, one must consider that, in the particular case of OSAS, it only yields a clear diagnosis in about two-thirds of patients, not accurately detecting the remainder. Therefore, the limitations of oximetry must be considered and all hospitals should have access to more detailed overnight studies, recording at least breathing pattern and leg movement. [16].

2.3.5 Radiographic and Endoscopic Evaluations of the Upper Airway

Modern upper airway imaging techniques have given relevant and advanced knowledge about pathophysiology and biomechanics of OSAS. Among such techniques are *Magnetic Resonance Imaging* (MRI), *Computed Tomography*, nasopharyngoscopy, cephalometry and fluoroscopy, which have objectively quantified the upper airway structures and identified specific craniofacial and oropharyngeal soft tissue structural risk factors for OSAS. However, there are no current approved clinical indications for imaging subjects with suspected OSAS. Regarding sleep disorders, to this day, imaging is only used in evaluation for upper airway surgery or oral appliances, a situation that might change in a near future due to the advantages associated with imaging, inexpensive, noninvasive, with no weight limitations techniques [36].

2.4 Biofeedback

Individuals exhibit voluntary yet unwittingly control over brain activation in a daily basis. Nevertheless, the extent to which an individual can learn to directly and consciously control the activation of specific brain regions is not yet known [15]. Biofeedback is a procedure supported by machinery that translates physiological processes into audio or visual real-time signals, with the goal of controlling central nervous system activity. Biofeedback controllable physiological functions include heart rate, skin conductance, muscle tone, brain waves and pain perception [15].

Research shows that biofeedback, alone or in combination with other behavioral therapies, is effective for treating a variety of medical and psychological disorders, namely headaches [49], migraines [48], incontinence [65], hypertension or attention disorders. In addition to continuous research, there are several biofeedback protocols available, namely for EMG, extremities temperature, skin conductance, neurofeedback (EEG training) and *Heart Rate Variability* (HRV) [76].

2.4.1 Biofeedback in Heart Rate Variability

A particular biofeedback protocol deals with HRV, and refers to the rise and fall of heart rate synchronized with each breath. However, preceding further protocol detail, a proper definition of HRV is demanded. *Heart Rate Variability* (HRV) is defined by the amount of heart rate fluctuations around the mean heart rate. In fact, the continuous changes in the sympathetic-parasympathetic balance force fluctuations in the sinus rhythm, with frequent cardiovascular control system induced small adjustments in heart rate (Fig. 2.10). There are three main periodic consequent fluctuations: respiratory sinus arrhythmia, baroreflex related and thermoregulation-related heart rate variability. Indeed, the heart shows fluctuations with a frequency equal to the respiratory rate, beating faster on the inhale and slower on the exhale [59].

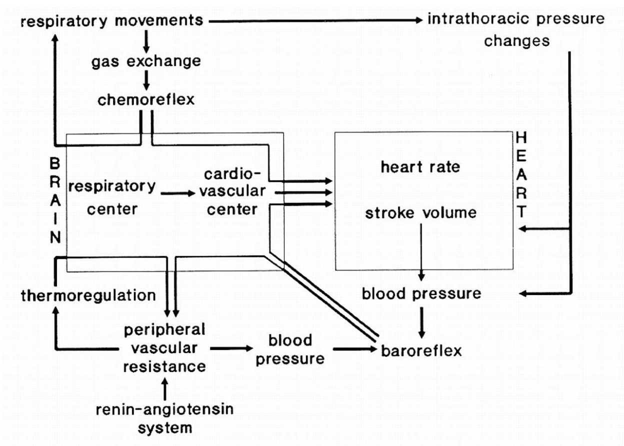

Figure 2.10: Diagram for the cardiovascular control mechanisms responsible for the main periodic fluctuations in heart rate (source: [59]).

HRV is a valuable tool to investigate the sympathetic and parasympathetic function of the autonomic nervous system and, therefore, predict the risk for sudden cardiac death in post-infarction and diabetic patients, for instance [59]. Additionally, HRV measurements are easy to perform, noninvasive and have good reproducibility. Nonetheless, standardized conditions are mandatory, since factors such as respiratory rate and posture influence HRV [28]. Another modulating factor to HRV is age, with increasing age associated with lower HRV [54]

Considering the magnitude of the HRV reflects a healthy variation between two autonomic influences of the heart, sympathetic and parasympathetic, lack of this variation suggests an imbalance between the two, and subsequent poor cardiovascular health. By taking control over one's emotional state, calming and breathing slower, the HRV can be increased.

Heart rate variability biofeedback can be achieved monitoring either heart rate alone, or heart rate plus respiration. Heart rate can be depicted through R to R intervals, which represented the distance between two subsequent R peaks in the *electrocardiogram* (ECG) and are further explained in the following section. Most common protocols involve the displaying of cyclic heart variations on a video screen, while the subject observes the trace and uses it as feedback for regulating the breath and, consequently, the emotional state. Each individual's HRV is maximized at a particular *resonant frequency* of breaths per minute, with observation determinable characteristic values that usually are around six per minute.

An improved HRV is not an immediate consequence, generally taking an average of four to ten sessions for relevant results to be observable. However, practicing with HRV biofeedback provides a model for real-life self-regulation, awareness of one's breathing and emotional state [76].

2.5 Physiological Monitoring Belts

The first wireless heart rate monitor was invented in 1977 as a training aid for the Finnish National Cross Country Ski Team. However, it was not until the middle 1980's that such devices became popular among athletic circles, with retail sales of wireless personal heart rate monitors starting in 1983. Such early models consisted of a monitoring box with a set of electrode leads that attached to the chest [7].

It must be referred that, throughout this thesis, terms such as *heart rate monitor*, *physiological monitoring belt*, *monitoring belt* or *chest strap* are used interchangeably. A heart rate monitor is a personal monitoring device that measures the heart rate of a subject, reporting either in real time or for later study. The heart rate is defined by the frequency of the cardiac cycle, a term referring to all the events occurring from the beginning of one heartbeat to the following one. Traditionally measured in *beats per minute* (bpm), resting heart rate (HR_{rest}) in healthy adults ranges from 60 bpm to 80 bpm [22].

Nowadays, the most common type of heart monitors comprises two elements: a chest strap transmitter and a wrist receiver (Fig. 2.11 A). While traditionally plastic straps required water or a liquid for good conductivity, recent units are designed with conductive smart fabric with built-in microprocessors that analyze the ECG signal to measure the heart rate. Other popular types of heart rate monitors include strapless wristwatch (Fig. 2.11 B), which calculates the heart rate using just two touch sensors; sports bra for women, which include the sensors in the fabric; or the combination of chest strap, wrist receiver and also a foot pod, which measures jogging velocity (Fig. 2.11 C) [7].

Furthermore, some heart rate monitors also estimate energy expenditure. However, various

Figure 2.11: Common athlete's monitoring devices: (A) chest strap and wrist receiver, (B) wrist-watch and (C) Chest strap, wrist receiver and also foot pod.

studies concluded that such monitors only provide a rough estimate of the real energy expenditure during running and cycling [13], with an underestimated real energy expenditure by 13% in running [43]. These studies also concluded that the lack of accuracy by such heart rate monitors is related to the monitor's prediction of both the maximal oxygen consumption, VO_2 max, and maximum heart rate, HR_{max}. In fact, accuracy is improved by inputting actual values.

Modern cardiac belts are complete performance-monitoring tools for both elite athletes and fitness enthusiasts, with the potential to revolutionize training for health, fitness and competition [7]. In fact, some cardiac belts currently available on the market monitor not only the heart, but also breathing frequency, temperature, posture and activity [71].

In what concerns the heart, a complete *electrocardiogram* (ECG) is recorded by some monitoring belts, using skin electrodes. An ECG is an exam which measures the electrical current generated by the heart during its contraction and relaxation [22]. A typical ECG comprises repeating cardiac cycles, similar to the one shown in Fig. 2.12. The P wave corresponds to the record of the electrical current through the upper heart chambers, the *atria*, which is followed by the QRS, the flowing of the electrical impulses produced to the lower heart chambers, the *ventricles*. On the other hand, the ST segment corresponds to the portion of time the ventricle is contracting but no electrical current is flowing through it. In fact, the ST segment is often similar to a straight line between the QRS complex and the T wave, with the latter corresponding to the relaxation of the lower heart chambers [73].

Another heart related physiological monitoring belts measurement are R to R intervals, which measure the distance between two consecutive ECG waveform peaks and, thus, are commonly referred to as R-R intervals. The monitoring devices autonomously recognizes the QRS wave complexes, calculating the time between subsequent R peaks [69]. It is important to refer that the heart rate presented by the monitoring belts is usually an estimation based on the R-R interval, thus called *instantaneous frequency*. This is given by

$$f_{inst} = \frac{60}{t(R_i) - t(R_{i-1})} \tag{2.1}$$

where sixty is the number of seconds in one minute, which arises the desired time unit - *beats per minute*. On the other hand, R-R intervals are usually measured in milliseconds (ms), with regular

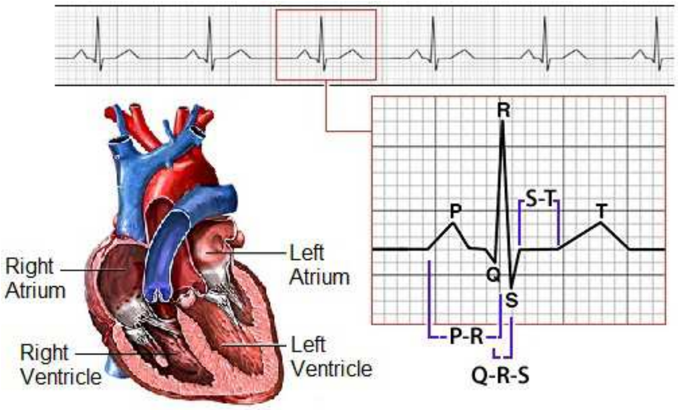

Figure 2.12: Illustration of a normal heart and ECG waveform (adapted from [50]).

values ranging from 600 ms to 1200 ms [22]. As a consequence of the R-R intervals definition, smaller distances correspond to higher heart rate values and stress, while, on the contrary, higher R-R intervals are associated with lower heart rate values, hence relaxed situations.

Breathing Frequency (BF), also frequently referred to as respiration rate, is another physiological parameter measured by some chest straps. BF is defined by the number of breaths taken within a certain period of time, being usually expressed in *breaths per minute* [73]. The measurement of this parameter involves counting the number of chest elevations, with average breathing frequencies of 12 breaths per minute (12/60 Hz) [3].

Moreover, some modern chest straps incorporate an accelerometer, which is useful for measurement of both posture and activity. Human standing position corresponds to a posture of 0°. On the other hand, activity evaluates the acceleration undertaken by the body in one to three axes. With the devastating impact of obesity on global health, a situation related to low levels of physical activity and sedentariness, the measure of physical activity, such as in walking, is increasingly studied [19].

Nowadays, in addition to the traditional recording and storing of information by physiological monitoring belts, data can also be transmitted over a ten meter range using Bluetooth® technology to a suitable device, traditionally a personal computer [69]. In many ways, training with such monitors is like having a full-time coach, helping subjects hold back when necessary and gradually building the desired fitness [7].

2.6 Mobile Phones

In the last few years, mobile phones have evolved into attractive platforms for innovative types of applications. These widely spread among the population devices provide considerable computing power and often offer an abundance of built-in sensors. Such features are an addition to more traditional personal information tools, such as names of people the user knows (from the phonebook), appointments the user has (from the calendar) or pictures and sound clips the user has recorded [35]. In fact, an increasing number of projects have tried to bridge the often described gap between the real and the virtual world. For instance, mobile phone cameras have been used to recognize 1D or 2D bar codes that link information to retail products [1], the GSM, GPS or WLAN modules for location based services [34] and the built-in microphone to generate noise-maps of environments [41].

However, when compared to design and prototyping of desktop software, mobile phone development still demands a high level of expertise in both phone architectures and their low-level programming languages. In fact, designing applications that leverage the mobile phone platform potential is still a highly time consuming process, particularly when full control of the device and its sensors is involved [2].

The broad variety of mobile phones available in the market is accompanied by a similar variety in developing platforms and *Application Programming Interfaces* (API), each with its own strengths and weaknesses. For instance, the *JavaME*'s API, present in many mobile phones, is very limited for in-depth phone control, which is why many developers choose to delve into low-level programming languages. Examples of such languages are as *C++ Symbian*, used on the majority of today's smart phones [23], *Objective C*, associated with iPhone®, or *C* associated with a *Java User Interface* (UI), which is the platform used by most Android® developers. Android is a recent but rapidly growing mobile OS owned by Google. In fact, Android OS based smartphones ranked first among all smartphone OS handsets sold in the U.S. in the second quarter of 2010.

One relevant exception is *Python for S60* (PyS60). This API was initiated and is officially supported by Nokia®, being implemented in native *Symbian C++* and offering direct access to most available phone functions. PyS60 is a port of the popular Python language to S60, thus carrying the emphasis of design philosophy in code readability, which makes it such an easy to learn and use language.

Python is a highly powerful and versatile language which comprises a very large and comprehensive basic library, a perfect candidate for this project. Although Python's basic library is very complete, specific tasks demand specific modules, which add numerous possibilities suitable to each process. However, rather than incorporating all the desirable features in the language's core, Python was designed to be highly extensible. In fact, new built-in modules can be developed in *C*, *C++* or *Cython* [57].

Compared to other programming alternatives, PyS60 markedly simplifies the process of programming. PyS60 is open source, meaning it is freely distributed and developers all over the world willingly contribute to its improving. In fact, tutorials for beginners, as well as for more advanced users are easily found with a simple Internet search. Furthermore, Nokia® provides a forum exclusive to PyS60 developers, in which one can search for answers to arising problems.

Nevertheless, PyS60 development is not without flaws. In fact, PyS60's Symbian heritage requires programmers to be comfortable with the typical Symbian development process, which includes knowing how to package an application for distribution or how to sign an application in order to gain access to sensors like GPS [2]. Situations that, nonetheless, have been improving in the last versions of the API, with PyS60 2.0.0 as its most recent.

Despite the aforementioned difficulties, the three most challenging and time consuming problems associated with any type of mobile phone development have not yet been mentioned. First, programming is usually done on a desktop or laptop computer, with testing applications requiring, repeatedly, the uploading, debugging and subsequent updating of the scripts. Second, programmers must ensure applications run on different device types. Third, developers often need to update previously deployed applications for bug fixing, once again undergoing the complex and time consuming process described above [2].

Notwithstanding all the challenges that this type of development entails, the unique possibilities inherent to mobile phone applications are a strongly, valid reward. In fact, mobile phones are ubiquitous, are portable, are powerful and, thus, properly designed applications can, at once, target enormous audiences, doing so with considerably low developing costs.

3

System Framework

Contents

Following the contextual framing accomplished in the previous chapter, in which the need for innovative, less expensive and portable diagnosis platforms was exposed, the present chapter presents the alternative proposed in this thesis to existing sleep assesemnt tools. The system, hereby designed as *Mobile Acquisition Platform for Sleep Assessment* (MAPSA), intends to be a highly portable physiological monitoring and user-interactive platform, with special focus on the diagnosis of sleep disorders. Essentially, there are two devices supporting the MAPSA - a physiological acquisition belt and a mobile phone. While the first device monitors the biological data, the second handles both the processing and storing of the data acquired and provides an user interface that also grants the possibility of registering self-reporting sleep and dream diaries.

This chapter is divided into three sections. The first one is necessary to define the problem that needs to be solved or, in this specific context, the situation that needs to be improved. This section is also necessary to define how the system will be of use to the user, clinicians, and what functionalities it should incorporate for the benefit of both the clinician and the patient. The second section establishes the system's architecture, the components that support it and the features intended for the system to possess, while the last section describes the computational implementation undertaken, considering each device's characteristics.

3.1 Problem Definition

With the increasing number of people bending their circadian rhythms to the limit, either for professional or recreational reasons, sleep disorders patients tend to grow in number and, therefore, so does the demand for sleep assessment exams. As stated before, although PSG is the benchmark for sleep diagnosis, several complaints point out to conditions that do not require such a thorough and, subsequently, expensive exam. Among such pathologies are, for instance, narcolepsy, PLMD, RLS, DSPS, SWSD and OSAS, which can often be diagnosed only recurring to different combinations of actigraphy, temperature, ECG and a sleep diary.

Sleep diaries, on the other hand, are extensive paper questionnaires which the patient must attentively fill in every morning. Furthermore, the crossing of the sleep diaries information with other variables is uncommon. First, the PSG is an exam that extensively monitors the patient, but for one night only. Second, even when actigraphy is performed for several days, in combination with a self-reported sleep diary, both data are presented to the physician as independent, who must then analyze the questionnaires and cross the days with the ones registered by the actigraph to make a proper attempt of diagnosis. Furthermore, some questionnaires are accompanied by a scoring system that characterizes the subject's sleep and associated disturbs. Since these questionnaires are filled by hand, so do the subsequent calculation of scores, a time consuming process that is yet to be automated.

Dream electronic-Diaries are, to this day, a disregarded tool, given the complexity associated to their analysis. If scoring sleep is a time consuming process, analyzing dreams is an overly complex process for physicians to bear, and thus often dreams are not considered in sleep assessment. On the other hand, when they are, the scoring problem presented for traditional sleep diaries is also a fit.

3.2 System Architecture

Considering the needs stated above, the *Mobile Acquisition Platform for Sleep Assessment* (MAPSA) was conceived in an attempt to offer the physicians a portable and inexpensive alternative to PSG that, nonetheless, is suitable for the assessment of sleep diseases, offering valuable data.

Although previous attempts to build portable acquisition systems from the ground were made, in this particular thesis a commercial physiological monitoring belt was used, focusing the system in a crossing of different types of information, available to the physician in a user-friendly interface.

While current marketed monitoring belts incorporate chest actigraphs, as well as ECG and temperature measurement, the user applications, if available, are for personal computers only and very limited in both options and acquisition times. Given the fact that some modern physiological monitoring belts connect to their storing data platform via Bluetooth®, new possibilities arise. In fact, considering that most modern mobile phones are equipped with several connectivity features, such as Wi-Fi or Bluetooth®, the physical constraints associated with a computer are no longer an issue. In the present system, a Bluetooth® connection between the monitoring belt and a mobile phone is intended, which enables a continuous processing and storage of the acquired data. Furthermore, a Wi-Fi connection between the mobile phone and an Internet server enables the secure periodic storage of all the information collected, also assuring that such information reaches the physician's computer terminal.

As for the flaws associated with sleep diaries, the present system proposes the autonomous analysis of the data from both outputs and its presentation to the physician in a parallel display with chosen time spans. Another proposed added value to MAPSA when related to other existing electronic sleep diaries is the possibility of sleep and insomnia classification. This information gives the physician a better understanding of the patient's quotidian complaints over time, via the autonomous calculation of insomnia scores. However, such a feature is just a plus to a traditional e-diary also available, in which routine activities such as sleep, meals, work-outs or complaints are presented as events. Studies have shown better patient compliance with electronic diaries, when compared with paper diaries [68].

In the context of dream diaries, four main features are presented by this system: the audio self-reporting of dreams by the patient, the subsequent automatic transcription of such dreams by an autonomous speech-recognition platform, the characterization of the dreams according to standard scales and the scheduling of this type of events in an electronic calendar, common to the electronic sleep diary. The aforementioned features present two main advantages: the audio dream reporting by the patient is much more comfortable, when compared to written reports, and the transcribed dreams present can be considered for key-words or patterns search.

In conclusion, the system hereby presented intends to offer an alternative supported by only two devices, a physiological monitoring belt and a mobile phone, comprising three interconnected main tools: the acquisition of physiological data, a *Sleep electronic-Diary* (SeD) and a *Dream electronic-Diary* (DeD). The architecture of the *Mobile Acquisition Platform for Sleep Assessment* is displayed in Fig. 3.1.

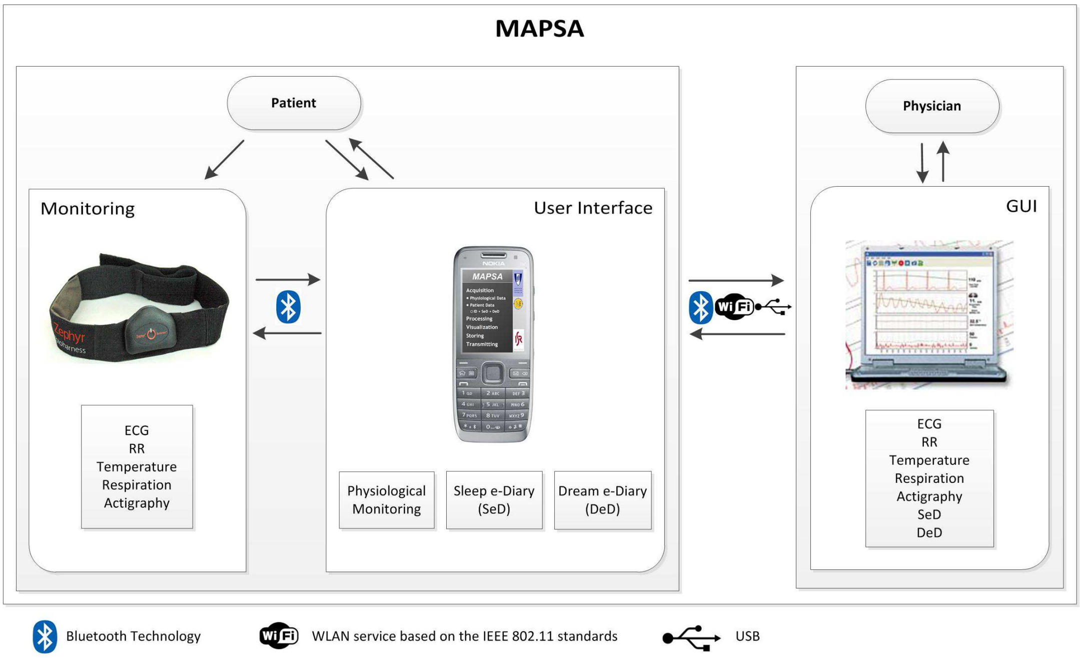

Figure 3.1: MAPSA system architecture.

The following paragraphs explain in further detail the features associated with each of the tools that support MAPSA, as well as the conceptualization behind the user interfaces developed. Furthermore, these subsections intend to capture the individual concepts that this system proposes, justifying their role in the system as a whole.

3.2.1 Physiological Monitoring Belt - Zephyr®BioHarness Bluetooth

According to the aforementioned motivations, the presented MAPSA system demanded a physiological monitoring belt incorporating Bluetooth® connectivity capabilities. After some market research, the *Zephyr® BioHarness Bluetooth* was chosen as an adequate fit, a physiological monitoring system which comprises two parts: a smart fabric chest strap and the *BioHarness Module*.

The subject wears a smart fabric chest strap which incorporates sensors to monitor heart ECG signals and respiration rate. On the other hand, attached to the strap is the *BioHarness Module*, which includes an infrared temperature sensor, for monitoring skin temperature, and a tri-axial accelerometer, for monitoring attitude (subject posture) and activity (acceleration) (Fig. 3.2). This module is detachable from the chest strap for cleaning purposes and can be charged in a docking station (Fig. 3.2 C), which connects to a personal computer via USB cable. Raw sensor data is acquired and transmitted by Class I Bluetooth® over a ten meter range to a corresponding Bluetooth® device, thus allowing physiological data monitoring [71].

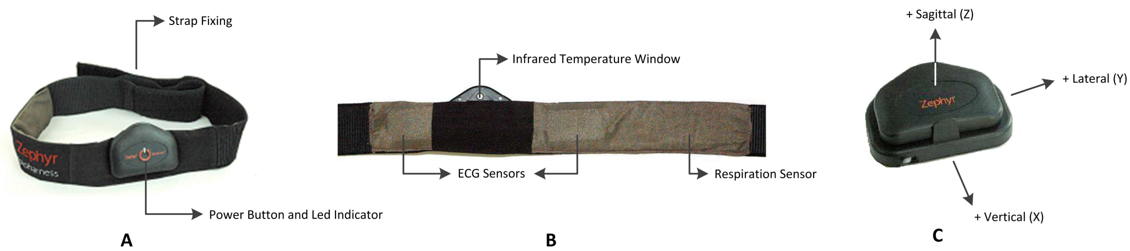

Figure 3.2: Zephyr® BioHarness (A) from a superior view and (B) anterior view. (C) *BioHarness Module* accelerometer axis orientation.

Using the added capabilities of both the chest strap and the detachable module, this physiological monitoring belt measures several parameters. These variables are essentially related to heart, breathing, temperature and posture measurements. The sampling frequencies of each parameter acquired as well as the associated measurement units are detailed in Table 3.1.

Table 3.1: Zephyr® BioHarness Bluetooth transmitted data description (source: [71])

Parameter	f_s (Hz)	Range	Units	Description
Heart Rate	1	0 - 240	bpm	Beats per Minute
ECG Waveform	250	0 - 1024	bits	-
Heart Rate R-R	18	Minimum 250	ms	alternate $\pm$ sign at new detection
Breathing Rate	1	0 - 70	bpm	Breaths per Minute
Breathing Waveform	18	0 - 4095	bits	breathing depth not available
Skin Temperature	1	0 - 60	°C	Degree Celsius
Posture	1	$\pm$ 180	Degress	Vertical = 0°
Activity Level	1	$\pm$ 3.3	VMU (g)	-
X axis Acceleration	50	$\pm$ 3.3	VMU (g)	Vertical Axis
Y axis Acceleration	50	$\pm$ 3.3	VMU (g)	Lateral Axis
Z axis Acceleration	50	$\pm$ 3.3	VMU (g)	Sagittal Axis

To start the monitoring, the subject must undergo some simple steps: put the garment on backwards first, for easier adjustment of tension and alignment of the Velcro® fastening, ensuring the strap is snug but comfortable; reposition the garment so that it is just below the chest muscles, the fasteners are centered on the torso and the middle snap above the sternum; attach the *BioHarness Module* and continuously press the power button until it starts flashing a red light [71].

3.2.2 Mobile Phone

The second device supporting the *Mobile Acquisition Platform for Sleep Assessment* is a mobile phone. Considering the architecture presented in Fig. 3.1, the mobile phone terminal application focuses on three areas: the connection to the physiological belt, the *Sleep electronic-Diary* (SeD) and the *Dream electronic-Diary* (DeD). Following is the characterization of each one of these subjects.

As soon as the *Zephyr*® *BioHarness Bluetooth*'s power button is pressed, the device starts transmitting data. However, the physiological monitoring belt must also have established a Bluetooth® connection with a Bluetooth® receiving device before data can be relayed to any application software [71]. This key function is entrusted to the mobile phone.

The *BioHarness Monitoring Tool* only needs two main options: *Start Acquisition* and *Data Visualization*, with the last referring to visualization of both previously record data and live data acquisition. When the patient selects the *Start Acquisition* option, the duration of the desired monitoring is selected and the connection is established without further interaction required.

In the context of the *Sleep electronic-Diary* (SeD), there are three actions available to the user in the main menu: *Insert Event*, *Show Calendar* and *Delete Event*. Although this suggests a simplistic approach, one must look at the structure of the SeD as a whole to understand that all the necessary features are present (Fig. 3.3).

The selection of *Insert Event* arises a new screen, in which the user selects an event and characterizes it with both date and time, necessary for the scheduling of the associate entry in the mobile phone's native calendar. In addition, when the event is characterized by intensity or further aspects, the application gathers all the necessary information, adding it to the scheduled event.

The classification of sleep is presented as subsequent to the entry of *Wake Up* event, for the type of questions necessary in insomnia's classification are related to the quality of the subject's main sleep episode, usually nocturnal. Therefore, each day's classification is stored, so that the necessary evaluation can later be performed.

For the visualization of events, the native mobile phone's calendar is called, presenting the user with a familiar and friendly interface that interactively enables the inspection of previous SeD related activities. The last main menu option, *Delete Event*, queries the user for both type and date of the event and deleting it, upon approval, from the SeD.

Considering the *Dream electronic-Diary* (DeD), the tool must provide the user with five main options: *Record*, *Listen* and *Delete* dreams. Additionally, the DeD must be able to transcript and transfer the dreams to the physician's computer terminal. Bearing this in mind, the DeD design is structured as follows in Fig. 3.4.

The application's main menu presents five possible actions to the user: *Record Dream*, *Listen to Dream*, *Read Dream*, *Delete Dream* and *Transcribe Dream*. The recording of the dreams is achieved using the built-in microphone, while the dreams play using the built-in speakers. At the

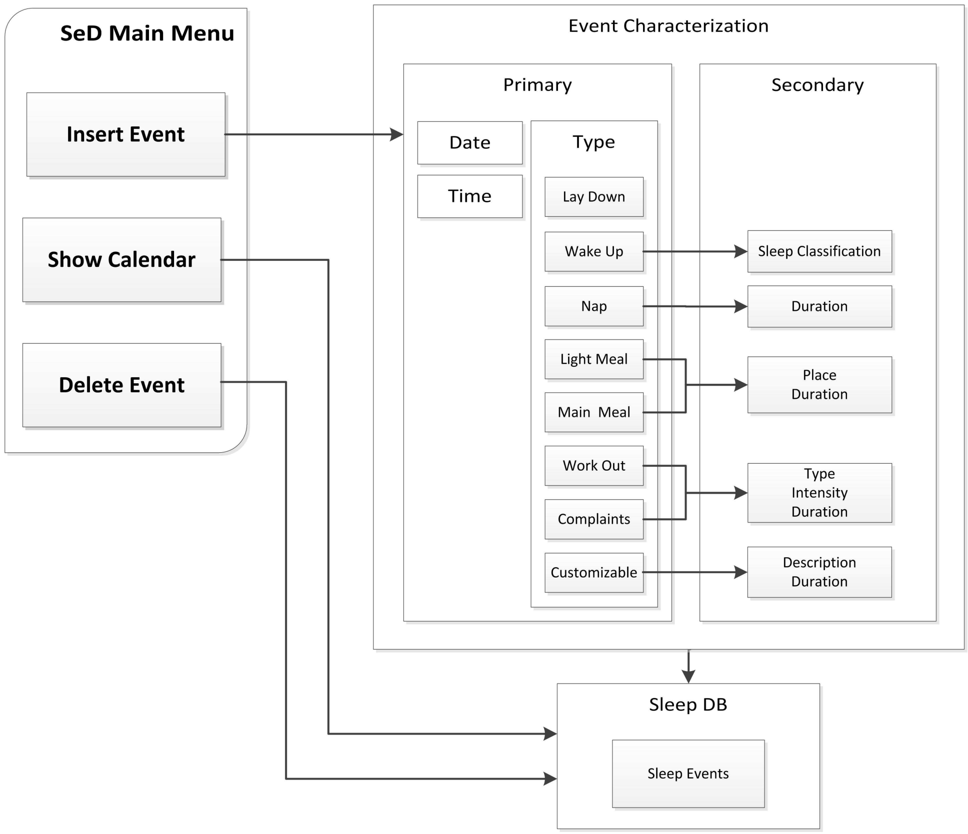

Figure 3.3: *Sleep electronic-Diary* (SeD) tool design.

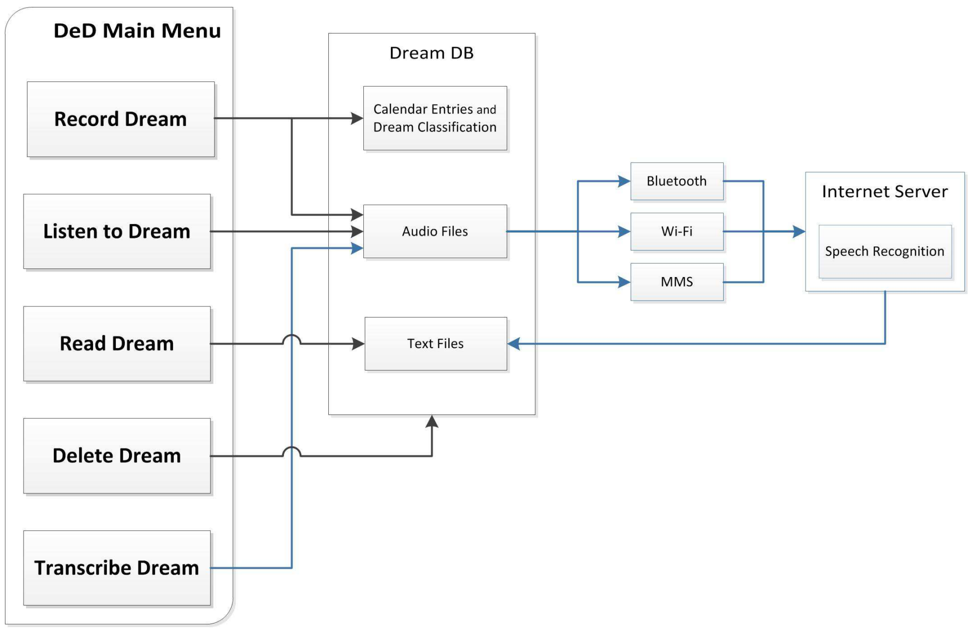

Figure 3.4: *Dream electronic-Diary* (DeD) tool design.

same time, the application automatically associates each recorded dream with an entry in the mobile phone's native calendar, enabling the observation of the subject dreams' frequency. Furthermore, following the dream recording, the subject must classify the dream by answering some questions provided by the application. These questions are supported by traditional questionnaires, using standardized scales of classification. The possibility of deleting dreams is relevant, for the subject might accidentally start recording a dream and feel the need to remove it from the database.

On the other hand, the previously mentioned automatic transcription of dreams is done using an independent speech recognition platform. For this transcription, the only required action by the user is the selection of the fifth option, *Transcribe Dreams*. With the selection of such an option, the application then transfers the audio files corresponding to the dreams to an Internet server, which independently performs the transcription and returns a text file to the mobile phone. The connection between the mobile phone and the Internet server is accomplished by either one of three available means: Bluetooth®, Wi-Fi or MMS®. Only succeeding the transcription of a certain dream it becomes available for the user to read in the mobile phone's screen, a possible option under the name *Read Dream*.

One highly relevant original contribution from this thesis is precisely the production of a Portuguese patent concerning the *Dream e-Diary* as a dream reporting platform suitable for sleep assessment purposes. This patent, written in Portuguese language for legal issues, extensively depicts all the aforementioned features and its summary is presented in Appendix A of this thesis.

On the other hand, insomnia assessment can be done recurring to Likert scales, widely used in survey research. With this type of scale, patients express their one to five level of agreement or disagreement to a certain statement [75]. In the previous chapter, several sleep related questionnaires were mentioned. From such a wide range of options, in this particular system an adaptation of the questionnaire used in CENC was designed, which inquires the patient in an objective manner, in questions with answers that are either number or Likert scales classifications.

In conclusion, the connection between the mobile phone and the physician's terminal must be referred. This connection ensures all the files subsequent from the tools described above reach the physician's computer terminal, and can be achieved by either one of three types of connection available: Bluetooth®, Wi-Fi or USB®.

3.2.3 Graphical User Interface (GUI)

The *Graphical User Interface* available in the physician's computer terminal, is designed as a complete and interactive visualization tool. In fact, the high amount of data transmitted by the mobile phone demands a highly adaptable application, with chosen time spans and information parameters. Moreover, as this is a platform intended for patients' diagnosis, unique identification stamps must also be added. In addition to SeD and DeD scheduling information, one must consider the monitoring information provided by the *Zephyr®* *BioHarness Bluetooth*, which comprises ECG, breathing and acceleration waveforms, as well as heart R-R and breathing rates, and also skin temperature and posture. In general lines, the design intended for the GUI is as presented in Fig. 3.5.

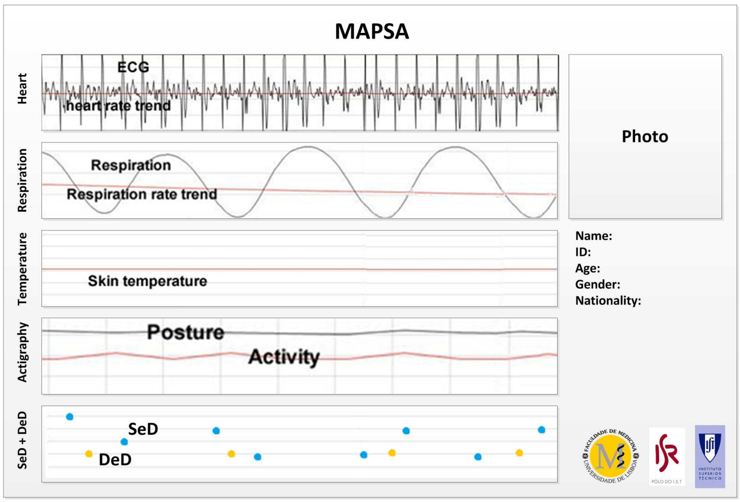

Figure 3.5: *Graphical User Interface* (GUI) design.

3.3 Computational Implementation

This section intends to explain the necessary computational implementation undertaken. Although such implementation was only necessary for the applications associated with the mobile phone and the computer, the first subject refers to the physiological monitoring belt. Such an option is justified by the necessary introduction to the *BioHarness*'s functioning and transmitting processes, which determinedly influenced the development of the mobile phone's *BioHarness Monitoring Tool*.

3.3.1 Zephyr®BioHarness Bluetooth

Considering the *Zephyr®* *BioHarness Bluetooth* handles a considerable variety of data, this information is monitored recurring to five individual packets: *General Data Packets*, *ECG Data Packets*, *R to R Data Packets*, *Breathing Data Packets* and *Accelerometer Data Packets*. In this context, a packet is a segment of ASCII characters corresponding to decimal codes, which contains a specified type and length (samples) of information, which is periodically sent to the receiving Bluetooth® device. Table 3.2 briefly characterizes these streaming packets. Each data packet must be individually enabled before the *BioHarness* starts its streaming and, thus, the monitoring can be done on the number and type of packets of interest [69].

The *BioHarness* uses a simple request/response (ACK) link transfer mechanism for most of the packets it processes, such as information on time, battery or worn status of the *BioHarness*

Table 3.2: Zephyr® BioHarness Bluetooth streaming packets description (adapted from [69] and [70])

Packet Type	Transmission Period (ms)	f_s (Hz)	*N*	Description
General	1008	1	1	Skin Temperature, Heart and Breathing Rate and Posture
Breathing	1008	18	18	Breathing Waveform
R to R	1008	18	18	Calculated from the ECG
ECG	252	250	63	ECG Waveform
Accelerometer	400	50	20	X, Y and Z accelerometer waveforms

Module. Exception must be made for streaming data packets, which have no ACK associated with the data transferred, a factor that would delay the whole process given the amount of real-time data being transferred [69].

The *Zephyr® BioHarness Bluetooth* only supports one connection at a time, using Bluetooth® *Serial Port Profile* (SPP) to communicate with other devices via a low-level protocol with a baud rate of 115,200 Bd (symbols per second). Additionally, as a protection against link failures, a timeout of 10 seconds has been implemented on the *BioHarness* link, meaning if no packets are received by an external device for more than 10 seconds, the link will be dropped by the *BioHarness Module* [69].

3.3.2 Mobile Phone

Recent improvements in processing power and RAM capacity brought mobile phones closer to computers, while trading off some efficiency for programmer convenience [35]. For instance, a typical modern smartphone, Nokia® E52, has a 600 MHz ARM processor and 128 MB of free RAM for applications. Such a mobile phone is ideally suited for exploratory programming and research prototyping, enabling interactive development and joining many ideas very rapidly. This kind of smartphone is Symbian OS-based, a platform used by several vendors such as Nokia®, Samsung® or Panasonic®. Therefore, Symbian OS applications can currently target a very large market of phones.

For this particular system, PyS60 was chosen as a developing language, for it is freely distributed, easy to both learn and use, yet still highly powerful. Using PyS60, the monitoring of the physiological belt, subsequent data processing and a user-friendly interface are possible on the mobile phone.

As stated before, although the *Zephyr® BioHarness Bluetooth* starts transmitting data as soon as the power button is pressed, a proper Bluetooth® connection with an external device in necessary for the beginning of the data monitoring. Therefore, the first step in the monitoring process is to establish an adequate Bluetooth® connection between the two devices, a service provided by the PyS60's *btsocket* module.

The *BioHarness Module* transmits the wide range of monitored data in several independent data packets. Each data packet type has an associated control string to determine its sending status. It must be referred that, in this context, a string is a segment of hexadecimal characters which are individually specified in the chest strap developer's booklet [70]. Therefore, the mobile phone must send an order corresponding to the activation of each data packet, ensuring its activation in the belt with the receiving of a known response string.

Once all the desired data packets are activated, the chest strap monitors and sends the information periodically, according to Table 3.2. Since each data packet has an associated date stamp unique for all the samples it contains, the implementation of routines that calculate the date stamp correspondent to each individual sample was necessary. Considering the date stamp given by the packet as associated with the first sample, t_0, the first parameter to determine is the time associated with the last sample of a given packet, t_f, according to

$$t_f = t_0 + (N-1)\frac{1000}{f_s} \tag{3.1}$$

where *N* is the *number of samples* and f_s is the *sampling frequency*. The 1000 present in the numerator is justified by the fact that all the time handling is done in milliseconds (ms).

Furthermore, a date stamp for each sample must be calculated, which is achieved by

$$t_i = t_0 + \frac{i}{f_s} \tag{3.2}$$

where t_i is the date stamp associated with any given sample.

With the computational implementation developed, the mobile phone acquires, processes and records the information contained in all the data packets sent by the *BioHarness Module*, updating the user with relevant, periodic, outputs.

Concerning sleep (SeD) and dream (DeD) diaries, as well as insomnia assessment, a separate tool was developed for the mobile phone, in an attempt to ease the patient's task of creating a sleep relevant activities' calendar. Once again, PyS60 was chosen as programming language, this time with major focus in its *appuifw* module, which provides a versatile range of user interface's options relevant for the type of application desired.

In fact, this type of diaries requires the user to access the application each time a relevant event takes place, entering some necessary information such as date and time, duration or place. Furthermore, in the context of sleep and insomnia evaluation, objective questions and Likert classification scales were implemented, also using the aforementioned modules capabilities.

Both the SeD and the DeD are connected with the mobile phone's native calendar. In fact, each registered event is entered in the calendar's database (DB), which can be assessed using the native calendar's interface. Furthermore, each event is also listed in specific text files, which represent the information sent to the physician's terminal. Such an option enables the use of the mobile phone's calendar for personal, non-sleep related purposes, such as register of birthdays or tasks, preventing any subsequent undesired confusion in data analysis. Dream reporting, on the other hand, is stored under wave format in the mobile phone's memory card.

3.3.3 Graphical User Interface (GUI)

For convenience, the *Graphical User Interface* was developed in the computer version of PyS60 and its predecessor, *Python*. In particular, a GUI toolkit extension was used, *wxPython*, which allows the design of highly functional graphical user interfaces sparing the time-consuming need of writing all the associated code, which is automatically generated. Nevertheless, it provides the necessary connection with external Python modules such as *Matplotlib* or user created Python functions, representing a highly powerful tool.

4

Application Outputs

Contents

The fourth chapter describes the features the developed system provides as outputs, subsequent to the computational implementation depicted in the previous pages. This chapter is divided into two major sections, each corresponding to a particular application of the system. While the first is sleep disorder's focused, presenting the graphical user interface developed for the physician's use, as well as the role of sleep and dream diaries in insomnia diagnosis, the second refers the possible use of this system on a different scope - heart rate variability biofeedback. It is relevant to refer that, although all the presented pictures show user menus in English, all the developed tools are available in Portuguese as well.

4.1 A Sleep Assessment System

This first section portrays the main motivation of this thesis - the development of a portable acquisition system for continuous monitoring over extended periods of time. Therefore, the interface illustrated in the following paragraphs is the result of the conceptual model designed. In an effort to bring the reader a proper understanding of both the user and the physician's user interfaces, the section is extensively illustrated.

4.1.1 Patient System Utilization

From the patient's point of view, the MAPSA system entails two devices: the *Zephyr® BioHarness Bluetooth* and the mobile phone. The first represents a passive tool, for the patient only needs to adequately position the chest strap and press a button (according to the instructions in section 3.2.1). All the necessary interaction involves the mobile phone, which both ensures the Bluetooth® connection with the belt and the required user interface for the registry of sleep related events, via *Sleep e-Diary* (SeD) and *Dream e-Diary* (DeD).

Considering the physiological monitoring, the developed tool presents the user with a simple interface, as illustrated in Fig. 4.1. In fact, when the user selects the *Start Acquisition* option, choosing either the duration of the monitoring (Fig. 4.1 B) or the ending time (Fig. 4.1 C and D), the mobile phone autonomously connects with the cardiac belt via Bluetooth®. Also, the monitoring is performed for the specified period of time, during which the mobile phone enters power save mode. If the monitoring is intended for strictly sleep disorder's diagnosis, no further interaction is required in what concerns the chest strap.

While the acquisition elapses, the patient undergoes his regular routine, using the *Sleep e-Diary* (SeD) to schedule the relevant activities or events (Fig. 4.2 A), such as meals or complaints. The main menu for this specific tool is presented in Fig. 4.2 B, in which the key option is definitely the first. This option enables the user to easily select the occurring event (Fig. 4.2 C), as well as its associated date and time, which are by default the current local time. The selectable events are shown in the detail illustrated in Fig. 4.2 D. Furthermore, for user convenience, the items in

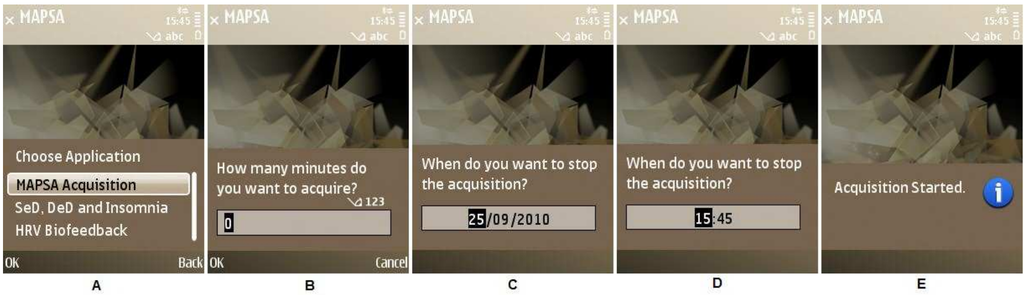

Figure 4.1: Physiological monitoring tool for mobile phone: (A) main menu, (B) monitoring time selection option 1, (C) monitoring time selection option 2 - date, (D) monitoring time selection option 2 - time, (E) acquisition start informative message.

this list can also be viewed using only the left and right joystick arrows.

Figure 4.2: (A) Sleep and dream application selection; (B) SeD's main menu, (C) SeD's primary event characterization, (D) SeD's primary event characterization detail.

In this SeD, *Lay Down* and *Wake Up* events are related. In fact, the tool imposes *Sleep* as an event each time consecutive *Lay Down* and *Wake Up* activities are inserted. Furthermore, the tool detects if the patient forgets the registry of either one of them, arising an error message (Fig. 4.3 A), inquiring the number of sleep hours (Fig. 4.3 B) and creating the associated event.

The third option is *Nap*, which does not need further characterization besides the duration of the event. On the other hand, the last option is a customizable event, adequate if no other option is a fit. The name of the activity and its duration are entered as secondary characterization.

Figure 4.3: SeD's characteristics: (A) lay down not registered error message, (B) subsequent number of sleep hours question, (C) meals secondary characterization, (D) work-out and complaints intensity selection and (E) complaints type characterization.

In what concerns *Meals*, a simple secondary characterization is necessary, which includes the place and duration of the event (Fig. 4.3 C). On the other hand, both *Work-Out* and *Complaints* need further characterization, which includes *Type*, *Intensity* and *Duration*. The *Intensity*'s Likert scale and the *Complaints*'s type selection are illustrated respectively in Fig. 4.3 D and 4.3 E.

All the registered events are scheduled in the native mobile's calendar, and thus can be consulted using a familiar interface. In Figure 4.4 the results of a sleep related scheduled set of events are shown: in (A) the calendar for the entire month, in which the sleep scheduled days are marked with a black triangle in the corner; in (B) an agenda view, which enables the visualization of all the events of any given day; in (C) a meal detail, which shows the associated location and duration of the event; finally, in (D) a complaint, with complaint type and intensity as details.

Figure 4.4: SeD's calendar with example routine events for an entire day: (A) month view, (B) agenda view, (C) main meal event detail and (D) headache complaint detail.

In addition to the regular possibility of deletion of events using the native calendar's interface, the SeD also provides such a possibility as a specific option (Fig. 4.2. In fact, the tool depicts the list of events filtered by user selected day (Fig. 4.5 A) and type (Fig. 4.5 B) to simplify the selection of events to delete (Fig. 4.5 C). In Fig. 4.5 D the associated confirmation message is shown. It should be added that similar messages are associated with all the actions performed in the SeD, to reassure the patient that all the events are, in fact, properly inserted or deleted.

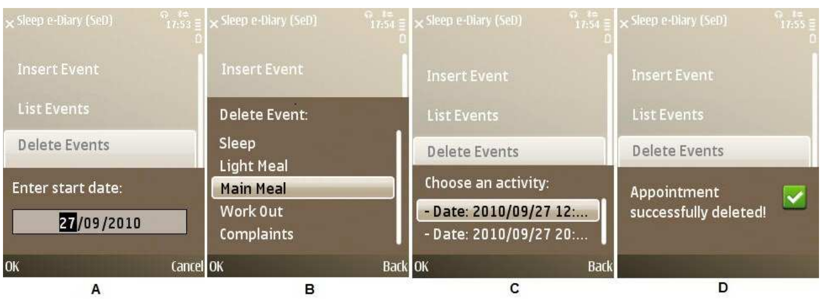

Figure 4.5: SeD's event deletion characteristics: (A) day selection, (B) event type selection, (C) associated deletable events, (D) confirmation message.

In the context of MAPSA system developed, the *Dream e-Diary* (DeD) presents three main menu options (Fig. 4.6 A): *Record Dream*, *Listen to Dream* and *Delete Dream*. The patient should select the first each time he intends to report a dream, usually immediately after waking up to ensure no details are forgotten. With the selection of *Record Dream*, the mobile phone starts recording an audio file until the patient finishes the report and chooses to stop the process (Fig. 4.6 B and C). Additionally, an associated event designated *DeD* is entered in the sleep calendar, which can be viewed as previously explained (Fig. 4.6 D).

Figure 4.6: DeD's characteristics: (A) main menu, (B) start recording dream message, (C) stop recording dream screen, (D) dream event in calendar and (E) listen or delete dreams list.

The two remaining options are *Listen to Dream* and *Delete Dream*. The selection of either one of these options returns a list of previously recorded dreams, from which the patient might select the ones to listen or to delete (Fig. 4.6 E). If a dream is selected to listen, the mobile phone plays the file recurring to the built-in speakers. However, the patient may stop the playing of the file before it reaches the end, since an option similar to the one shown in Fig. 4.6 C is presented. In the case of *Delete Dream* selection, one or more dreams are deleted from the *database* (DB), which is formed by three vertices: the audio files, the calendar entries and the text file sent to the physician's terminal, that will be further mentioned. Similarly to the SeD, confirmation messages are shown to the user along the registering or deleting process (Fig. 4.5 D).

The previous lines intended to extensively depict the options covered by both the *Sleep e-Diary* (SeD) and the *Dream e-Diary* (DeD). While the first shows an interactive and user-friendly, yet very complete alternative to normal paper sleep assessment diaries, the second is an interface designed for the comfortable patient's registry of dreams. Nonetheless, some features were not yet mentioned, for they concern sleep assessment at a deeper level, suitable for analysis that does not necessarily involve the acquisition of physiological variables over extended periods of time. These features are sleep and dream classification, as well as insomnia severity index calculation, respectively according to [46] and [45].

Considering the SeD, a sleep classification system was implemented. In fact, following the registry of each sleep event, a sleep quality questionnaire arises (Fig. 4.7), which is based on the one currently under use in CENC. The complete set of questions is presented in Appendix B. As illustrative examples, two types of questions are portrait in Fig. 4.7 A and B, one which the user answers with a number and other with an associated Likert scale of classification.

In the context of the DeD, a dream classification scale was also associated with the diary (Appendix B). Therefore, each time a dream is reported, the scheduling of that event in the associated

Figure 4.7: Sleep quality assessment integrated in SeD: (A) initial message, (B) question 1 and (C) question 7 and associated classification scale.

calendar is followed by an informative message and four questions (Fig. 4.8. These questions intend to assess the type of dream in question and can be useful when related to other sleep events such as early awakenings, reported in the sleep questionnaire.

Figure 4.8: Dream classification (A) start message, (B) question 1 and classification scale, (C) question 4 and classification scale.

Furthermore, an insomnia classification was added as a separate tool. Considering the insomnia severity index by Morin [45], available in Appendix B, seven questions regarding the preceding two weeks are inquired to the patient. Each question has an associated classification scale with scores that range from zero to four. The adding of all the seven questions' scores provides a number that ranges from zero to twenty-eight and that classifies the patient's insomnia. In fact, this tool starts with an informative message for the patient (Fig. 4.9 A), followed by the necessary seven questions, from which an example is presented in Fig. 4.9 B, concluding with the calculated insomnia assessment index, displaying a message with the diagnosis (Fig. 4.9 C).

Each of the aforementioned parameters, either physiological monitoring belt, SeD or DeD related, are registered in adequate *comma-separated-values* (csv) files. In fact, the magnitude or description is always associated with a proper date stamp, to enable a posterior cross integration of all the collected information.

4.1.2 Physician System Utilization

On the other hand, from the physician's point of view, the mobile phone interaction is not at all relevant. In fact, the important features are the connection between the mobile phone and

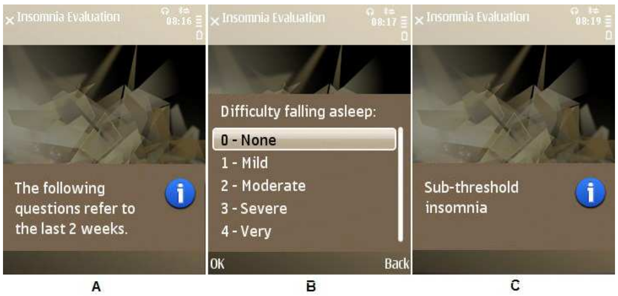

Figure 4.9: Insomnia severity index calculation: (A) initial message, (B) question 1 and (C) example of diagnosis.

a computer terminal and the visualization of the collected data in a proper interface, which aids in the diagnosing of sleep disorders. The mobile phone-computer terminal connection might be achieved by one of three methods: Internet, Bluetooth® and USB® connection. While the last is more appropriate in the case of long term acquisitions using the physiological monitoring belt, due to the size of the files involved, if SeD and DeD are the only tools used, the Bluetooth® connection might be used.

Once all the monitoring files are at the computer terminal, the visualization of the physiological parameters acquired by the chest strap, as well as the sleep and dream diaries events can be achieved in the developed GUI (Fig. 4.10).

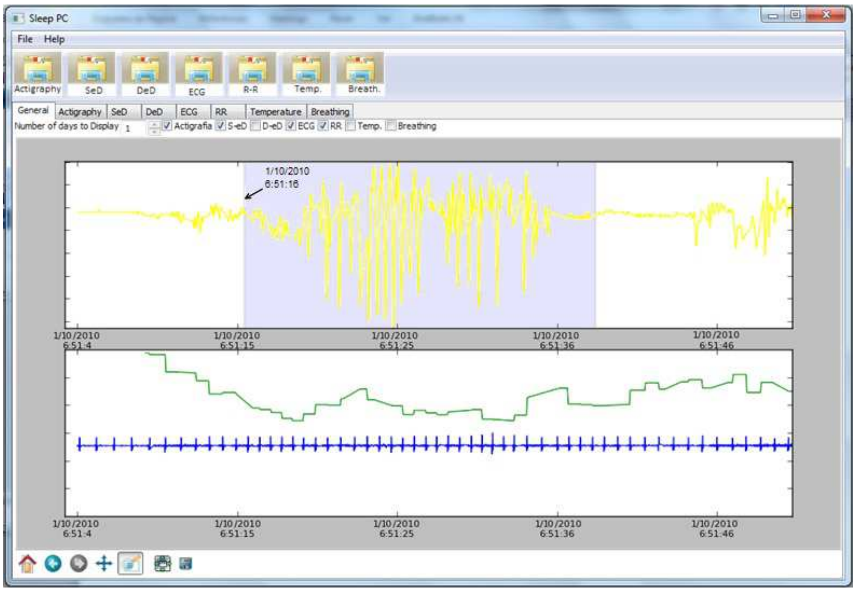

Figure 4.10: Visualization of physiological parameters and sleep and dream events in computer environment.

This monitoring depicts a short span of time so that variations in variables such as ECG, breathing waveform or activity could be observable. In yellow, the actigraphy data collected is represented, while in green are the R-R intervals and in blue the ECG waveform. The light blue background depicts an entry to the SeD, with its start time indicated by the black pointer.

Above the graphs is the selection of observable variables. The top icons, if pressed, allow the selection of monitoring files. The underlying tabs enable the visualization of specific details associated with each one the parameters, further depicted in 4.11. Furthermore, after the loading of several variables, the associated graphs can be disabled by pressing the squares beneath the tabs, next to which is the selection of number of days to visualize. On the bottom of the screen, options associated with zoom and time spans are displayed. The user can easily grab the screen and advance to the right or the left of the graphs, to understand the evolution of the variables.

From the physician's perspective, the possibility of an adaptable platform, in which the number and type of parameters to visualize is adjustable, is even more relevant for special types of analysis which do not require the physiological monitoring belt. In the developed GUI, actigraphy information collected previously to this work with a wrist device is also considered, aiming at the simultaneous display of this data and both SeD and DeD events. This GUI allows the selection of the desired files to analyze, which are preferably time consistent, since the purpose is to observe the cross analysis provided by the two types of monitoring.

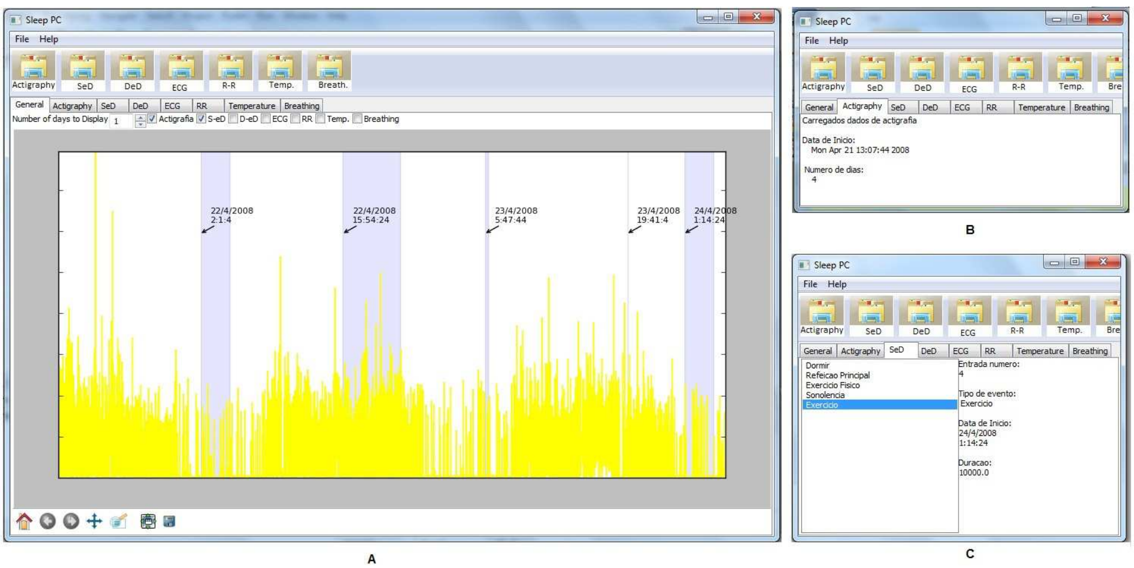

Figure 4.11: GUI actigraph and SeD plus DeD environment: (A) actigraphy and SeD data, (B) Actigraphy data acquisition details and (C) SeD list of events with specific details associated.

In Fig. 4.11 A the result of a simultaneous wrist actigraph and SeD monitoring is depicted. In yellow the magnitude of the acceleration derived from the patient's movements is shown, while the light blue spans of time indicate the events registered in the SeD. The interaction is at all similar to the previously depicted for the visualization of all the chest strap parameters. While the first tab is the main one, which has already been explained, the second tab characterizes the actigraphy data considered, in both date and length (Fig. 4.11 B). The third tab is associated with the SeD, showing further detail about each scheduled event (Fig. 4.11 C), and the last one is similar, but considers DeD events.

4.1.3 Discussion

The development of a complete interactive visualization system, in which the physician might select the desired time spans and physiological parameters, is definitely a valuable tool. However, though simple enough as an initial idea, the establishment of a proper Bluetooth® connection between the *Zephyr® BioHarness Bluetooth* and the mobile phone revealed to be a highly complex and time consuming process. Furthermore, the processing of the acquired values to adequate physiological values was not as intuitive as was expected. Therefore, the development of a complete, multiple patient prepared platform is not yet a reality. Nonetheless, highly important progress was achieved, and the mobile phone accompanied monitoring over extended periods of time is now a tool able to generate data appropriate for long term sleep assessment analysis.

In fact, the multi-parameter analysis associated with this system is recorded in adequate csv files containing both the date stamp and the magnitude or the type of the parameter, respectively in the case of physiological variables or sleep and dream events. Such files are adequate for an ordinary analysis in *Microsoft Excel*, which provides the possibility of a graphical view of the collected results, but can also be used for the main purpose they were designed to - the integration in a physician oriented interface.

The SeD was a tool idealized and patented in the context of a previous thesis [26]. In the present approach, however, numerous improvements were made. In fact, the tool is more complete and user-friendly, the events are simultaneously registered in the native phone's calendar and in a text file, with the first enabling the proper visualization of the registered events, and the associated csv files were designed to ease the integration of the events in the physician's computer terminal application. Furthermore, the possibility of deleting events erroneously entered was added, a feature that was lacking in the previous SeD version.

The DeD as it was conceived in section 3.2.2 intends to be a helpful tool in the diagnosing of sleep disorders. In fact, the tool as a whole can provide some very interesting innovative features, such as word pattern recognition. However, such tool needed support by an external and web based speech recognition platform. These kinds of platforms are currently only commercially available, something that is not viable in the context this DeD is set on. Moreover, the fact that Portuguese speech recognition platforms are scarce and still under development is a major obstacle. Although the upload of the audio files to a server could be achieved, having an independent platform autonomously transcribing the audio files was not possible.

Considering these setbacks, a more feasible DeD was implemented. This DeD includes the audio reporting of dreams and the automatic association of such events with a calendar common to the SeD. This approach to sleep assessment is considered to be valid in the context of this thesis, as it provides the groundwork necessary to a more complete and interesting future approach.

The main system depicted in this thesis considers both a physiological monitoring belt and a mobile phone. Nevertheless, the mobile interface developed, in what sleep and dream diaries are concerned, can be used as an independent tool. In fact, this possibility is of interest if one considers that physicians often diagnose sleeping disorders recurring to physical exams and sleeping diaries over periods of several weeks only, as well as on an overnight PSG and sleeping diaries, or even on actigraphy in addition to sleep diaries.

In that sense, the development of the GUI started with the connection between actigraphy, SeD and DeD. This possibility alone presents the system as an innovative and helpful tool in the diagnosis of sleep disorders. In fact, the relationship between actigraphy and subjective sleep assessment such as sleep diaries was considered to be highly relevant by several studies, both in the detection of sleep and wakefulness states and in the comparative analysis of this type of information [55] [32] [4] [42].

The platform as it is currently available is regarded as a valuable tool in the sleep assessment context, locally but also in foreign markets, as the system was implemented with both Portuguese and English versions. Naturally, the tool needs further improvements, such as the selection of magnitude scales or the development of an associated patient DB. However, several highly determinant steps have already been taken to accomplish that purpose.

4.2 Biofeedback in Heart Rate Variability

This section suggests a wider range of possible uses for the MAPSA system, with the application of the combo monitoring belt - mobile phone in biofeedback. Biofeedback is a technique that enables an individual to learn how to change physiological activity for the purpose of improving health and performance [38]. In fact, considering the variety of parameters monitored by the physiological belt, the mobile phone might serve the purpose of displaying biofeedback relevant information, in an attempt to achieve brain control activation.

4.2.1 System Utilization

In the utilization of the developed platform in biofeedback, the chest strap and the mobile phone are the only tools required. The subject wears the physiological monitoring belt as was previously described (section 3.2.1), pressing the central button to turn the power on. The mobile phone interface, as in the sleep related approach, handles the Bluetooth® connection, which will trigger the beginning of the physiological acquisition. In this particular application, only the RR-intervals packet is requested from the *Zephyr® BioHarness Bluetooth*, for the remaining variables are not relevant for the type of monitoring intended.

The interface starts by inquiring the exam duration and displaying a message when the acquisition starts, an approach similar to the previously depicted in Fig. 4.1 B and C. However, in the present utilization of the system, the subject is not passive to the acquisition, as in the previous situation. In fact, once the acquisition starts, each time a R-R packet is processed by the mobile phone, a bar graph is displayed to the user, in which the corresponding real-time values are presented above each bar. It should be referred that each R-R packet includes eighteen samples, which are sent with a frequency of 18 Hz (Table 3.2), while each graph comprises five equally distributed samples of each packet, thus the values shown are always real-time.

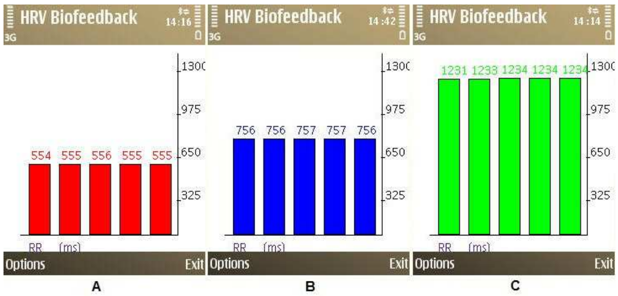

Figure 4.12: R-R interval bar graph representation in three different moments in time: (A) stress situation, (B) average situation and (C) extremely relaxed situation.

In Fig. 4.12, three instantaneous monitoring examples of one subject are displayed, in an attempt to show the adaptation capability inherent to the system. As normal R-R interval's values range from 600 ms to 1200 ms [22], the maximum bar value of the graph was established in 1300 ms. For coherence reasons, this value is set independently from the R-R variations in time, but is adaptable in saturation situations. If the acquisition's values range below 600 ms, the displayed bars are red (Fig. 4.12 A), while if values range above 1200 ms, green bars are displayed (Fig. 4.12 C). Such variations in the bar's colors intend to mirror the subsequent variations in the R-R distance. Smaller distances are related to stress situations, while higher distances are associated with relaxed. Considering adequate R-R intervals can differ according to the subject using the system, the thresholds that establish the difference in the bar's colors are adaptable.

4.2.2 Discussion

Although biofeedback is definitely not the main focus of this system, the type of physiological monitoring achieved by the combo chest strap - mobile phone suggested this type of additional approach. In fact, in what concerns medical applications, biofeedback is probably one of the major potentials to mobile phones. If biofeedback is a process that resorts to machinery in order to translate physiological parameters into some type of audio or visual signal, mobile phones might as well be used for their numerous user interaction capabilities, which include the built-in speakers and all the graphical outputs that can be provided by the integrated screen.

In this particular approach, the mobile phone's screen is the key aspect. As an addition to the traditional previously depicted interface, in which the physiological parameters are monitored, processed and stored in the mobile phone, this interface shows the values registered for the R-R intervals in real-time. However, attending the definition of biofeedback, this values are shown as graphical outputs, through bar graphs updated with time.

Despite the current approach, in which the chest strap and the mobile phone are presented as the tools required for this type of HRV biofeedback, there are also other possibilities. In fact, a specific computer terminal GUI interface could be developed, in which several attempts to perform brain activation could be compared, thus enabling the observation of the subject's evolution. On the other hand, concerning the mobile phone's interface, the evaluation of sympathetic and parasympathetic contributions to the autonomic nervous system in real-time bar graphs would be very interesting, namely to detect defective cardiovascular function.

Nevertheless, the system as it is enables the subject to perceive the physiological changes undergoing as he tries to perform brain control activation. Furthermore, to a layman, the RR-intervals or breathing rate observation are probably more intuitive and, thus, adequate than two bars representing the sympathetic and parasympathetic contributions, which require some insight into the matter. In conclusion, although this methodology was not extensively tested in the context of this thesis, considering protocols which point out that brain control activation is only possible after several sessions, evidence suggests that this system has the potential to be a valid fit for HRV biofeedback.

5

Conclusions and Future Developments

In the present thesis a system called *Mobile Acquisition Platform for Sleep Assessment* (MAPSA) was developed, which aimed at contributing to the sleep diagnosis field. This is a highly portable system, easy-to-use for both the patient and the physician, developed as an attempt to answer the needs expressed by numerous health care providers for alternatives to *polysomnography* (PSG). In fact, the diagnosis of several common sleep disorders, such as *Delayed Sleep Phase Syndrome* (DSPS), *Shift Work Sleep Disorder* (SWSD) or *Obstructive Sleep Apnea Syndrome* (OSAS), does not require as much data as a complex exam like PSG offers. Therefore, the key objective of this thesis is to provide a system capable of acquiring several types of sleep related information. Such information complies both physiological parameters monitored by a chest strap and routine events registered in a mobile phone, via sleep and dream electronic diaries.

First, an overview of the topics concerning the MAPSA was performed. As this system mainly focus on sleep disorders, a physiological background to sleep and associated pathologies was developed, as well as a technological background on sleep assessment tools. Furthermore, this technological background was extended to the tools supporting the developed system - physiological monitoring belts and mobile phones. In addition, biofeedback was briefly contextualized, as heart rate variability control is proposed as a particular application of the MAPSA in a wider context.

Following this theoretical background, the existing flaws in the context of mobile sleep assessment are depicted in an attempt to define the existing problem, which suggests the motivation of this thesis. Essentially, there were three parcels to gather: the physiological monitoring, the *Sleep e-Diary* (SeD) and the *Dream e-Diary* (DeD). Therefore, a model was conceived, in which the physiological monitoring belt, the mobile phone and the physician's computer terminal are brought together. This conceptualization was explained through several commented diagrams. The MAPSA was then implemented in *Python* and *Python for S60*, respectively for computer and mobile phone, with versions in both English and Portuguese languages. These are characteristics that take into account the potential use of the MAPSA in several health care units.

The implementation of the designed model is supported by an explanation on how to use the tool and what outputs to expect, accompanied by several illustrative pictures. Several approaches to the usage of this system are depicted. In fact, the MAPSA can be used to perform simultaneous physiological monitoring and sleep related information register, but the independent use of the sleep applications, not recurring to the chest strap, is also valid. Moreover, the platform is able to show real-time graphical information on RR-intervals, a feature that adds *Heart Rate Variability* (HRV) biofeedback as a possibility and, thus, widens the scope of applications of the MAPSA beyond sleep.

The *Mobile Acquisition Platform for Sleep Assessment* depicts a different and innovative approach to sleep disorders diagnosis, which traditionally involves PSG as the main assessment exam. While not as thorough as PSG, the MAPSA does not significantly interfere in the subject's routine and offers the possibility of a cross analysis of several sleep related parameters. Such parameters include physiological measurements, as *electrocardiogram* (ECG), breathing rhythm and waveform, superficial temperature and activity, but also information on the subject's quotidian events, through the sleep and dream electronic diaries it incorporates. Although the platform might suffer some changes in the future, most of the important features are already present. In particular, the extended monitoring of both physiological and user registered parameters is possible and the interactive computer interface to analyze in detail actigraphy, SeD and DeD is implemented. Furthermore, the classification of sleep and dreams and the integration of an insomnia severity index calculation are functional. Moreover, the real-time visualization of RR-intervals evolution through bar graphs is a reality.

It is important to keep in mind that the system developed is evolutionary. In fact, despite the current usefulness associated with MAPSA, in a near future this system might represent a much more complete and useful tool. Possibilities are nearly endless. The full development of the GUI intended for the physician's terminal computer, as well as the development of a proper patients' database are very interesting and promising features. Furthermore, the physiological acquisitions for selectable periods of time during the day, or the implementation of pathology detection algorithms in the mobile phone, are also valid approaches. In fact, these algorithms could focus on sleep diseases only, but also on heart or breathing pathologies, with early contact of the physician in case of serious pathologies, as well as automatic calls to an emergency number when required. The extension of the *Dream e-Diary*, comprising the automatic transcription of dreams and word pattern recognition would be very interesting as well. Furthermore, in what biofeedback is concerned, the development of an algorithm that autonomously calculated sympathetic and parasympathetic contributions would be a very interesting tool in autonomic nervous system studies. Naturally, with the implementation of all these features, proper evaluation of the tool is mandatory. In fact, contacting several clinicians to test and provide feedback on the use and on the functionalities of this tool is determinant. Moreover, clinical trials and validation studies are mandatory, accompanied with other assessment tools for comparison purposes.

In conclusion, this mobile acquisition system should be developed to meet both current needs and future challenges of health care providers. As intelligently as machines might be programmed, in this particular case mobile phones, they do not personify the knowledge acquired over years of experience by the physicians. Nonetheless, tools like MAPSA should be seen as helpful devices, highly relevant in the early and accurate assessment of sleep-disturbed patients.

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Appendix A - Patente de Invenção Nacional

Sistema de registo da descrição de sonhos em diário electrónico, implementado em telemóvel, para monitorização de longa duração e diagnóstico de distúrbios do sono.

O presente invento, aqui designado Diário Electrónico do Sonho (”Dream electronic Diary” - DeD), é um diário electrónico do sonho para registo áudio da descrição de sonhos, episódios considerados relevantes para o diagnóstico de distúrbios do sono.

Este diário de sonhos, concebido para ser utilizado em telemóveis de forma a ser altamente portátil e de simples utilização, comporta duas funcionalidades principais. A primeira corresponde ao registo áudio dos sonhos ao qual fica associado uma entrada no calendário do telemóvel. A segunda é a tradução automática para linguagem escrita dos dados de áudio num computador, o que permite ainda a anotação e classificação automáticas dos sonhos de acordo com a detecção de determinadas palavras-chave encontradas no texto transcrito. Nesta configuração a transferência de dados entre o telemóvel e o computador é transparente para o utilizador.

Appendix B

A - Sleep Classification

Table 5.1: Sleep classification questions and answer type (based on [46] and CENC sleep questionnaire).

Question	Answer Type
How long did it take you to sleep (min)?	number
How many times did you wake up?	number
How long were you up during the night (min)?	number
How many drinks did you ingest?	number
How many sleeping pills?	number
Did you take caffeine 6 h before lay down?	number
How do you feel?	0 - Not well 1 2 - Moderately 3 4 - Very well
How was your sleep?	0 - Not good 1 2 - Moderate 3 4 - Very good

B - Dream Classification

Table 5.2: Dream classification questions and answer scales (based on CENC questionnaire).

Question	Answer Type
Emotionality	1 2 3 4 5
Positive emotionality	1 2 3 4 5
Negative emotionality	1 2 3 4 5
Relation to day-to-day life	0 - None 1 2 - Moderate 3 4 - High

C - Insomnia Evaluation

Table 5.3: Insomnia severity index (adapted from [45]).

Number	Parameter	Answer Type
1a	Difficulty falling asleep	0 - None 1 - Mild 2 - Moderate 3 - Severe 4 - Very
1b	Difficulty sleeping	0 - None 1 - Mild 2 - Moderate 3 - Severe 4 - Very
1c	Early wake up problem	0 - None 1 - Mild 2 - Moderate 3 - Severe 4 - Very
2	Sleep satisfaction level	0 - Very satisfied 1 - Satisfied 2 - Neutral 3 - Unsatisfied 4 - Very unsatisfied
3	Sleep interference in day-to-day life	0 - None 1 - Little 2 - Some 3 - Much 4 - Very much
4	Perception of your sleep problems by others	0 - None 1 - Barely 2 - Somewhat 3 - Much 4 - Very much
5	Concern with your sleep problems	0 - None 1 - Barely 2 - Somewhat 3 - Much 4 - Very much

The guidelines for scoring/interpretation are the following:

- Add scores for all seven items; Score = 1a + 1b + 1c + 2 + 3 + 4 + 5
- Classify according to score range:
  - From 0 to 7 = No clinically significant insomnia
  - From 8 to 14 = Sub-threshold insomnia
  - From 15 to 21 = Moderate severity clinical insomnia
  - From 22 to 28 = Severe clinical insomnia