UNIVERSITY OF CRETE

DEPARTMENT OF COMPUTER SCIENCE

FACULTY OF SCIENCES AND ENGINEERING

HypnOS: A Sleep Monitoring and Recommendation System for Intelligent Homes

by

Eleni Tsolakou

MSc dissertation submitted in partial fulfillment for the

Master of Science Degree in Computer Science and Engineering

Heraklion, April 2020

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To my grandmothers Athanasia and Eleni,

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Abstract

Sleep is vital for maintaining good physical and mental health. Unfortunately, in today's fast-paced society many people suffer from sleep-related problems, which have negative consequences on sleep quality and therefore on quality of life. Thanks to continuous technological improvements, an abundance of sophisticated sleep trackers has been created. However, a holistic approach that takes advantage of the already prominent Ambient Intelligence (AmI) technologies rather than merely relying on isolated devices, is still missing.

This thesis introduces HypnOS, a system that monitors sleep in an unobtrusive way and provides personalized sleep recommendations to the residents of an Intelligent Home. Particularly, it monitors sleep patterns in order to detect possible sleep abnormalities and then provide effective guidance to avoid them in order to improve their overall sleep quality. To assess overall sleep quality and to provide personalized sleep insights, the following parameters are utilized: (a) sleep-related parameters and bio-signals obtained from a variety of wireless sleep trackers (i.e. wearable activity tracker/watch, under-the-mattress sleep tracker, EEG headband); (b) contextual information by exploiting the infrastructure of an Intelligent Home (e.g. stress levels); (c) habitual information (e.g. smoking, alcohol) and subjective measurements (e.g. mood, alertness, sleepiness) by using a daily sleep diary.

Additionally, HypnOS utilizes the ambient facilities (e.g. lighting system, speakers, scent diffuser) of the Intelligent Bedroom so as to enhance the environment (e.g. lights, sound, scent) and create experiences that can potentially facilitate the falling asleep and waking up processes. In more detail, it offers a smart alarm which aims to wake up users gently (e.g. using natural sounds) and a collection of relaxation programs that assist users having difficulties in falling asleep (e.g. through appropriate ambient lighting conditions). Overall, HypnOS is an unobtrusive sleep monitoring and recommendation system that not only detects sleep abnormalities, but also presents insights to the residents about the potential causes of their sleep-related issues, enabling them to act accordingly.

Keywords: Sleep Monitoring · Sleep Hygiene · Ambient Intelligence

Περίληψη

Ο ύπνος είναι ζωτικής σημασίας για τη διατήρηση της καλής σωματικής και ψυχικής υγείας. Δυστυχώς, στη σύγχρονη εποχή με τους γρήγορους ρυθμούς ζωής, πολλοί άνθρωποι υποφέρουν από προβλήματα που έχουν αρνητικές συνέπειες στην ποιότητα του ύπνου, και συνεπώς στην ποιότητα ζωής τους. Χάρη στις συνεχείς τεχνολογικές εξελίσσεις, έχει δημιουργηθεί μια πληθώρα από εξειδικευμένες συσκευές παρακολούθησης ύπνου. Ωστόσο, εξακολουθεί να λείπει μια ολιστική προσέγγιση που αξιοποιεί τις επιπλέον δυνατότητες που προσφέρουν οι τεχνολογίες Διάχυτης Νοημοσύνης σε σχέση σε μεμονωμένες συσκευές.

Η παρούσα εργασία εισάγει το HypnOS, ένα σύστημα που παρακολουθεί τον ύπνο των κατοίκων μιας Έξυπνης Κατοικίας, με μη-παρεμβατικό τρόπο, μέσω διαφόρων τεχνολογιών Διάχυτης Νοημοσύνης και παρέχει εξατομικευμένες συμβουλές βελτίωσης της ποιότητάς του. Συγκεκριμένα, εξετάζει την ατομική συμπεριφορά του κάθε χρήστη στον ύπνο για να εντοπίσει πιθανές ανωμαλίες και στη συνέχεια να παράσχει καθοδήγηση για την αντιμετώπιση τους. Για την αξιολόγηση της συνολικής ποιότητας ύπνου, καθώς και για την παροχή εξατομικευμένων συμβουλών αξιοποιούνται: (α) μετρήσεις ύπνου και βιοσήματα τα οποία συλλέγονται από ένα σύνολο συσκευών καταγραφής (φορετές συσκευές/βραχιόλια/ρολόγια, συσκευές που τοποθετούνται ως υπόστρωμα στο κρεβάτι και φορετές συσκευές καταγραφής εγκεφαλικής δραστηριότητας), (β) πληροφορία από το γενικότερο πλαίσιο χρήσης της Έξυπνης Κατοικίας (π.χ. επίπεδα του στρες), και (γ) δεδομένα που σχετίζονται με καθημερινές συνήθειες (π.χ. κάπνισμα, κατανάλωση αλκοόλ) και υποκειμενικές μετρήσεις (π.χ. διάθεση μέσα στη μέρα, αίσθημα υπνηλίας), κάνοντας χρήση ενός ημερολογίου που συμπληρώνεται καθημερινά από τους χρήστες.

Επιπλέον, το HypnOS χρησιμοποιεί τις εγκαταστάσεις διάχυτης νοημοσύνης της Έξυπνης Κρεβατοκάμαρας (π.χ. σύστημα φωτισμού, ηχεία, συσκευή αρωματοθεραπείας) για να ενισχύσει το περιβάλλον (π.χ. φώτα, μουσική, άρωμα) και να δημιουργήσει εμπειρίες που διευκολύνουν τον ύπνο καθώς και την αφύπνιση. Συγκεκριμένα, προσφέρει ένα έξυπνο ξυπνητήρι που ανιχνεύει τον βέλτιστο χρόνο αφύπνισης του χρήστη (π.χ. χρησιμοποιώντας ήχους της φύσης) καθώς και διάφορα

προγράμματα χαλάρωσης σε περιπτώσεις που ο χρήστης δυσκολεύεται να κοιμηθεί (π.χ. κατάλληλη διαμόρφωση του έμμεσου φωτισμού). Συνολικά, το HypnOS αποτελεί ένα σύστημα παρακολούθησης και συμβουλευτικής ύπνου, που όχι μόνο ανιχνεύει ασυνήθιστες συμπεριφορές ύπνου, αλλά και ενημερώνει τους χρήστες σχετικά με τις πιθανές αιτίες αυτών, προκειμένου αυτοί να ενεργήσουν κατάλληλα.

Λέξεις-Κλειδιά: Παρακολούθηση Ύπνου · Υγιεινή του Ύπνου · Διάχυτη Νοημοσύνη

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Chapter 1

Introduction

Today's fast-paced modern world is becoming more and more sleep-deprived. People have come to consider sleeping as a luxury instead of a necessity. Hours that should be spent resting are instead spent on television, games, the Internet and work. According to the National Sleep Foundation's updated sleep duration recommendations, the proposed sleep duration is 14-17 hours for newborns, 12-15 hours for infants, 11-14 hours for toddlers, 10-13 hours for preschoolers, 9-11 hours for school-aged children, and 8-10 hours for teenagers. 7-9 hours is recommended for young adults and adults, and 7-8 hours of sleep is recommended for older adults [1]. Unfortunately, according to the American Sleep Association, the 37% of 20-39 year-olds and the 40% of 40-59 year-olds report short sleep duration, while 35.3% adults report <7 hours of sleep during a typical 24-hour period [2].

Sleep is essential for optimal cognitive performance, physiological processes, emotional regulation, and overall quality of life. Research consistently demonstrates that sleep is a significant component of physical and mental health, as well as of overall well-being. As it is strongly indicated by many experimental studies [3]–[10], short sleep duration and sleep disturbances are associated with poor performance of the body's daily tasks, depressive disorders, impaired memory, poor academic performance, decreased motivation, suicidal thoughts, obesity, and cardiac morbidity.

Consequently, it is important to regulate the sleep process and improve the overall sleep quality. In order to achieve this purpose and improve the quality of our lives, we first need to monitor our sleep behavior in order to identify our sleep patterns and second to provide effective guidance to improve our sleep quality. Continuous technological improvements provide us with remarkable research tools which can be used to accomplish the above and develop an enhanced technological system which aims to detect sleep abnormalities and provide personalized sleep guidelines in order to improve sleep quality.

Researchers have investigated numerous technologies and approaches to monitor individuals' sleep behavior at home [11]. One goal of such technologies is to track sleep aspects including the frequency, duration, and quality of sleep [12]. Another important goal is to collect information that can increase users' awareness of their sleep habits to persuade them to adopt healthier routines for the improvement of their sleep quality. Many of these approaches are still in the lab research, but there are also commercial solutions, ranging from smart alarm clocks to advanced monitoring devices. In particular, sleep technologies may include alarms that ensure people wake up at the desired time, sleep monitors that monitor users while they sleep, and environmental monitors that monitor the environment in which people sleep [13]. All the above solutions provide useful tools for tracking and improving sleep.

1.1 Human Sleep

Sleep appears to be important for vital functions such as neurological development, learning, memory, emotional regulation, cardiovascular and metabolic function [4]. The sleep process is discussed in many research studies. However, there is no standardized definition for sleep. Many attempts have been made in order to define what sleep is, producing a variety of definitions such as, for example:

- "Sleep is a reversible behavioral state of perceptual disengagement from, and unresponsiveness to, the environment" [14]
- "Sleep is an essential biological function with major roles in recovery, energy conservation, and survival" [4]
- "Sleep is a homeostatically regulated biological function" [15].
- "Sleep is not just the absence of waking, but an active neurophysiological process and the primary activity of the developing brain" [3].

Sleep is one of the most important functions of our daily life. We spend approximately one-third of our lives asleep because this is a part of our body's daily cycle. Of major concern is the widely decline over the past century, particularly during the past 20–30 years, at an international level, where the majority of the population assigns less importance to sleep compared with other daily activities such as work, reading, and the use of electronics such as television, computers, and mobile phones [4]. Sleep

disturbances and reduction in sleep duration have been postulated as contributing factors to the development of many common and complex diseases [4] such as insomnias, parasomnias [16], obesity, diabetes and psychological disorders [6]. Moreover, insufficient sleep is associated with impairments not only in physical but also in mental health. For example, different types of depression may be caused by specific forms of sleep disturbances. Difficulties in falling asleep are associated with psychological depression, whereas sleep maintenance problems and early morning awakenings are accompanied by biological depression [17].

In conclusion, it is clear that quality sleep is critically essential not only for good health, but for the overall quality of life. This need can be achieved by focusing on technologies that monitor sleep, help users to better understand their sleep patterns, and raise awareness of adopting healthy sleep behaviors [11].

1.2 Ambient Intelligence

Nowadays technological advances in hardware and software provide important tools which can be used to help improve sleep quality. These technological tools support sleeping by monitoring sleep and improving the wake-up process, providing data for reflecting on sleeping behaviors, and persuading users to adopt healthier sleep behaviors. For example, persuasive technologies promote changes in sleep habits, while pervasive sleep technologies help in monitoring and identifying sleep patterns [18]. Sleep monitoring technologies offer an unobtrusive and cost-efficient way to monitor sleep in free-living conditions. Sleep patterns and sleep habits can be studied outside the lab without the need for complex and very expensive equipment. Similarly, it is no longer necessary to visit a sleep medicine laboratory to monitor sleep in order to improve sleep quality. We can accomplish these targets in the comfort of our home, or everywhere else there is only a bedroom to sleep, since pervasive computing creates environments where simple objects in the real world turn into source of information and communication.

According to the Information Society Technologies Advisory Group of the European Commission (ISTAG, 2003), “Ambient Intelligence (AmI) concept provides a vision of the Information Society where the emphasis is on greater user-friendliness, more

efficient services support, user-empowerment, and support for human interactions" [19]. In an AmI environment, intelligent and intuitive interfaces are embedded in various everyday objects, and the recognition and response to the presence of people is possible in a seamless, unobtrusive and usually invisible manner [20].

AmI environments take advantage of sensors, networks, pervasive computing, and artificial intelligence in order to be sensitive, responsive, adaptive, transparent, ubiquitous, and intelligent. For example, Smart Homes possess their own intelligence and make decisions regarding their state and interactions with its residents. A Smart Home is an environment enriched with intelligent technologies where various household artifacts (e.g., bed, bedside table. closet, and sofa) can have embedded sensors to gather information about their use and in some cases even to act independently without human intervention [21].

This dissertation addresses the question of how the aforementioned technologies can help the improvement of sleep quality, and therefore the quality of life. The proposed approach has two main objectives: 1) create an unobtrusive sleep monitoring system for Intelligent Homes, able to detect sleep abnormalities and 2) provide personalized sleep hygiene guidelines in order to improve sleep quality. During this process, Ambient Intelligence technologies help retrieve contextual data and create suitable environments adapted to users' needs.

1.3 Thesis Contribution

This thesis describes the vision of a system that monitors sleep in an unobtrusive way and provides personalized sleep recommendations to the residents of an Intelligent Home. Particularly, it aims to detect sleep abnormalities by exploiting a variety of sleep tracking devices (e.g., wearable activity tracker, under-the-mattress sleep tracker, EEG headband) and to provide personalized sleep hygiene recommendations (e.g., avoiding stimulants such as caffeine and nicotine close to bedtime) based on a variety of monitored data. Furthermore, it utilizes the infrastructure of an Intelligent home to retrieve and extract relevant contextual information about the user's daily routines and habits (e.g. diet, work schedule,

fitness). The combination of sleep measurements and contextual information can not only indicate that the sleep quality is poor, but outline potential causes as well.

From an end-user perspective, the system presents daily detailed sleep reports including – amongst others – details regarding sleep patterns, movements during sleep, hours of sleep, etc., receive personalized sleep recommendations to raise their awareness in order to change their sleep habits that affect sleep and activate any of the system's sleep/relaxation programs in case that they have difficulty falling asleep. In addition, a daily sleep diary is provided as an extra functionality that supplements the basic monitoring from the sleep trackers in order to collect information about residents' habits and their subjective measurements. Finally, the system offers a smart alarm which is a common alarm clock enhanced with smart features that aim to wake up users in a gentle way at the optimal wake up time.

1.4 Thesis Structure

The remainder of this thesis is divided into the following chapters:

- **Chapter 2** describes sleep background theory.
- **Chapter 3** presents related work on sleep monitoring and recommendation systems.
- **Chapter 4** examines the requirements which an ambient sleep management system should meet in order to fulfill its mission to help users improve their sleep quality.
- **Chapter 5** provides an overview of HypnOS approach and presents the design and the implementation details of the system.
- **Chapter 6** describes the evaluation process and its results.
- **Chapter 7** presents the conclusion of this thesis and suggestions for future work.

Chapter 2

Background Theory

2.1 Basic Science of Sleep

In recent years, different theories have been made to explain the meaning of sleep in order to identify the complex phenomena involved in the sleep process and understand the various aspects of the ultimate function of sleep. Several hypotheses and theories have been put forward to address the above research objectives. However, a unified theory of sleep has not yet been elaborated. Considering that we spend nearly one third of our lives sleeping, the processes that happen during sleep remain mysterious and need more investigation.

2.1.1 Sleep Architecture

The first part that we should examine in order to understand the sleep process is the architecture of sleep. Sleep architecture refers to the “basic structural organization of normal sleep” [22]. In more details, sleep process is divided into two types of sleep: non-rapid eye-movement (NREM) sleep and rapid eye-movement (REM) sleep [14]. REM and NREM sleep are differentiated from each other by unique characteristics, including variations in brain wave patterns (Figure 1), eye movements, and muscle tone [22]. NREM sleep is further divided into three stages: stages 1, 2 and 3. When REM and NREM are charted on a diagram, this is called a hypnogram (Figure 2). Over a normal sleep period REM and NREM alternate in sleep cycles. Each cycle lasts on an average from 90 to 110 minutes. A normal sleep period in adults contains 4–6 such cycles. Sleep cycles and stages were uncovered with the use of electroencephalographic (EEG) recordings that trace the electrical patterns of brain activity. It is stated that in the group age of adults, NREM sleep accounts for 75–80% of total sleep time, while REM sleep accounts for 20–25% [23]. NREM sleep is believed to function primarily as a restful and restorative sleep phase, and a period of relatively low brain activity. It is further divided into three stages primarily based on EEG criteria [23]. Stage 1 NREM (N1) sleep occupies 3–8% of sleep time; stage 2

(N2) comprises 45–55% of sleep time; and stage N3 or SWS makes up 15–23% of total sleep time [24].

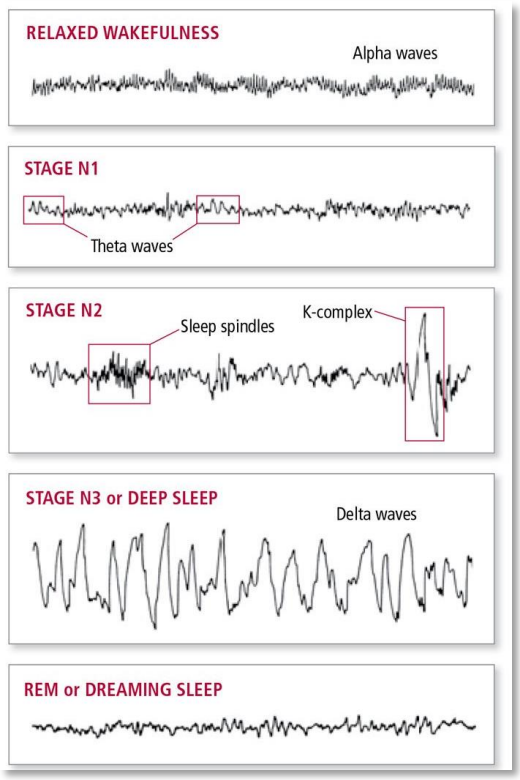


Figure 1: EEG brainwave patterns during sleep stages [25]

Stage 1 NREM (N1)

This is the stage where the transition from wakefulness to sleep happens. It is also known as the ‘‘lightest sleep’’ stage because an individual is possible to be responsive enough to external stimulus [24]. It usually has duration from 1 to 7 minutes in the initial cycle [22]. It is characterized by diminished alpha waves (8 - 13 Hz) to less than 50% in an epoch intermixed with slower theta waves (4 - 7 Hz) and beta waves in EEG [23]. In general, alpha waves are associated with wakefulness. In addition, muscle activity decreases slightly, and slow eye movements (SEMs) appear [3].

Stage 2 NREM (N2)

This is the stage where true sleep process starts. In a normal sleep episode, N2 begins after approximately 10 to 12 minutes of N1. NREM Stage 2 lasts approximately 10 to 25 minutes in the initial cycle and progressively lengthens [22]. It is characterized by a decreased awareness of outside stimuli and decreased muscle activity. Concerning EEG activity, there are characteristic sleep spindles and K- complexes [24]. “Sleep spindles, also referred to as sigma waves, are small bursts of higher frequency activity”. “K-complexes are brief bursts of high negative voltage, followed by larger positive voltage peak, and then a larger and slower negative voltage peak” [3].

Stage 3 NREM (N3)

This is the stage that sleep becomes really deep sleep. That’s why it is also known as “deep sleep” stage. Stage N3 begins after about 30 to 60 minutes of Stage N2 [23]. N3 stage is the stage where an individual is least responsive to external stimuli and thus it is difficult to awaken. Regarding EEG it is characterized by delta waves (0.5-2 Hz), which are high-amplitude and low-frequency waves [3], [24]. Stage N3 is briefly interrupted by stage 2 NREM, which is followed by the first REM sleep approximately 60–90 minutes after sleep onset [22].

Rapid Eye Movement (REM)

REM is the stage which is associated with dreaming, including nightmares and perceptual learning. It is thought to have a role in consolidating and integrating memories and in the development of the central nervous system (CNS) [24]. Awakenings can occur more easily in this stage while being woken during a REM period can leave grogginess and sleepiness sense. The main REM stage features are bursts of rapid eye movements, high brain metabolic rate, variable heart rate, active suppression of peripheral muscle tone, and lack of normal thermoregulation. EEG during REM sleep consists of low-voltage, high-amplitude beta and theta waves [22]. During REM sleep, there may be some alpha waves in the EEG lasting for a few seconds.

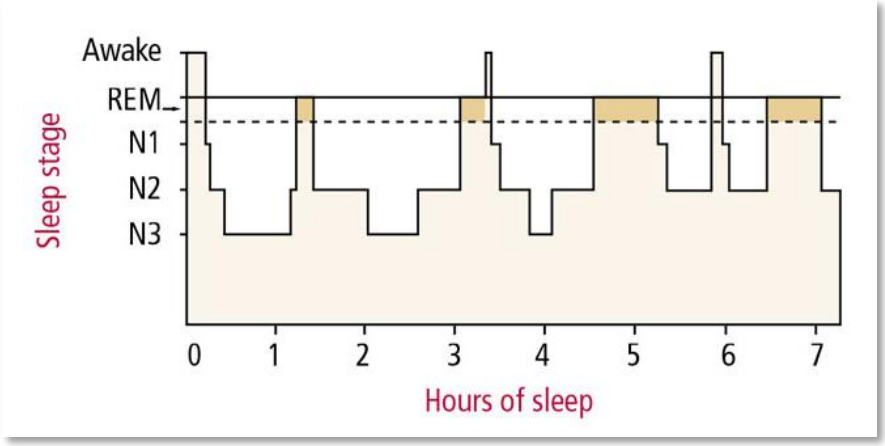


Figure 2: Hypnogram of a normal healthy adult [25]

2.1.2 Sleep Regulation Mechanisms

In order to understand better the overall sleep process, we have to understand the mechanisms that regulate sleep and wakefulness cycles. Sleep is regulated by two overlapping but distinct systems: the circadian system and sleep/wake homeostasis (Figure 3). The circadian system is responsible for the endogenous synchronization of biologic rhythms, including sleep, cyclically within the 24-h day, and is adjusted through the influence of exogenous factors. “Sleep/wake homeostasis describes the body's internal neurophysiologic drive toward either sleep or waking” [26]. The most important principle of homeostasis is equilibrium where body is driven toward a balance between sleep and wakefulness [3].

2.1.2.1 Circadian System

The circadian system (Process C) consists of cyclic changes in the body endogenously generated biological rhythms with a periodicity of 24h. Such biological rhythms include the sleep and wake cycle, alertness, body temperature cycle, daily cycles of hormonal secretion (e.g., melatonin and cortisol), and blood pressure regulation [27]. The circadian drive for wakefulness increases progressively during the day, peaks during the early evening hours and then suddenly subsides at the beginning of the night, at around the time of the onset of secretion of the hormone melatonin. Later in the night, the circadian process actively promotes sleep, and

particularly REM sleep. During the day, homeostatic sleep drive increase is countered by the progressive increase in the circadian drive for wakefulness. During the night the homeostatic dissipation of sleep propensity is countered by the circadian increase in sleepiness. Under normal conditions, when we work during the day and sleep at night, these two processes combine to produce consolidated episodes of daytime wakefulness and nocturnal sleep [28].

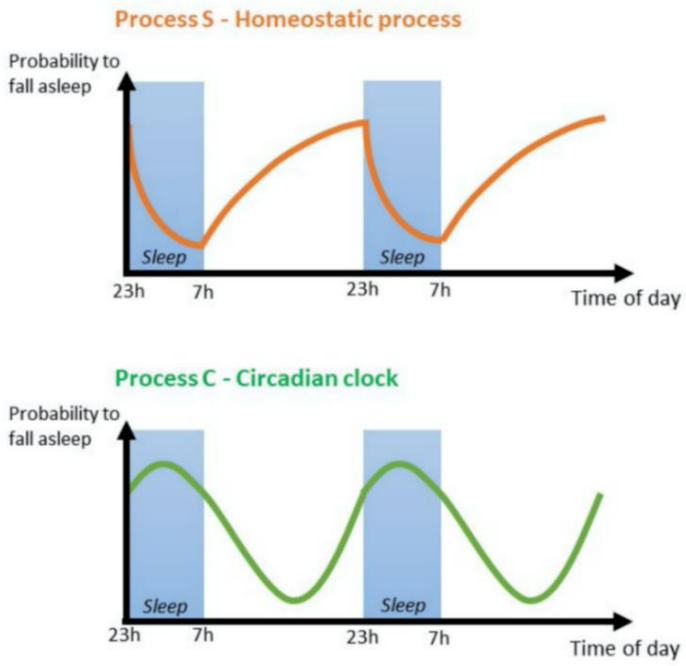


Figure 3: Regulation of sleep and wake through Process S and Process C [29]

2.1.2.2 Sleep and Wake Homeostasis

The homeostatic system (Process S) is a separate system which is the biological drive to maintain equilibrium between sleep and waking. The homeostatic sleep drive reminds the body to sleep after a certain time and regulates sleep intensity. This system assumes that sleep debt increases with cumulative waking hours, leading to an accumulation of sleep promoting substances called somnogens in the central nervous system (CNS). Increasing somnogen levels during waking hours drive the body toward sleep. Adenosine is widely accepted to be one such somnogen. Adenosine is a byproduct of biological activity in the brain and thus accumulates with

activity, increasing sleep propensity, and then dissipates with rest and sleep [3]. Factors that influence sleep-wake needs include medical conditions, medications, stress, sleep environment, and nutrition habits. However, exposure to light is the greatest influence. Specialized cells in the retinas of the eyes process light and tell the brain whether it is day or night and can advance or delay sleep-wake cycle [30].

2.1.3 Sleep Parameters

Sleep is a complex bio-behavioral process that can be characterized along multiple dimensions in relation to health and functioning [31]. These include sleep duration, continuity, architecture, and quality. Each of these dimensions of sleep has been associated with indices of health diseases. Moreover, across the life span, from infancy through old age, each of these dimensions' changes [32]. According to many sleep studies [33]–[35], other parameters that also moderate sleep dimensions are sex, race/ethnicity, and mental and physical health conditions. The most used sleep parameters across different studies include total sleep time (TST), wake after sleep onset (WASO), sleep onset latency (SOL), number of awakenings (NAWK), sleep efficiency (SE) and sleep architecture parameters including light (N1,N2), deep (N3) and REM sleep [36]. These parameters are the most measurable characteristics of sleep that are closely related to physical and mental wellbeing, and some of them such as SOL and WASO are important indicators of sleep disorders.

Sleep Duration

The assessment indices of sleep duration are Time In Bed (TIB) and Total Sleep Time (TST). In more details, Time In Bed (TIB) may be defined as the total hours elapsed between getting into bed to go to sleep at night and waking up in the morning. Total sleep time (TST) is defined as time in bed minus the amount of time needed to fall asleep (sleep latency) and the amount of time spent awake during the night (wakefulness after sleep onset) [31].

Sleep Continuity

Measures of sleep continuity focus on one's ability to initiate and maintain sleep. There are two parameters in order to assess sleep continuity. These are Sleep Onset Latency (SOL) and Wake After Sleep Onset (WASO). Sleep Onset Latency (SOL)

refers to the length of time, in minutes, it takes to transition from wake to sleep. Wake After Sleep Onset (WASO) is defined as the amount of time, in minutes, spent awake after sleep has been initiated and before final awakening. Sleep Efficiency (SE) is a proportional sleep continuity measure which is the percentage of time spent asleep while in bed [31]. It is calculated by dividing the amount of time spent asleep (in minutes) by the total amount of time in bed (in minutes). In order to characterize sleep continuity as normal, the following condition must be satisfied : SOL ≤ 46 minutes, WASO ≤ 41 minutes and SE > 75% [36].

Sleep Architecture

Sleep architecture refers to the pattern of the two types of sleep, namely NREM and REM sleep stages as well as quantitative measures derived from power spectral analysis of the EEG [31]. Within NREM sleep, sleep architecture parameters include the amount of time spent in each of stages N1, N2, and N3. Measures specific to REM sleep include the total amount of time spent in REM sleep. In order to characterize sleep architecture as normal, the following condition must be satisfied: REM sleep ≤ 41%, N1 stage ≤ 21%, N2 stage ≤ 81%, and N3 stage ≥ 10% [36].

Sleep Quality

Sleep quality generally refers to subjective perceptions about one's sleep and can be assessed using purely qualitative indicators (e.g., sleep that is "restful," "sound," "restorative," "of good quality") or a combination of qualitative and quantitative indicators. Sleep diaries often include one or more qualitative indicators about the previous night's sleep, which are assessed using visual analogue or Likert-type scales [31].

2.2 Sleep Assessment Methods

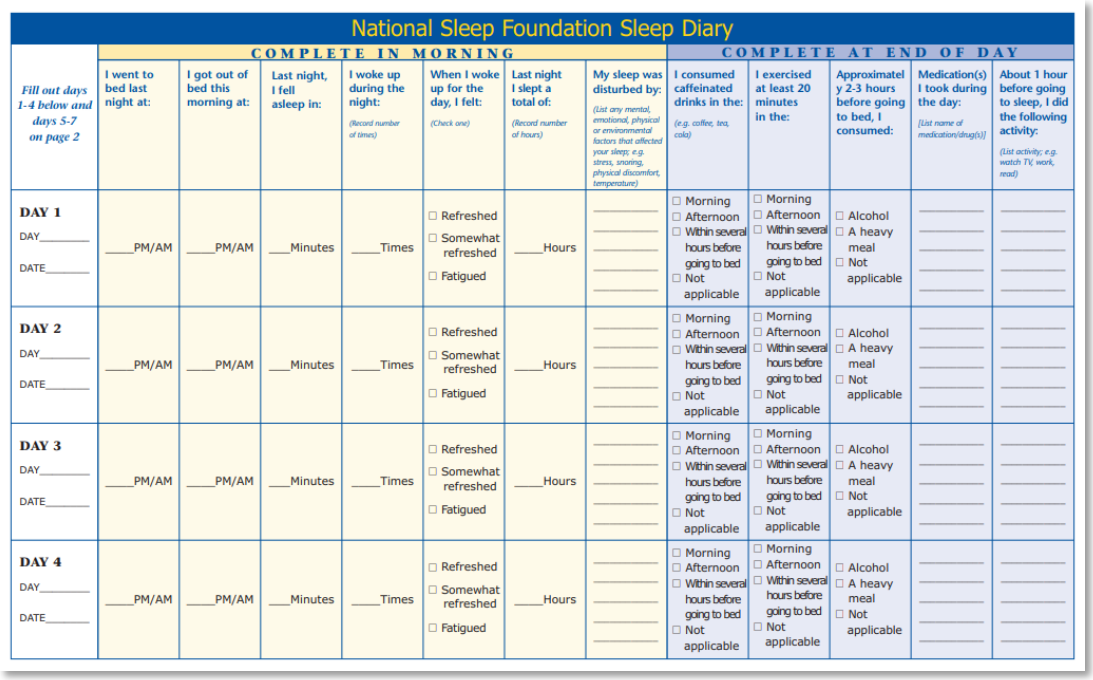
In the past years, assessing sleep has gained considerable attention especially in sleep medicine. Moreover, in the general population assessment of sleep may provide a better understanding of both the prevalence of impaired sleep and the extensiveness of its implications. Sleep doctors, scientists and researchers are investigating the optimal method to assess sleep. In the past years, to assess various aspects of sleep and especially sleep quality, different methods have been developed

including objective methods such as polysomnography and actigraphy and subjective measures, such as sleep diaries and questionnaires [37]. Each method has its advantages and its limitations.

2.2.1 Subjective Methods

Regarding subjective methods, sleep diaries are one of most common methods for self-assessment. They are easy to use and only take some minutes each day to complete. Moreover, there is agreement that such self-monitoring diaries can provide information on sleep schedule, bedroom environment, sleep habits and other related factors. However, researchers have not agreed on a standardized sleep diary format. In fact, there are multiple lab sleep diaries with different formats such as numerical sleep/wake estimates, Likert ratings, and visual analogue scales [38]. Despite the lack of a standardized format, the sleep diary has been regarded as the “gold standard” for subjective sleep assessment.

The oldest sleep diary is the Pittsburgh Sleep Diary (PSD) [39] which contains components that are completed two times a day, at bedtime and at wake up time. In more details, PSD gathers information that concern factors related to activities during the day (bedtime components) and factors related to last night’s sleep (wake up time components). However, hundreds of other sleep diaries have appeared from different organizations, hospitals, and sleep centers. In 2005, a workgroup developed a standardized sleep diary, the Consensus Sleep Diary (CSD) [40], which consists of nine core questions [38]. CSD is primarily used for the purposes of insomnia research, but also for clinical and research applications [37]. Furthermore, another well-known and widely-used daily sleep diary is the National Sleep Foundation (NSF) [41] sleep diary (Figure 4), which is completed two times a day: in the morning after wake up and in the evening before bedtime as the PSD.



National Sleep Foundation Sleep Diary

Fill out days 1-4 below and days 5-7 on page 2	COMPLETE IN MORNING							COMPLETE AT END OF DAY				
	I went to bed last night at:	I got out of bed this morning at:	Last night, I fell asleep in:	I woke up during the night: (Record number of times)	When I woke up for the day, I felt: (Check one)	Last night I slept a total of: (Record number of hours)	My sleep was disturbed by: (List any mental, emotional, physical or environmental factors that affected your sleep; e.g. stress, snoring, physical discomfort, temperature)	I consumed caffeinated drinks in the: (e.g. coffee, tea, cola)	I exercised at least 20 minutes in the:	Approximately 2-3 hours before going to bed, I consumed:	Medication(s) I took during the day: (List name of medication/drug(s))	About 1 hour before going to sleep, I did the following activity: (List activity; e.g. watch TV, work, read)
DAY 1 DAY_____ DATE_____	____PM/AM	____PM/AM	___Minutes	____Times	☐ Refreshed ☐ Somewhat refreshed ☐ Fatigued	____Hours	_____	☐ Morning ☐ Afternoon ☐ Within several hours before going to bed ☐ Not applicable	☐ Morning ☐ Afternoon ☐ Within several hours before going to bed ☐ Not applicable	☐ Alcohol ☐ A heavy meal ☐ Not applicable	_____	_____
DAY 2 DAY_____ DATE_____	____PM/AM	____PM/AM	___Minutes	____Times	☐ Refreshed ☐ Somewhat refreshed ☐ Fatigued	____Hours	_____	☐ Morning ☐ Afternoon ☐ Within several hours before going to bed ☐ Not applicable	☐ Morning ☐ Afternoon ☐ Within several hours before going to bed ☐ Not applicable	☐ Alcohol ☐ A heavy meal ☐ Not applicable	_____	_____
DAY 3 DAY_____ DATE_____	____PM/AM	____PM/AM	___Minutes	____Times	☐ Refreshed ☐ Somewhat refreshed ☐ Fatigued	____Hours	_____	☐ Morning ☐ Afternoon ☐ Within several hours before going to bed ☐ Not applicable	☐ Morning ☐ Afternoon ☐ Within several hours before going to bed ☐ Not applicable	☐ Alcohol ☐ A heavy meal ☐ Not applicable	_____	_____
DAY 4 DAY_____ DATE_____	____PM/AM	____PM/AM	___Minutes	____Times	☐ Refreshed ☐ Somewhat refreshed ☐ Fatigued	____Hours	_____	☐ Morning ☐ Afternoon ☐ Within several hours before going to bed ☐ Not applicable	☐ Morning ☐ Afternoon ☐ Within several hours before going to bed ☐ Not applicable	☐ Alcohol ☐ A heavy meal ☐ Not applicable	_____	_____

Figure 4: The NSF sleep diary

In addition to subjective methods, sleep questionnaires offer a very cost-effective way to obtain extensive information on sleep patterns, sleep problems, sleep context, and sleep-related behaviors [42]. They are often the first diagnostic test used in primary care, and they provide a general measure of the subjective quality of sleep. Until now, many questionnaires have been validated through large statistical studies and are commonly used in almost all sleep centers.

A widely used questionnaire and scoring tool for sleep quality evaluation is the Pittsburgh Sleep Quality Index (PSQI) [43]. The Pittsburgh Sleep Quality Index was originally developed to provide clinicians with a valid, standardized measure of sleep quality that could reliably categorize individuals as either “good” or “poor” sleepers (Figure 5). It is a 19-item questionnaire that assesses sleep quality using subjective ratings for 7 different components (i.e., sleep quality; sleep latency; sleep duration; habitual sleep efficiency; sleep disturbance; use of sleeping medication; and daytime dysfunction) [37]. Moreover, the Epworth Sleepiness Scale (ESS) [33] is a self-administered questionnaire for the likelihood of dozing off or falling asleep in a variety of different situations. Respondents are asked to rate their usual chances of dozing

off or falling asleep while engaged in eight different activities. The ESS measures a general level of daytime sleepiness, or their average sleep propensity in daily life.

During the past month,

1. When have you usually gone to bed? _____
2. How long (in minutes) has it taken you to fall asleep each night? _____
3. What time have you usually gotten up in the morning? _____
4. A. How many hours of actual sleep did you get at night? _____
   B. How many hours were you in bed? _____

5. During the past month, how often have you had trouble sleeping because you	Not during the past month (0)	Less than once a week (1)	Once or twice a week (2)	Three or more times a week (3)
A. Cannot get to sleep within 30 minutes				
B. Wake up in the middle of the night or early morning				
C. Have to get up to use the bathroom				
D. Cannot breathe comfortably				
E. Cough or snore loudly				
F. Feel too cold				
G. Feel too hot				
H. Have bad dreams				
I. Have pain				
J. Other reason (s), please describe, including how often you have had trouble sleeping because of this reason (s):				
6. During the past month, how often have you taken medicine (prescribed or "over the counter") to help you sleep?				
7. During the past month, how often have you had trouble staying awake while driving, eating meals, or engaging in social activity?				
8. During the past month, how much of a problem has it been for you to keep up enthusiasm to get things done?				
9. During the past month, how would you rate your sleep quality overall?	Very good (0)	Fairly good (1)	Fairly bad (2)	Very bad (3)

Figure 5: The PSQI sleep questionnaire

2.2.2 Objective Methods

Objective methods provide most detailed information on sleep architecture and clinical diagnoses. Moreover, they are useful for the objective assessment of daytime sleepiness and for the documentation of specific sleep behaviors and patterns. Some of these methods are unobtrusive and cost-effective, while others are expensive and intrusive [42].

The gold standard of objective methods is polysomnography. The term polysomnography (PSG) was proposed by Holland et al. [44] in 1974 to describe the recording, analysis, and interpretation of multiple, simultaneous physiologic characteristics during sleep. It is a complex procedure because it requires lots of special equipment (Figure 6) and trained technicians to setup the equipment [45]. The following parameters are included in a conventional clinical sleep study which uses PSG recording [45]:

- Central, frontal, and occipital electroencephalogram (EEG)
- The recording of eye movements (electrooculogram or EOG)
- The recording of chin muscle activity (chin electromyogram or EMG)
- The recording of leg muscle activity (right and left anterior tibialis EMG)
- Electrocardiogram (ECG)
- Nasal and oral airflow
- Respiratory effort (based on chest and abdomen excursion)
- Pulse oximetry

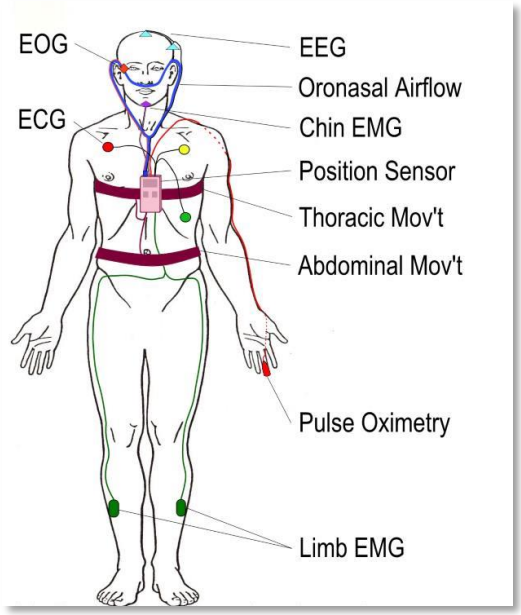


Figure 6: Various electrodes and sensors used in PSG [46]

Another laboratory test for assessing sleep disorders is actigraphy. Technological advances have led to the development of battery powered, long-life, light-weight, non-invasive, wearable accelerometers measuring tri-axial movement (i.e., actigraphy) [37]. These devices are worn on the wrist or ankle to record acceleration or deceleration of body movements, which indirectly indicates the state of sleep or wakefulness [47]. Actigraphy is useful to document rest–activity patterns over days and weeks. Today watch-sized actigraphy (Figure 7) are used in clinical settings to sense basic sleep patterns, such as hours slept, sleep efficiency, and number of awakenings [42], [48]. Actigraphy has many remarkable advantages over PSG

method with the most important being easy accessibility, inexpensive recording over extended periods of days, weeks, or months, as well recording of 24h activities everywhere (home, work, laboratory) [47].

Figure 7: Sample of two actigraphs [49]

The aforementioned objective methods require patients to be observed in a sleep clinic by a sleep expert using costly and obtrusive sensor technology or to monitor only basic sleep measures that are inadequate in order to assess overall sleep quality. In contrast, prior research has shown that people are most interested in unobtrusive sleep monitoring technology that does not require additional devices [50]. With this in mind, it is desirable to create sleep monitoring systems that are contactless and are installed at home and more particularly in bedroom. Bedroom is the shelter from the stresses of the day and the main activity that happens in there is sleep. So, any technological solution that aims to monitor sleep and consequently improve sleep quality must be embedded in there and be as invisible as possible in order not to keep residents awake.

2.3 Sleep Complaints & Disorders

In modern society where life is moving at a fast and stressful pace, sleep disorders are highly widespread. Sleep disparities may include insufficient sleep duration, irregular timing of sleep, poor sleep quality, sleep/circadian disorders, and other mental or physical disorders. Actually, according to many health studies, 30% of adults and 60% of adolescents don't get enough sleep [51], and 20% of the adults

experience excessive daytime sleepiness [52]. Besides, the 5–25% of adults are more likely to have sleep disordered breathing (SDB) [53] and the 20–30% report insomnia symptoms [51]. Finally, the 1/3 of the U.S. workforce is engaged in shift work [54], [55], which obviously affects sleep.

Moreover, sleep complaints are very common in the general population according to many epidemiologic studies. Some common sleep complaints are trouble falling asleep and staying asleep (insomnia); falling asleep during the day, inability to sleep at the right time; and complaints of thrashing or moving in bed with repeated leg jerking. According to surveys [47], the 51% of sleep complaints concern hypersomnia, the 31% insomnia, 15% parasomnia, and 3% sleep-wake schedule disorders. The most frequent complaint is a combination of all types of insomnia symptoms (38.6 %), and 20–33% of those having a combination of all types of symptoms have sever daytime impairment [56]. Consequently, the significance of the diagnosis and treatment of sleep disorders is strongly underlined.

Classification of sleep disorders

In addition, it is necessary to classify sleep disorders in order to facilitate the understanding of each disorder and its symptoms. Along the years, several attempts have been made by many organizations to organize and to classify sleep disorders [57]. The American Academy of Sleep Medicine (AASM) created the International Classification of Sleep Disorders, which was updated from its previous version in 2014 (ICSD-2 to ICSD-3). In 2013, the American Psychiatric Association (APA) published the fifth revised edition (DSM-V), an update of the DSM-IV section of the Diagnostic and Statistical Manual of Mental Disorders, which includes a section entitled ‘Sleep Wake-Disorders’. ICSD-3 is the most well-known classification. According to ICSD-3, sleep disorders are listed in seven main categories and each of them is subcategorized into more categories [58]:

1. Insomnia disorders
2. Sleep-related breathing disorders
3. Central disorders of hypersomnolence
4. Circadian rhythm sleep-wake disorders
5. Parasomnias

6. Sleep related movement disorders
7. Other sleep disorders

2.4 Sleep Improvement Methods

Sleeping well affects mental and physical health. Short sleep duration and poor sleep quality have negative consequences to many vital functions including cardiovascular metabolic and emotional regulation [4]. Furthermore, as it has been stated earlier, sleep complaints especially those that are related with insomnia disorders, are increasingly widespread. Many attempts have been made in order to improve sleep quality with the most important amongst others, raising awareness about sleep hygiene, creating the optimal environment for sleep and practicing relaxation techniques for better sleep promotion.

2.4.1 Sleep Hygiene

Peter Hauri was the first that introduce the term “sleep hygiene” [59]. Sleep Hygiene (SH) provides recommendations for patients to help them improve their insomnia. These recommendations are generally aimed at having the individual avoid behavior that interferes with a normal sleep pattern, as well as to engage in behavior that promotes good sleep. Despite a lack of consensus on an exact definition of Sleep Hygiene, there are many different definitions in literature, including:

- “Sleep hygiene refers to a list of behaviors, environmental conditions, and other sleep-related factors that can be adjusted as a stand-alone treatment or component of multimodal treatment for patients with insomnia” [59].
- “Sleep hygiene refers to those behaviors that are believed to promote improved quantity and quality of sleep” [59].
- “Sleep hygiene may be described as practicing behaviors that facilitate sleep and avoiding behaviors that interfere with sleep” [60].
- “Sleep hygiene is a term used to describe a collection of behaviors related to the promotion of good sleep” [42].

The original SH rules were introduced by Hauri in 1977 [61] and they are listed in the Table 1 below:

Table 1: Hauri's sleep hygiene rules

1.	Sleep as much as needed to feel refreshed and healthy during the following day, but not more. Curtailing time in bed a bit seems to solidify sleep; excessively long times in bed seem related to fragmented and shallow sleep.
2.	A regular arousal time in the morning seems to strengthen circadian cycling and to finally lead to regular times of sleep onset.
3.	A steady daily amount of exercise probably deepens sleep over the long run, but occasional one-shot exercise does not directly influence sleep during the following night.
4.	Occasional loud noises (e.g. aircraft flyovers) disturb sleep even in people who do not awaken because of the noises and cannot remember them in the morning. Sound attenuating the bedroom might be advisable for people who have to sleep close to excessive noise.
5.	Although an excessively warm room disturbs sleep, there is no evidence that an excessively cold room solidifies sleep, as has been claimed.
6.	Hunger may disturb sleep. A light bedtime snack (especially warm milk or similar drink) seems to help many individuals sleep.
7.	An occasional sleeping pill may be of some benefit, but the chronic use of hypnotics is ineffective at most and detrimental in some insomniacs.
8.	Caffeine in the evening disturbs sleep, even in persons who do not feel it does.
9.	Alcohol helps tense people to fall asleep fast, but the ensuing sleep is then fragmented.
10.	Rather than trying harder and harder to fall asleep during a poor night, switching on the light and doing something else may help the individual who feels angry, frustrated, or tense about being unable to sleep.

Today, there are many different versions of SH rules which contain various additions to and deletions from the overall list (Figure 8). In some instances, sleep specialists have adopted more limited SH rules that focus only on aspects of the sleep environment, effects of exercise, and use of caffeine, alcohol, and nicotine [59]. Another version of sleep hygiene instructions is presented in the Table 2 below:

Table 2: Another version of sleep hygiene rules

1.	No alcohol within four hours of bedtime
2.	No caffeine after 4 p.m.
3.	No vigorous exercise within 2 hours of bedtime
4.	No napping during the day
5.	Engaging in non-specific relaxing activities before bedtime
6.	Not going to bed hungry or thirsty
7.	Sleeping in a comfortable environment including regulation of noise, temperature, and mattress quality

Taking into account the available versions of sleep hygiene recommendations, the most common sleep hygiene-related factors that influence sleep quality are the following:

Sleep and Wake Up Time Regularity

A clear association between sleep schedule irregularity and sleep problems has been demonstrated. In fact, irregular bed and wake up times increase inter-night variability in sleep timing which, in turn, results in the desynchronization of sleep-wake timing and other endogenous circadian rhythms. Moreover, irregular sleep and wake up schedules are associated with greater daytime sleepiness [62].

Sleep hygiene recommendations often encourage regular bed and/or wake-times which are intended to maximize the synchrony between physiological sleep drive,

circadian rhythms, and the nocturnal sleep episode. In more details, sleepers should adhere to regular bed and wake times because this consistency promotes sleep propensity and consolidation [59].

Caffeine Intake

Caffeine is the most commonly-used substance to promote wakefulness and eliminate sleepiness [59]. It is found in many drinks and foods that are common in our everyday life such as tea, coffee and chocolate drinks can disrupt sleep in many ways. More particularly, caffeine consumption makes it harder to fall asleep. It also leads to sleep lightly and to have more awakenings during the night. Besides, it makes sleepers go to the toilet during the night.

One of the most common recommendations for appropriate sleep hygiene practices is to avoid caffeine close to bedtime. However, there isn't clear evidence regarding the consumption of caffeine at earlier time points in the day. Specific recommendations on what time of day to discontinue caffeine use vary widely from 4 to 11 hours prior to bedtime [62], [63].

Alcohol Consumption

Although alcohol make individuals feel sleepy and help them fall asleep faster at night, it actually disrupts sleep later. In the second half of the night, sleep after drinking alcohol is associated with more frequent awakenings, night sweats, nightmares, headaches and is much less restful. Furthermore, it has been demonstrated that alcohol affects negatively REM sleep [59].

Sleep hygiene recommendations encourage to avoid alcohol just before bedtime [59]. More particularly, it has been shown that alcohol use six hours prior to bedtime lead to significant fragmentation of subsequent sleep. Moreover, alcohol consumption during daytime leads to sleep latency reduction. Finally, for non-dependent individuals, occasional consumption of alcohol, even in small amounts, shortly before bedtime can impair sleep. The impact of afternoon or early evening alcohol use on sleep is not yet clearly understood [62].

Nicotine Use

Nicotine is another stimulant which promotes arousal and wakefulness [59]. In fact, nicotine use is associated with increased sleep latency, decreased total sleep time, frequent early morning awakening, REM and deep sleep stage elimination [62].

In the context of sleep hygiene, smoking should ideally be avoided altogether, and certainly for at least 2 hours before bed. There is little evidence on the effects of nicotine on sleep in nonsmokers. Further investigation of occasional and passive smoking will clarify accurate recommendations for non-dependent smokers by evaluating factors such as timing, frequency, and type of nicotine exposure [62]. On the other hand, for smokers, early nicotine withdrawal has been associated with sleep fragmentation which has as a side effect insomnia disorders.

Nutrition Intake

There is enough evidence that food intake timing, mainly in the evening, is negatively correlated with several sleep-related parameters (sleep efficiency, sleep latency, N2 sleep, REM sleep, latency, REM percentage, and WASO). Moreover, type of food intake is also a contributing factor for sleep quality. More specifically, intake of high fat and preceding the sleeping period are associated with higher sleep latency [64]. On the other hand, tryptophan is an ingredient producing serotonin for inducing calmness and drowsiness the brain. Proteins from the food we eat are the building blocks of tryptophan, which is why the best bedtime snack is one that contains both a carbohydrate and protein, such as cereal with milk, peanut butter on toast, or cheese and crackers [65].

Exercise Regularity

A common sleep hygiene recommendation is that regular exercise promotes good sleep quality, but should be avoided close to bedtime. In general, exercise has effects on body temperature, arousal, and/or adenosine levels and consequently may improve sleep [62].

As it has been demonstrated timing of exercise is significantly associated with sleep quality and duration [59]. According to a National Sleep Foundation’s poll about nighttime exercise and its consequences on sleep [66] morning exercise may be an optimal time for regular exercise with respect to sleep quality. However, evening

exercising was not associated with disturbed sleep, even among those who identified themselves as poor sleepers. These data suggest that, with respect to good sleep, it is better to exercise than not exercise, even if the only time to exercise is close to bedtime.

Stress

The term stress refers to “an event or events that lead to acute or chronic physiological (and psychological (anxiousness, vigilance) responses. Stress can precipitate cognitive arousal (i.e., worry) and physiological arousal, which are both antithetical to problems with sleep initiation and maintenance” [62]. Through the years, a variety of sleep recommendations that concern stress levels have emerged, encouraging individuals to reduce worry or engage in relaxing activities, particularly right before bedtime.

Today, there are several relaxation techniques which aim to reduce stress and arousal, such as breathing relaxation and guided imagery. These techniques have been examined in relation to sleep and have provided some preliminary support for stress management as an effective recommendation to promote sleep [62]. Consequently, it is essential to direct individuals toward stress management techniques.

Noise

Noise is a relatively clear source of disturbance especially during the sleep process. In fact, there are many noisy sources within a bedroom which come from not only from the external environment (local traffic, music, and plumbing) but also from the internal (music, TV, voices). Regarding sleep, nocturnal noise increases the number of arousals and results in lighter sleep.

This is the reason why most sleep hygiene recommendations advice individuals to minimize noise in their sleeping environment [59], [62], [67]. As many sleep experts recommend, the relationship between noise and sleep is moderated by specific characteristics of the noise itself such as continuity, type, relevance and by individual differences in noise sensitivity.

Naps

Naps have been shown to be beneficial in attenuating the decrements in mental performance associated with sleep loss due to extended duty hours, such as encountered in long haul airline pilots or shift workers, who have difficulty obtaining sufficient daytime sleep. However, daytime napping has been shown to disrupt the homeostatic sleep drive and, as a consequence, to decrease the depth of the major sleep episode and increase latency to sleep onset [59]. Thus, while naps are helpful especially in cases where sleep cannot be obtained in sufficient quantity, they are detrimental to subsequent nocturnal sleep under normal conditions.

Figure 8: Sleep Hygiene tips [68]

2.4.1.1 Sleep Hygiene Education

Nowadays, there is an increasing demanding for sleep promotion strategies because of the global public health concern over sleep [62]. These strategies should apply not only in clinical settings, but also in the general population in order to improve sleep. It has been found that greater sleep hygiene knowledge is associated with better

sleep hygiene practice, which in turn, is related to better sleep quality [62]. There are several reasons why sleep hygiene education should be promoted in the general population. Firstly, individuals that want to avoid medical treatment for their sleep problems could use sleep hygiene education [62]. In addition, sleep hygiene education is a relatively inexpensive lifestyle intervention. Next, it is a more appealing option for the general population instead of other complex medical practices [64]. Unfortunately, there is no significant effort in promoting the adoption of these practices.

Sleep hygiene education should be emphasized in order to increase awareness of the importance of adopting healthy sleep hygiene practices [69]. During sleep hygiene education, “individuals learn about healthy sleep habits and are encouraged to follow a set of recommendations to improve their sleep” [69]. Sleep hygiene education will be successful if individuals are aware of the potential benefits and consequences of modifying multiple aspects of their behavior. However, sleep hygiene behaviors are affected by individual differences. Consequently, attention must be dedicated to develop effective, personalized strategies to maximize sleep improvement.

2.4.1.2 Sleep Hygiene Index

In recent years there has been increased attention to the improvement of sleep quality by promoting good sleep habits and raise sleep hygiene awareness. Several approaches have been elaborated in order to assess sleep hygiene of individuals. Two of the most known instruments are the Sleep Hygiene Awareness and Practice Scale [70] and the Sleep Hygiene Self-Test [71]. However, these instruments don’t provide a clear reasoning for item selection [60].

A newly introduced instrument is the Sleep Hygiene Index (SHI). The SHI is a 13-item self-administered questionnaire which aims to assess the presence of behaviors thought to comprise sleep hygiene. Participants are asked to indicate how frequently they engage in specific behaviors (always, frequently, sometimes, rarely, never) (Figure 9). Finally, the 13 item scores are summed in order to provide a global assessment of sleep hygiene. Higher scores indicate more abnormal sleep hygiene status [60].

0	1	2	3	4
Never	Rarely	sometimes	Frequent	Always

1. I take daytime naps lasting two or more hours.	0 1 2 3 4	_____
2. I go to bed at different times from day to day.	0 1 2 3 4	_____
3. I get out of bed at different times from day to day.	0 1 2 3 4	_____
4. I exercise to the point of sweating within 1 hr of going to bed.	0 1 2 3 4	_____
5. I stay in bed longer than I should two or three times a week.	0 1 2 3 4	_____
6. I use alcohol, tobacco, or caffeine within 4hrs of going to bed or after going to bed.	0 1 2 3 4	_____
7. I do something that may wake me up before bedtime (for example: play video games, use the internet, or clean).	0 1 2 3 4	_____
8. I go to bed feeling stressed, angry, upset, or nervous.	0 1 2 3 4	_____
9. I use my bed for things other than sleeping or sex (for example: watch television, read, eat, or study).	0 1 2 3 4	_____
10. I sleep on an uncomfortable bed (for example: poor mattress or pillow, too much or not enough blankets).	0 1 2 3 4	_____
11. I sleep in an uncomfortable bedroom (for example: too bright, too stuffy, too hot, too cold, or too noisy).	0 1 2 3 4	_____
12. I do important work before bedtime (for example: pay bills, schedule, or study).	0 1 2 3 4	_____
13. I think, plan, or worry when I am in bed.	0 1 2 3 4	_____
	Total score =_____	

Figure 9: Sleep Hygiene Index [60]

2.4.2 Optimal Sleep Environment

As sleep hygiene rules strongly indicate, creating good sleep environment conditions (e.g., reduce light exposure, noise), promote better sleep. The sleep environment can be defined as the space in which the sleep process happens. The most common sleep environment is the bedroom. It could be characterized as the sanctuary from our daily stresses. Scientific sleep studies have shown that poor sleep quality or disrupted sleep could be caused due to environmental factors. In fact, sleep experts recommend sleeping in a cool, dark, quiet and without disruptors room to ensure the best quality of sleep [72]. Relevant environmental factors could be changes in air temperature, relative humidity, indoor air quality (IAQ), illumination, and noise [73]. However, it is sometimes difficult for a person to assess which factors in the environment may be causing disrupted sleep. An indicative list of factors (Figure 10) that are associated with the sleep environment is presented in the next sections.

Figure 10: Tips to design a sleep-friendly environment [74]

Noise

In general, it is easiest to sleep in a quiet place. Sudden or repetitive noises can interrupt sleep. In particular, noises at levels as low as 40 decibels or as high as 70 decibels can keep someone awake. When we hear noise, we may not become fully conscious, but we certainly will come out of the deeper stages of sleep. If we are trying to sleep in a noisy environment, our ability to enjoy restful deep sleep will be compromised. Noise reduction in a bedroom can be achieved by wearing earplugs, using a white noise machine or keeping a radio or television on low volume to drown out street noises [74].

On the other hand, while certain noises cause interrupted sleep, soft, steady sounds can be soothing. Some people have found that ‘white noise’ tapes help them fall asleep and sleep more soundly, while others prefer low familiar tones [75].

Temperature

Human body heat peaks in the evening and then drops to its lowest levels when individuals are asleep. In general, most sleep scientists believe that a slightly cool room contributes to good sleep. That's because it mimics what occurs inside the body when the body's internal temperature drops during the night to its lowest level. An optimal bedroom temperature is thought to be between 16°C (60°F) and 18°C (65°F). In most cases, temperatures above 75°F and below 54°F will disrupt sleep, but sleep researchers fail to agree on the ideal temperature for sleep. The point at which sleep is interrupted due to temperature or climate conditions varies from person to person and can be affected by bed clothes and bedding materials selected by the sleeper [74]. For example, young children and elderly people may require a slightly warmer environment.

To keep a bedroom cool, it is essential to turn the thermostat down at night in cold weather and to use blankets, comforters or electric blankets in order to lock in heat without feeling too heavy or confining. Moreover, a too hot room can also lead to disruptive sleep. In fact, research suggests that a hot sleeping environment leads to more wake time and lighter sleep at night, while awakenings multiply. An air conditioner and a humidifier may be useful solutions for keeping the bedroom cool.

Lighting

Lighting is one of the factors that affects the perceived atmosphere [76]. Color temperature, brightness and contrast, are some of the most important lighting attributes. Solid-state lighting technologies, especially LED (Light Emitting Diodes) based lighting sources, makes possible the control of color temperature, and spectral, spatial, temporal and polarization properties [77].

Lighting design decisions in interior spaces can influence or modify a human’s impression of perceptual clarity, spaciousness, relaxation or tension, prominence or anonymity, pleasantness, and spatial complexity [78]. With regard to impression of relaxation, peripheral and non-uniform spatial lighting with low brightness helps to create a relaxing atmosphere [76].

At the same time, the right color temperature lighting can be advantageous to human health, well-being, and productivity [77]. Under most circumstances, cool colors (e.g.,

blue, green, purple) have been associated with peaceful, calm, and restful environments, while warm colors (e.g., red, orange, yellow) are physically and emotionally arousing, exciting, and distracting [79]. More specifically, blue is mainly experienced as calming and relaxing color because reminds people of the sky, ocean, beach or water, and green as calming, relaxing, happy, comforting, peaceful, and hopeful because reminds people of outdoors, nature, grass, trees, and springtime [80]. In addition, darkness promotes the releasement of melatonin, which relaxes the body and helps to fall asleep faster.

Bedding and Mattress

The bed is by far the most significant element of a good night's rest. It is near impossible to get a deep, effective sleep on an uncomfortable bed. So, it is important to keep comfort as a priority. Mattresses lacking comfort, space and support are likely to promote tiredness. A mattress too soft will cause the person to slouch, while one that's too firm can apply pressure to hips and shoulders. There are a variety of options in how people choose to sleep, and there is no one right way. Variations may relate to personal preference, cultural practices, financial situations, and many other factors. One thing to consider may be the size and firmness of the mattress [74], [75].

Electronics and Blue Light

Bedrooms should be relaxed and restful places. Thus, it is important to create calm spaces that have no requirement for technological devices. Unfortunately, most people consider bedrooms as extensions of living rooms and offices, and so introduce digital distractions into the mix [75]. Electronic devices like TVs, computers, tablets, and smart phones, all have a high concentration of blue light. Blue light is the strongest wavelength, and thus the most disruptive to melatonin production. Melatonin is the hormone responsible for sleep which is produced in the evening by the brain. Leaving the lights on and using electronic devices tricks the brain into thinking it is still daytime, thus delaying melatonin production and keeping people awake longer [81].

According to the 90% of sleep studies in adolescents, there is an adverse association between screen time usage and sleep. In young people, screen time exposure should be limited, especially before or during bedtime hours, in order to minimize harmful

effects on sleep and well-being [82]. To sum up, sleep environments should be used only for sleep and any type of electronic device should be avoided just before and during bedtime in order to promote good sleep [74].

Colors

It is widely known that colors are strongly connected with people's psychology, so they are able to induce emotions and mindset. Color psychology should be applied in a bedroom. Consequently, it is essential to focus on choosing colors that relax and calm individuals.

According to a sleep study that was conducted in British households [83], there are some basic rules to follow for deciding the colors of bedroom walls, bedding and general décor of the bedroom. Particularly, light pastel colors are calming, as are neutral, earth or skin-based tones. On the other hand, darker colors will make the room feel smaller, and perhaps cozier. Besides, accent decorative pieces should have colors parallel to each other on the color wheel rather than ones that contrast. The contrast in color is stimulating to the eyes and thus not calming. Finally, the best color for the bedroom according to the survey is blue. Blue is the color that promotes calmness and it has been shown to reduce blood pressure and heart rate. Actually, it has been reported that individuals with blue bedrooms get the most amount of sleep [83].

Scents

Another way to make a room feel relaxing is through ambient scent, since specific scents have been shown to have a positive impact on mood [84] and induce relaxation [85]. Aromatherapy, has been used for centuries to promote relaxation, mental and physical wellness. In addition, it is found that it reduces anxiety and increases sleep [86]. In fact, inhaling essential oil molecules may activate brain chemicals involved in controlling sleep [87]. Today, these oils are increasingly being studied by scientists in search of a more rigorous, specific understanding of their benefits to sleep and health. In order to tune the ambient scent, a smart aromatherapy diffuser, which spreads the essentials oils through air without human intervention, can be used.

Scents of essentials oils that can induce help in the promotion of good sleep and in many cases extend the total sleep time with less early morning awakenings are: lavender, bergamot, chamomile, sweet marjoram, sandalwood, clary sage [88], [89], rose [90], ylang-ylang [91], orange [92] and spiced apple [93]. Conversely, lemon and peppermint are arousing, activating scents.

2.4.3 Relaxation Techniques for Sleep

Relaxation techniques have been central issue of interest in the areas of medicine, stress management, well-being and overall lifestyle [94]. Relaxation refers “a state of relative freedom from both anxiety and skeletal muscle tension” and relaxation response is “a state of decreased psychophysiological arousal: a calming state [95]. Numerous research studies have extensively examined many different relaxation techniques for several years. Scientifically proven relaxation techniques in combination with a created relaxing space can reduce the psychophysiological arousal and improve people’s mental well-being [96]. In particular, many of these relaxation techniques reduce stress and can be further used to help people fall asleep faster in cases where long sleep onset latency is detected. To that end, relaxation techniques have the ability to decrease sleep onset latency and therefore to promote good sleep quality [97].

2.4.3.1 Meditation Practices

Meditation, with its global effects on body and brain functions helps to establish a body and mind harmony. It is also true that meditation influences sleep and its functions. Actually, there is enough literature evidence that meditation enhances significantly slow wave sleep (SWS) and rapid-eye movement (REM) sleep. Moreover, several studies have examined the relationship between meditation practices and melatonin levels. By considering the important role of melatonin in sleep maintenance, it might be concluded that meditation practices enhance melatonin levels and hence quality of sleep [98].

Guided Imagery

Guided imagery was used by ancient Greeks, by Tibetans, and later by Freud as a healing tool and it is based on the belief that it is the power of imagination and visualization. Belleruth Naparstek, a pioneer in the field of guided imagery, describes it as “a process of deliberately using the imagination to help the mind and body heal, stay well, or perform well. It is a directed, deliberate daydream, a purposeful creation of positive sensory images sights, sounds, smells, tastes, and feel in the imagination” [99]. In this way, it can control negative thoughts such as fears and concerns. In other words, it connects the conscious mind with the unconscious mind, and helps the mind direct the body toward positive, desirable responses [100]. Furthermore, it is a mind-body technique that can be used to reduce stress and promote sleep. In other words, guided imagery is another terrific component of a nightly pre-bed routine.

To practice guided imagery, users should focus their attention to the visualization of a safe place, followed by the creation of more specific guided images in the mind’s eye. Images can be sensory or affective; however, the most successful images tend to be those that involve all the senses (vision, sound, touch, smell, and taste). Guided imagery exercises have several different levels and forms that range from visualizations of places, situations, thoughts and memories to more organized and targeted imaginative metaphor and storytelling. All these exercises engage all the senses in a focused period of imagination. Five types of guided imagery are usually practiced: (1) pleasant imagery such as imagery of a peaceful location; (2) physiologically-focused imagery such as imagery of white cells fighting disease or cancer cells; (3) mental rehearsal such as successfully performing a public task; (4) mental reframing such as imagery that reinterprets a past experience and its associated emotions; and (5) receptive imagery that involves scanning the body for diagnostic or reflective purposes [101].

Diaphragmatic Breathing

Several meditation techniques involve breathing exercises for relaxation. Most, if not all, involve diaphragmatic breathing (DB), which is the act of breathing deeply into the lungs by flexing the diaphragm rather than the ribcage [102]. DB is relaxing and therapeutic, reduces stress and is a fundamental procedure of Pranayama Yoga, Zen, and other meditation practices. In fact, it has been shown that several

physiological indicators, including skin conductivity, heart rate, and breathing rate are significantly lower during diaphragmatic breathing [103]. In general, diaphragmatic breathing has many benefits. The most important of them are:

- It helps people relax, lowering the harmful effects of the stress hormone cortisol on the body.
- It lowers heart rate and blood pressure.
- It helps people cope with the symptoms of post-traumatic stress disorder (PTSD).
- It improves core muscle stability.
- It improves body's ability to tolerate intense exercise
- It slows breathing rate so that it expends less energy.

These findings declare that by practicing breathing exercises the body is relaxing and therefore is prepared for sleep. Other breathing exercises for better sleep are '4-7-8' breathing [104], 'Buteyko' breathing and Papworth method [105].

2.4.3.2 Listening to Music

Music is an important part of individual's everyday life and serves many different functions in society. Moreover, music is one of the most-used self-help strategies to promote stress reduction and sleep improvement. Many clinical studies have shown that music has the potential to reduce stress and therefore it is possible to prevent psychological pre-sleep arousal and thus improving the preconditions for sleep. Therefore, listening to music could be beneficial for people with sleep onset problems [94], [106].

The response to a musical stimulus depends on the musical attributes (e.g., type, tempo, energy), the people who are involved (e.g., listener, composer, performer), and the current listening situation (e.g., place, time, other people being present). There are also several studies that compare the effects of different types of music on the relaxation response. Classical music appears to be more beneficial for stress management compared to other music types (e.g., hard rock [107], heavy metal [108], jazz and pop [109]). Furthermore, instrumental music accompanied by nature sounds seem to be another great choice [110].

In the context of the current work, interest has been focused on the potential musical attributes that promote relaxation on the listener to enhance sleep quality. A research study which was conducted in older adults, has shown that music intervention at bedtime improved the fundamental components of sleep quality including shorter sleep onset latency, less daytime dysfunction, longer sleep duration, greater perceived sleep quality and greater sleep efficiency [111].

Chapter 3

Related Work

There are several research studies which have investigated numerous sleep technologies as well as approaches to monitor sleep behavior at home by collecting information about individuals' sleep patterns. The main objectives of these studies are the monitoring of sleep patterns, the improvement of sleep quality and the promotion of sleep habits awareness in order to persuade individuals to adopt healthier sleep routines.

3.1 Literature Review

Best Effort Sleep [112]**:** An approach which uses a sensor-based inference algorithm on the mobile phone to predict sleep duration by exploiting various smartphone usage patterns (e.g. the time and length of smartphone usage or recharge events) and environmental observations (e.g. prolonged silence and darkness). Quantitative and qualitative comparisons between BES approach and popular commercial wearables have been carried out and the results have shown that the BES model can accurately infer sleep duration (± 42 minutes).

DoppleSleep [113]**:** A contactless sleep sensing system that facilitates continuous and unobtrusive long-term sleep monitoring using a single Doppler radar sensor. It tracks an individual's physical body movements, heart beat and breathing during sleep, and objectively infers sleep quality. The results showed that the system promises great detection for physical movements, heart and breathing rate and continuous, passive, unobtrusive sleep monitoring in real-world settings.

iSleep [114]**:** A mobile application which monitors an individual's sleep quality using smartphone sensors. In particular, it uses the built-in microphone of the smart-phone to detect events that are closely related to sleep quality, including body movement, couch and snore, and infers quantitative measures of sleep quality. The results show that iSleep achieves consistently above 90% accuracy for event classification in a variety of different settings.

Polysomnography (PSG) [115]**:** The “gold standard” of sleep assessment which is mainly performed for sleep disorders diagnosis in a hospital or sleep clinic. In more details, it is an overnight sleep monitoring study which utilizes a recording montage that combines multi-channel recordings including electroencephalography (EEG), electrooculography (EOG), chin electromyography (EMG), respiratory effort, airflow, electrocardiography (ECG), oximetry, and anterior tibialis EMG. However, the PSG method is impractical for long-term use because it is intrusive and usually requires an overnight stay in a sleep laboratory or clinic [37].

ShutEye [116] **:** It provides a peripheral display on the wallpaper of the user mobile phone to promote awareness about recommended activities that promote good sleep quality. Based on user preferences about desired bed-time and activities, it displays guidance about when engaging in those activities is likely to affect sleep without requiring any explicit interaction from the user. Results indicate that a simple, recommendation-based peripheral display can be a very low-effort but still effective method for improving awareness of healthy sleep habits.

SleepExplorer [117]**:** A web application designed to visualize sleep data and to show correlations between sleep-tracking data and other self-tracking data (i.e., physiological, psychological, lifestyle, and environmental data), helping users make sense of their sleep. It was found that SleepExplorer helps organize a flux of self-tracking data to personalize the definition of sleep quality in multiple dimension, guides tracking activities, highlights connections in the data, and leads to intention for behavior change to improve personal sleep.

SleepHunter [118]**:** It’s a mobile service that provides a fine-grained detection of sleep stage transition for sleep quality monitoring and intelligent wake-up call. The core idea is to leverage built-in sensors of mobile phones to sense sleep-related events, and further predict the dwelling time of each sleep stage by a statistical model based on these observable events. The results show that system achieves desirable detection accuracy.

SleepSense [119]**:** A non-contact and cost-effective sleep monitoring system which is used for continuous recognition of the sleep status, including on-bed movement, bed exit, and breathing section. It consists of three parts: a Doppler radar-based

sensor, a robust automated radar demodulation module, and a sleep status recognition framework. According to the results, SleepSense achieves an overall 95.1% accuracy rate in identifying various sleep status. Also, the error rate for breathing rate extraction in this study is only 6.65%.

SleepTight [120]**:** A self-monitoring application which provides feedback to help people change their behavior by capturing sleep measures from a sleep diary and contributing factors (e.g. meals, exercise, caffeine) from an activity section. It leverages Android's widgets both to reduce the capture burden and to improve access to information. The results from this study demonstrated that using mobile phone's widgets is a quick way to capture contextual data, self-reflection, and engagement.

Toss 'N' Turn [48]**:** An Android app that captures sensor data for use in inferring sleep duration and quality. Moreover, the app asks people to fill out a daily sleep diary based on the PSQI. Results have shown that TNT system classifies sleep state with 93.06% accuracy, daily sleep quality with 83.97% accuracy, and overall sleep quality with 81.48% accuracy.

3.2 Consumer Sleep Technologies

Although many of the approaches are still running in sleep labs, in the recent years, consumer sleep technologies have appeared on the market. Consumer sleep technologies can be categorized by delivery platform, including mobile device applications (integrated with a mobile operating system and utilizing mobile device functions such as the camera or microphone), wearable devices (worn on the body), embedded devices (integrated into furniture or other fixtures in the sleep environment) and accessory appliances (like smart lights and smart alarms) [121].

3.2.1 Mobile Device Applications

Calm [122]**:** A popular mobile application for meditation and sleep which offers various techniques to help users relax and to fall asleep faster. In more details, it provides mindfulness techniques for managing stress, calming anxiety and facilitating deep sleep. Moreover, it gives the ability to users to listen bedtime stories (for kids

and adults) read aloud by people with soothing voices in order to fall asleep effortlessly.

Pillow [123]**:** The app offers heart rate analysis and a detailed sleep stage analysis for each sleep session, by using graphs that are easy to read and to interpret. It also provides a smart alarm function which monitors the movements and the heart rate of the users in order to wake them up at the lightest possible sleep stage. The most important feature is that it provides personalized recommendations which are constantly updated with helpful information that will help users make the right decisions to improve their sleep.

Relax Melodies [124]**:** A mobile application which offers a variety of sounds, meditations and soothing music. It provides sleep-inducing programs which feature guided exercises and sessions to help users achieve deep sleep, better sleep, stress and anxiety relief, more effective napping, and more. All these programs have been approved by health and sleep professionals.

Sleep As Android [125]**:** This app has multiple features, including: nature sounds to facilitate sleep onset; accelerometer-derived “sleep cycle” tracking; snoring detection and “antisnoring” (e.g., phone vibrates or emits tongue-click sounds to rouse the patient to stop snoring); smart alarm (e.g., the app will require the user to complete a mentally or physically engaging task such as answering arithmetic questions before the wake-up alarm will terminate); sleep graphs illustrating sleep duration, “sleep debt,” and “light” and “deep” sleep percentages, etc. [121].

Sleep Cycle [126]**:** A famous mobile application which helps users track “sleep trends” over time. When placed on the sleep surface, the mobile device’s built-in accelerometer measures movement as an indicator of the presence or absence of sleep. The program features a “smart” alarm clock, engineered to wake the user within a preset time range each morning, triggered when the app senses a period of “light sleep,” with the objective of producing a more pleasant awakening experience.

SleepScore™ [127]: An app that uses just the smartphone microphone and speaker capabilities to track and measure breathing rate and body movements. It provides personalized advice and recommendations for improving sleep based on the sleep data. Moreover, it offers a nightly Sleep Score in order to inform the user about sleep

quality, and it also tracks this score over time to see how sleep is improving and spot trends that can help keep on the path to consistently great sleep.

3.2.2 Wearable Devices

Dreem 2 EEG Headband [128]: It's a wireless EEG headband worn during sleep which records, stores, and automatically analyzes physiological data in real time. The physiological signals which are recorded via sensors embedded in the device are: brain cortical activity via 5 EEG dry electrodes, movements, position, and breathing frequency via a 3-D accelerometer located over the head; and heart rate via a red-infrared pulse oximeter located in the frontal band. Furthermore, Dreem 2 uses an algorithm to classify sleep stages and to provide sleep parameters and other physiological signal analysis [129].

Fitbit Charge 3 [130]**:** A very popular fitness tracker which understands health and takes action to improve it. Concerning the sleep process, it has many features that are associated with sleep. It monitors sleep automatically and classifies sleep stages in order to make users be aware of their sleep patterns and to understand better their sleep. Besides, it helps users retain a consistent sleep schedule by recommending them a personalized sleep routine according to their sleep goals. Finally, it provides personalized sleep insights to improve sleep quality.

OURA Ring [131]**:** It's a finger-wearable that utilizes a pulse oximeter to measure blood volume via arteries on the finger. In fact, it can be used as a sleep tracker which combines pulse volume and 3D accelerometer data to interpret stages of sleep and distinguish between light sleep, deep sleep and REM instead of using EEG sensors to detect sleep staging. Besides, it gives advice about suitable bedtime window and provides useful sleep insights in order to guide users to make optimal choices for their sleep.

Sleep Profiler [132]**:** It's a mobile, self-application sleep EEG device developed for home sleep environment usage without the assistance of a professional technician. It provides three channels of frontal EEG, a pulse rate and an optional ECG. Also, it monitors head movement and position. Sleep Profiler provides data on total time and percentage of sleep, rapid eye movement and slow wave sleep, sleep efficiency and

average number of cortical, sympathetic and behavioral arousals. The accompanying software automatically scores the resulting EEG record using an algorithm that spectrally decomposes the EEG signal, computes descriptors of sleep and categorizes each epoch as one of the sleep stages [133].

Withings Steel HR [134]**:** It is a wearable activity and sleep tracker with a built-in heart-rate sensor. It provides automatic sleep tracking and monitors a number of sleep parameters that are associated with sleep quality, such as time to fall asleep, time in bed, time asleep, time awake, duration of light and deep sleep, sleep score, resting heart rate and a heart-rate graph through the night. Also, it offers a smart alarm function with a gentle vibration at the optimal wake up point of the sleep cycle.

3.2.3 Contactless Devices

Beddit 3 [135]**:** A sleep tracker consists of a thin, narrow sensor strip which is placed underneath the sheets. During the night, it tracks a number of sleep metrics. In the morning, it offers a sleep score to see how well users have slept. It also calculates averages for heart and breathing. Moreover, it provides a smart alarm for awakening in the optimal phase of light sleep and sleep insights for users to be aware of their sleep health. Besides, it is equipped with environmental sensors to monitor bedroom conditions such as temperature and humidity.

EarlySense [133]**:** a contact-free monitoring system comprising an under-the-mattress piezoelectric sensor and a smartphone application which collects vital signs such as heart rate and respiration rate and calculates sleep-related parameters. This system was compared with the PSG where the results showed similar values for average total sleep time (TST), wake state, rapid eye movement, and non-rapid eye movement sleep, with 96.1% and 93.3% accuracy of continuous measurement of HR and RR, respectively [136].

Eight Sleep Tracker [137]**:** It is a mattress equipped with sensors built into the cover which track sleep and make temperature adjustments to ensure a good night's rest. In particular, Eight collects environmental data (room temperature, humidity, noise and levels of ambient light) and measures heart and breathing rate, movement, bed

temperature and sleep metrics which can be viewed on the companion android or iOS app. Moreover, it uses a smart alarm which identifies the moment of lightest sleep during the specified 30-minute wake-up window that the user has indicated. Also, its sensors will auto detect whether users snore.

Emfit QS [138]**:** It's an in-bed contactless sleep monitoring solution for general sleep analysis. It uses a technique known as ballistocardiography, with its bio-sensors housed in a thin strip which should be place under the mattress or mattress topper. It measures common metrics such as movement, breathing, heart-rate and sleep stage classification, but it can also track and measure heart rate variability, recovery, and stress levels, all of which can be viewed through the accompanying web application. Like other similar devices, Emfit QS calculates and provides a Sleep Score.

Withings Sleep Mat [139]**:** It is a sleep tracker that sits underneath the mattress and features advanced sleep tracking as well as integrated home automation features. It uses a ballistocardiography technique which monitors breathing, movement and heart-rate, and translates these into data that are related to sleep. In particular, it breaks down sleep data into light sleep, deep sleep and also REM sleep, and it also calculates a sleep score measured out of 100.

3.2.4 Accessory Appliances

Philips Wake-Up Light [140] **and HUE Smart Bulbs** [141]**:** Both employ "smart" light bulbs designed to give the user a more pleasant awakening experience by turning on dimly 30 minutes before a preset wake-up time, and gradually brightening to gently wake the user. At wake-up time a natural sound or radio will turn on and gradually get louder. Users can change the color of the smart bulb using an integrated mobile device app and program lights to turn on or off at specific times [121].

Resmed S+ [142]**:** It's a standalone sleep monitoring device that sits on the bedside stand and helps users monitor, analyze and improve their sleep. It offers various features including sleep analysis with charts, personalized suggestions based on sleep data, relaxation programs to sleep more easily and a smart alarm which wakes users up in the right sleep phase. In addition, it monitors the quality of the sleeping

environment by recording the ambient light, noise and temperature of the bedroom [121].

Withings Aura [143]**:** A multi-functional sleep system incorporating sleep tracking, bedroom environmental monitoring, sleep-wake programs and smart alarm function. It can be paired with the sleep sensor mattress pad that was mentioned above. As for sleep/wake programs, it offers a “go to sleep” program where a slowly changing red-tinged glow is emitted, accompanied by a chosen soundtrack. The wake-up program is supported through a ‘smart alarm clock’. It uses light from the blue/white light spectrum [121].

3.3 Progress Beyond the State-of-the-Art

As analyzed in the previous sections, monitoring sleep behaviors, detecting sleep patterns and offering sleep recommendations toward improving sleep quality have been topics of growing research interest, as well as commercial interest. Most research studies concern mobile applications that are able to monitor sleep, but they solely rely on built-in phone’s sensors to determine sleep patterns, so they usually underestimate, overestimate or lose important sleep measures and bio-signals. Furthermore, most of the aforementioned systems and applications require explicit user interaction to initiate the sleep monitoring process (e.g., press a start button, use a voice command). On the other hand, clinical methods such as PSG monitor sleep automatically by utilizing many recording channels, but they require patients to be observed in a sleep clinic using costly and obtrusive sensor technology.

Furthermore, as discussed earlier, many of the available commercial sleep devices track sleep and provide sleep recommendations to improve sleep quality, but they lack contextual information regarding daytime user activities and habits which are necessary in order to generate more meaningful and personalized sleep recommendations. In addition, most existing approaches include mechanisms to relax or to wake up users in order to facilitate sleep or wake up process, but they rely on a single device application or they require the user to be in a specific setting. Finally, currently available systems lack the means to adjust the sleeping environment to the needs of the users.

With all these in mind, HypnOS approach enhances the aforementioned implementations by creating an unobtrusive sleep monitoring system for Intelligent Homes, able to detect sleep abnormalities and provide personalized sleep hygiene guidelines based on a variety of monitored data (e.g., user daily activities and habits) in order to improve sleep quality. Table 3 presents the functionalities of the currently implemented systems in comparison with HypnOS system.

Table 3: Comparison matrix between existing systems and HypnOS[2]

		Sleep Monitoring				Sleep/Wake Up Improvement			
		Sleep Metrics	Bio-signals	Daily Habits	Context Info	Insights	Environment	Relaxation	Alarm
Literature Review	DoppleSleep [105]	⊖	-	-	●	-	-	-	-
	iSleep [106]	●	●	-	-	-	-	-	-
	PSG [31]	⊖	-	-	-	-	-	-	-
	ShutEye [108]	●	●	-	-	-	-	-	-
	SleepExplorer [109]	-	-	○	-	●	-	-	-
	SleepHunter [110]	-	-	○	-	●	-	-	-
	SleepSense [111]	⊖	-	-	-	⊖	-	-	-
	SleepTight [112]	●	●	-	-	-	-	-	-
	Toss 'N' Turn [42]		-	⊖	-	●	-	-	-
Mobile Device Applications	Calm [114]	⊖	-	-	-	-	-	-	-
	Pillow [115]	⊖	⊖	-	-	●	-	-	●
	Relax Melodies [116]	-	-	-	-	-	-	●	-
	Sleep As Android [117]	⊖	-	⊖	-	●	●	●	●
	Sleep Cycle [118]	⊖	-	⊖	-	●	-	●	●
Wearable Devices	Dreem 2 EEG Headband [120]	●	●	⊖	-	-	-	●	●
	Fitbit Charge 3 [122]	●	●	⊖	-	●	-	-	●
	OURA Ring [123]	●	●	⊖	-	●	-	-	-
	Sleep Profiler [124]	●	●	-	-	-	-	-	-
	Withings Steel HR [126]	●	●	⊖	-	-	-	-	●
Contactless Devices	Beddit 3 [127]	●	●	-	-	●	-	-	●
	EarlySense [125]	●	●	-	-	-	-	-	-
	Eight Sleep Tracker [129]	●	●	-	-	●	●	●	●
	Emfit QS	●	●	-	-	-	-	-	-
	Withings Sleep Mat [131]	●	●	-	-	-	-	-	-
Accessory Appliances	Philips Wake-Up Light [132] & HUE Smart Bulbs [133]	-	-	-	-	-	●	-	●
	Resmed S+ [134]	●	●	-	-	●	●	-	●
	Withings Aura [135]	●	●	-	-	-	●	●	●
HypnOS		●	●	●	●	●	●	●	●

[2] "●" Automatically/Yes; "⊖" Semi-automatically; "○" Manually; "-" No

Chapter 4

Requirements Elicitation

Following the bibliographic study, the next step was to define the requirements of the HypnOS. To that end, an iterative, User-Centered Design methodology [144] was followed, with special attention given to the pre-design stages, as described in the Design Thinking process [145].

4.1 Design Process

“Design Thinking is a non-linear, iterative process which seeks to understand users, challenge assumptions, redefine problems and create innovative solutions to prototype and test” [146]. This method consists of 5 phases: Empathize, Define, Ideate, Prototype and Test (Figure 11).

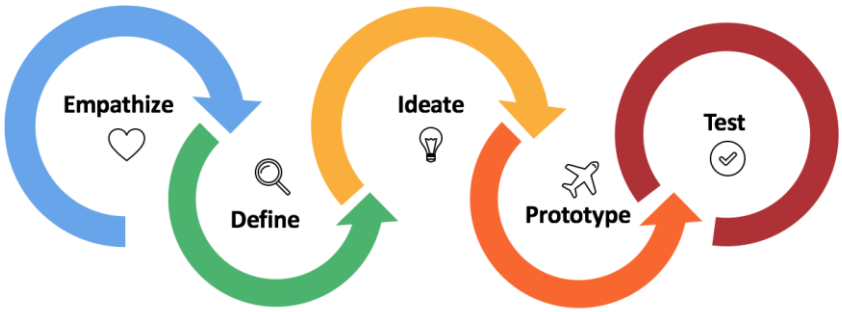


Figure 11: The 5 stages of the Design Thinking process [147]

The Empathize step of the process requires gaining an empathic understanding of the problem under investigation. To that end, HypnOS’s design team consulted with sleep experts from a sleep research laboratory, (Department of Respiratory Medicine, Medical School, University of Crete) in order to gain valuable feedback and insights. As an outcome, it was suggested that HypnOS should not provide medical-level services, since the required equipment for retrieving medically acceptable data would make the system far too obtrusive for a home environment. Additionally, it was made clear that patients in sleep labs are often overwhelmed by the level of surveillance,

which includes electrodes attached to various places on the body and head, as well as cameras recording the patient all night, which results in discomfort and is generally an unpleasant experience.

Therefore, in the Define step of the process, it was decided that the scope of the system would be to monitor, as unobtrusively as possible, the sleep behavior of the individuals in order to identify their sleep patterns. It was also suggested that in combination with the monitoring of their daily habits - through other ambient monitoring services of the Intelligent Home - the system could offer valid insights in form of advice to improve sleep hygiene and therefore their sleep quality.

Next, in the Ideation process, several brainstorming sessions took place during which dozens of ideas were produced and then filtered appropriately. By properly shaping those ideas, a set of preliminary system requirements was extracted and constructing the final requirements of the HypnOS system. In the Prototype phase, the design team followed an iterative design process where low and high-fidelity interactive prototypes were created for the HypnOS app. Moreover, before proceeding with user testing, the overall setup and the application prototypes were iteratively evaluated by experts so as to uncover issues in terms of interaction and ergonomics.

Finally, once the interactive prototypes had been created, a heuristic evaluation was conducted, aiming to eliminate serious usability problems before proceeding to user testing. Afterwards, a user-based evaluation on the HypnOS mobile application was conducted where real users interacted with the mobile application in order to gain qualitative insights about how they use the system and what their exact problems are with the concrete interface being tested.

4.2 HypnOS Requirements

The requirements that were extracted are grouped into three categories: intelligent environment services which describe the functionality of the system that is related with the Intelligent Home, system functions which are strongly related with the functionality of the system and the end user operations which refer to the user interface operations.

4.2.1 Intelligent Environment Services

i. **Monitoring sleep-related parameters:** The intelligent environment should monitor parameters that can detect sleep patterns and assess overall sleep quality.
   a. The environment should monitor users' sleep parameters.
   b. The environment should monitor users' bio-signals.
   c. The environment should retrieve knowledge regarding users' daily habits and routines such as nutrition intake and stress levels.

ii. **User tracking:** The intelligent environment should track users' location.
   a. The environment should detect if users are in bed or not.
   b. The environment should determine if users are indoors or outdoors.
   c. If users are indoors, the environment should determine their exact location inside the home and if someone else is in the same room as they are.

iii. **Offering bedroom adjustments:** The intelligent bedroom environment should offer several features that can create a relaxing space for sleeping.
   a. The environment should have a smart lighting system.
   b. The environment should have a speaker and voice assistant.
   c. The environment should have a smart scent diffusion system.
   d. The environment should have a smart temperature control system.
   e. The environment should have a smart blinds/curtains control system.

4.2.2 System Functions

i. **Identifying sleep patterns**: The system should recognize when users are experiencing usual or unusual sleep behavior.
   a. The system should process the information received from the environment in order to detect sleep abnormalities.
   b. The system should be able to assess overall sleep quality and to define a sleep quality indicator (e.g., poor, fair, and good).

ii. **Offering sleep insights:** The system should provide personalized recommendations that are related with users' sleep routine in order to motivate them to change their daily habits that affect sleep.

a. The system should give users tips that promote good sleep hygiene (e.g., do not drink coffee just before sleep, keep a consistent bedtime schedule).
b. The system should advice users to seek out professional help when they are facing sleep issues over a long period of time.
c. New recommendations should be easily added to the system.

iii. **Sleep diary completion:** The system should offer a sleep diary in order to collect additional information that is associated with subjective or external sleep related factors.
a. The system should offer sleep diary as a supplementary to the basic sleep monitoring function.
b. The system should send a notification reminder for the completion of the sleep diary.
c. Sleep diary completion should be optional.

iv. **Offering smart wake up:** The system should detect the optimal wake up time in order to wake up users in a gentle way.
a. The system should detect the lightest possible stage of sleep in combination with the desired wake up time.
b. The system should offer the ability to users to set the desirable wake up time explicitly.
c. The system should offer various features to wake up users.

v. **Offering relaxation programs for sleep:** The system should be able to provide a relaxing immersive experience to help home residents relax and fall asleep effortlessly.
a. The system should adjust the lighting conditions.
b. The system should play audio content from the available speakers.
c. The system should release a pleasant smell using the available scent diffuser.
d. The system should adjust temperature conditions using the available smart temperature control system.

e. The system should adjust external light using the available smart blinds/curtains control system.

vi. **Keeping history log:** The system should keep records containing necessary information required to help users understand their sleep patterns and their overall sleep quality.
   a. The system should store sleep-related measurements (e.g., sleep duration, sleep stages).
   b. The system should store bio-signals measurements (e.g., heart rate, respiration rate).
   c. The system should store all the available personalized recommendations.
   d. The system should store all available data associated with a noticeable improvement or deterioration in the quality of sleep (e.g., daily habits, external factors).

vii. **Notifying user:** The system should send users notifications when necessary.
   a. Users should be notified every morning after wake up to complete the sleep diary.
   b. Users should be notified every night before go to bed to complete the sleep diary.
   c. Users should get a notification to set a wake up time for the next day if they haven't set it already.

4.2.3 End User Operations

i. **Managing history reports:** Users should get a clear picture of their sleep quality and patterns.
   a. Users should be able (at any time and place, and on multiple devices) to view their sleep report for a given year, month, week or day and to observe fluctuations.
   b. Users should be able to view diagrams and graphs that are related with sleep parameters and bio-signals for better understanding.

ii. **Viewing sleep recommendations:** Users should be able to view personalized recommendations.
    a. Users should be able to view recommendations about their sleep.
    b. Users should be able to view recommendations about their daily routine.
    c. Users should be able to enable/disable recommendations' view.

iii. **Completing sleep diary:** Users should record subjective information about their sleep quality and their habits during the day.
    a. Users should record their personal perception about last night's sleep in the morning after wake up.
    b. Users should record the habits that they had during the day just before go to sleep.
    c. Users should be able to complete the sleep diary optionally.
    d. Users should get a notification reminder to complete the sleep diary.

iv. **Setting alarm:** Users should be able to set desirable wake up time explicitly.
    a. Users should be able to enable/disable the smart wake up function.
    b. Users should be able to select the days of week that the alarm will be repeated.
    c. Users should be able to enable/disable snooze option.
    d. Users should be able to enable/disable various ambient effects for waking up smoothly including light, sound, temperature and blinds.

v. **Starting a relaxation program for sleep:** Users should be able to practice relaxation techniques for sleep.
    a. Users should be able to start a sleep/relaxation program at any time.
    b. Users should be able to choose an existing sleep/relaxation program or to create a custom one according to their preferences.
        c. Users should be able to enable or disable specific program features (e.g., lights, scent, sound).
        d. Users should be able to add a program to favorites.
        e. Users should be able to stop a running program whenever they want.

vi. **Changing settings:** Users should be able to change certain settings.
    a. Users should be able to enable/disable notifications.
    b. Users should be able to mute notifications for a specific period of time.

vii. **Reacting to notifications:** Users should be able to react to system notifications.
    a. Users should be able to ignore notifications.
    b. Users should be able to take a certain notification-specific action.

Chapter 5

HypnOS Approach

The HypnOS system is an unobtrusive sleep monitoring and recommendation system for Intelligent Homes [148]. Particularly, it aims to detect sleep abnormalities by exploiting a variety of sleep tracking devices, and to provide personalized sleep hygiene recommendations based on a variety of monitored data (e.g., sleep-related parameters, bio-signals, subjective measurements). Furthermore, it utilizes the infrastructure of an Intelligent Home to retrieve and extract relevant contextual information about the user's daily routines and habits (e.g. nutrition, work schedule, fitness).

From an end-user perspective, the system presents daily detailed sleep reports including – amongst others – details regarding sleep patterns, movements during sleep, hours of sleep, etc., receive personalized sleep recommendations to raise their awareness in order to change their sleep habits that affect sleep and activate any of the system's sleep/relaxation programs in case that they have difficulty falling asleep. In addition, a daily sleep diary is provided as an extra functionality that supplements the basic monitoring from the sleep trackers in order to collect information about residents' habits and subjective measurements. Finally, the system offers a smart alarm which is a common alarm clock enhanced with smart features that aim to wake up users in a gentle way at the optimal wake up time.

5.1 Key Features

Pervasive sleep monitoring, personalized sleep recommendations and facilitation of sleep and wake up process are the key features in the development of HypnOS system.

5.1.1 Pervasive Sleep Monitoring

The HypnOS system tracks sleep activity, detects sleep abnormalities and assesses sleep quality by monitoring resident's sleep-related parameters (e.g., sleep duration,

snoring activity), bio-signals (e.g., heart rate, breathing rate), daily habits (e.g., caffeine and alcohol consumption), subjective measurements (e.g., sleepiness feeling, subjective sleep quality) and contextual information (e.g., daily activities, nutrition). For the collection of the required information, it utilizes sleep trackers (Figure 12), a daily sleep diary offered by the HypnOS mobile application, and the ambient monitoring services of the Intelligent Home. More information about the different data that HypnOS collects is available at APPENDIX A.

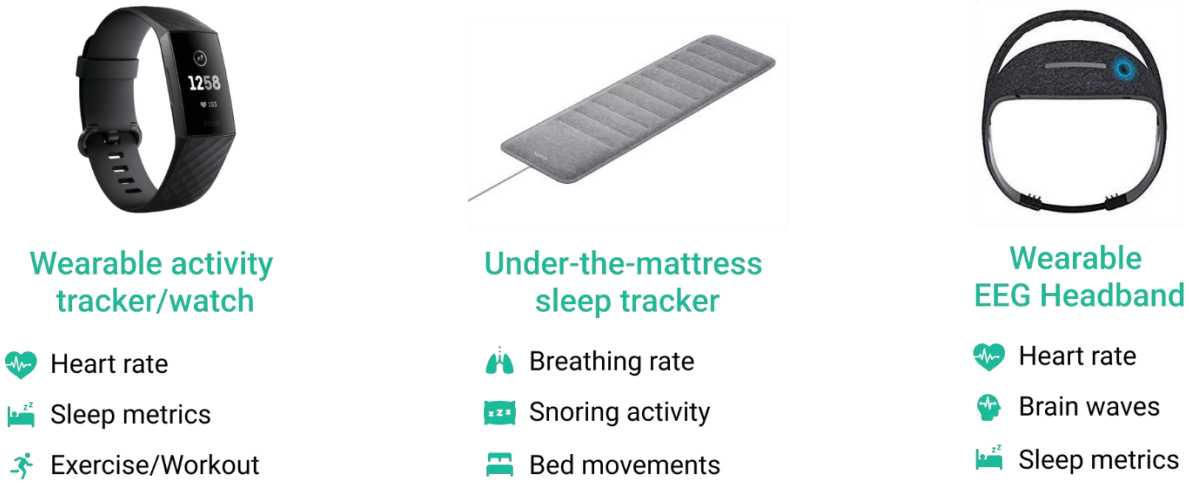


Figure 12: Sleep trackers utilized by HypnOS

5.1.2 Personalized Sleep Recommendations

HypnOS fuses data (e.g., sleep-related parameters) that are available through various sleep trackers, ambient micro-services of the Intelligent Home (e.g. nutrition micro-service) and HypnOS mobile application sleep diary (e.g., sleepiness feeling during the day) so as to gain insights about the causes of the residents' sleep-related issues and act accordingly. More specifically, it provides personalized, data-driven sleep recommendations based on a collection of sleep hygiene rules so as to help residents be aware of the potential habits that affect more their sleep quality.

5.1.3 Facilitation of sleep and wake up process

HypnOS interoperates with the ambient facilities of the Intelligent Bedroom (Figure 13) so as to adjust a variety of environmental factors (e.g. light, sound). Thus, it

enhances the bedroom environment and create experiences that can potentially facilitate the falling asleep and waking up processes. To enhance wake up experience, HypnOS offers a smart alarm which detects the optimal time to wake up residents gently (i.e. when they are in the lightest possible sleep stage) and adjusts bedroom environment according to their preferences (e.g., raise the blinds on alarm ringing). To facilitate sleep process, it provides relaxations programs that are ambient in the bedroom when residents have difficulty in falling asleep.

Figure 13: Ambient facilities of the Intelligent Bedroom

5.2 Architecture Overview

HypnOS is deployed in the technologically enhanced bedroom (Figure 14) of the Intelligent Home simulation space located at the AmI Facility within the FORTH-ICS campus. The facilities of the Intelligent Bedroom work in conjunction with AmIHomeOS [149] - the distributed computational framework of the Intelligent Home in order to transform the room into an all-inclusive environment. In more details, its hardware infrastructure consists of: (i) an extensive grid of sensors and actuators that monitor and control various aspects (e.g. motion sensors), (ii) smart commercial equipment (e.g. smart lights, aroma diffuser), (iii) devices and wearables (e.g. smart wristbands of various sorts, EEG devices, smart TVs, tablets), and (iv) technologically augmented custom-made furniture (e.g. clothes hanger, nightstands, wardrobe).

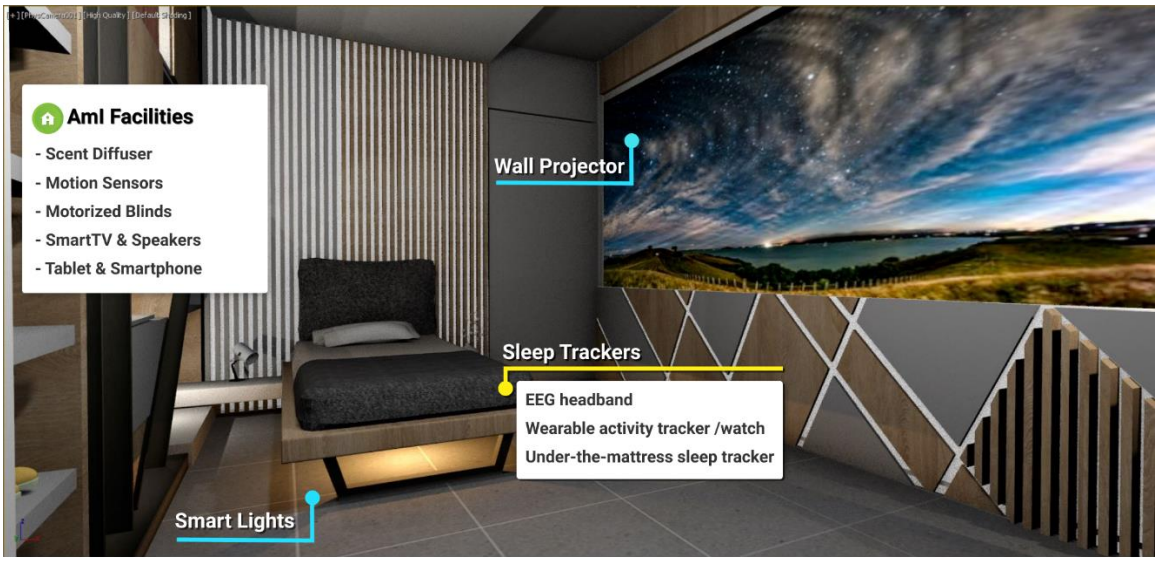


Figure 14: 3D representation of the Intelligent Bedroom

The Figure 15 illustrates the overview of HypnOS's architecture. Firstly, the system continuously monitors sleep-related data and bio-signals of the residents and informs the data collector when new data are available. Next, data collector aggregates these data, preprocesses them in order to have a consistent format and finally it stores them into a data store in the form of a personalized sleep record. Afterwards, the intelligent framework requests residents' sleep-related data from the data store and contextual information from the AmI environment to perform intelligent tasks including recognition of sleep patterns, reasoning, and planning. Finally, the intelligent processes that take place in the intelligent framework result in valuable data that are represented in the end-user application which also interoperates with AmI environment.

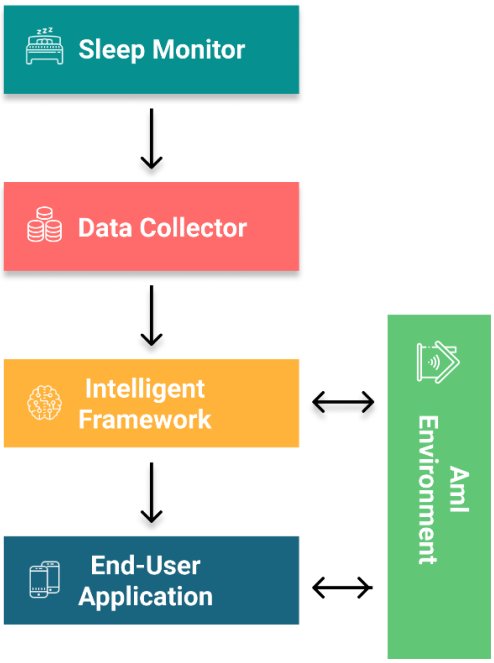


Figure 15: High-level system architecture

5.3 Sleep Monitor

HypnOS monitors data from various sources in order to gather information about residents' sleep behavior and make a first estimate of their sleep quality. In particular, it employs (i) various wireless sleep trackers (ii) the sleep diary from HypnOS mobile application and (iii) the ambient monitoring services of the Intelligent Home in order to monitor sleep. When these sources are outside the AmI environment, they communicate with AmI bridge - a middleware communication component – when new data are available. Then, the AmI bridge forwards this notification to the sleep monitor data bus which requests directly the new data from it. Sources that run into the AmI environment do not have to communicate with the AmI bridge. They communicate directly with the sleep monitor data bus when they have new data (Figure 16). Finally, when notified, the sleep monitor data bus requests data from all the available sources in order to send them to the data collector.

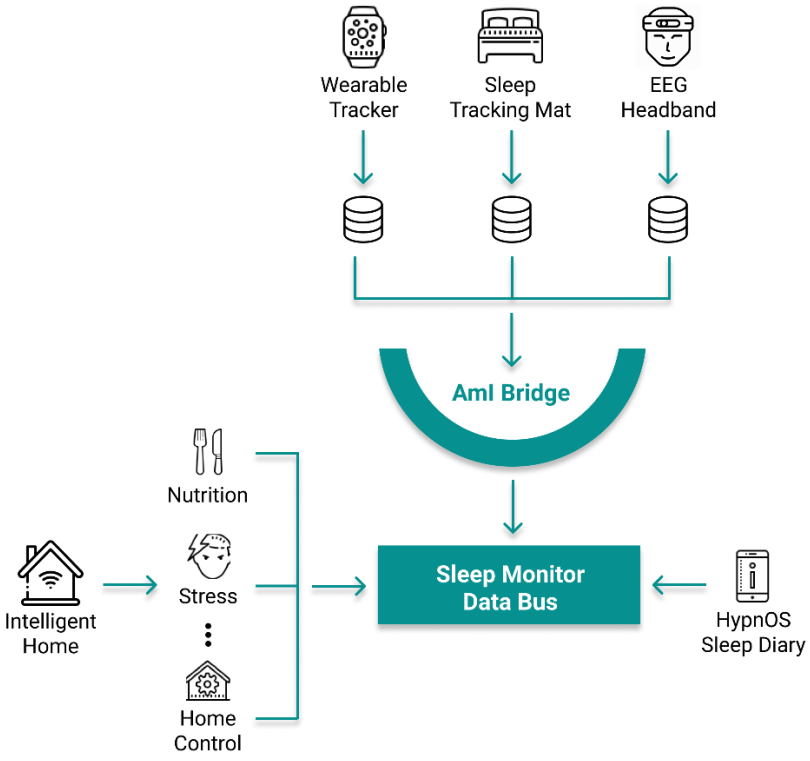


Figure 16: Sleep Monitor decomposition

5.3.1 Sleep Trackers

During the past few years, continuous technological improvements have led to the introduction of an abundance of sophisticated wireless sleep trackers both for commercial and research purposes [150]. Today, consumer sleep technologies are increasingly popular to the general public for the purpose of self-monitoring and improving sleep. Consumer sleep technologies can be wearable devices (e.g., attached on the body), embedded devices (e.g., integrated into furniture), accessory appliances and conventional desktop/website resources [121].

HypnOS employs a group of wireless sleep trackers including a wearable activity tracker/watch (e.g., Fitbit Charge 3 [130], Withings Steel HR [134]), an under-the-mattress sleep tracker (Emfit QS [138], Withings Sleep [139]) and a wearable EEG headband (Dreem 2 [123], BrainBit [152]). These devices are equipped with a large number of sensors such as 3-axis-accelerometer, which tracks motion patterns, a pulse oximeter which tracks heart-rate, a pneumatic sensor for breathing rate

tracking, a ballistocardiography sensor for continuous heart and breathing rate, EEG sensors for EEG brainwaves monitoring and a microphone for snoring detection.

Each of these devices monitors sleep and bio-signal data and stores them in its web server. When new data are available, they sent a notification to AmI Bridge. This component works as a “bridge” of communication between sleep trackers’ web servers and the AmI environment. Next, AmI Bridge forwards this notification to the sleep monitor data bus, which receives the notifications and directly requests the new data from the sleep trackers’ APIs.

5.3.2 HypnOS Sleep Diary

In sleep medicine, “the sleep diary has been regarded as the “gold standard” for subjective sleep assessment” [38]. In general, sleep diaries allow people to self-assess their sleep by collecting data every day. It is usually completed over a period of time (usually one or two weeks). This means that sleep diaries collect lots of sleep-related information, and also that this kind of information is precise enough. Moreover, it is not so dependent on memory, because it is often filled in just after waking up and/or just before going to sleep. There are also sleep diaries that are distributed as mobile apps. According to a survey that has been conducted comparing the use of paper and electronic sleep diaries it was concluded that they are similar with respect to their diagnostic power [153].

Today, there are several sleep diaries available. In our endeavor to create a custom sleep diary as a supplementary functionality to the basic monitoring, the most popular sleep diaries (e.g., Pittsburgh Sleep Diary (PSD) [39]), Consensus Sleep Diary (CSD) [38] and National Sleep Foundation (NSF) [41]) have been examined. Almost all of them coincide in similar information about users’ daily life including sleep metrics (e.g., total sleep duration, number of awakenings), habitual information (e.g., alcohol and caffeine consumption) and subjective measurements (e.g., sleep quality, restfulness feeling after wake up).

To that end, HypnOS mobile application offers a sleep diary - the HypnOS Sleep Diary (HSD) – which is the superset of the aforementioned diaries (Figure 17). In more details, PSD consists of 23 questions, CSD 20 questions and NSF 15 questions

where the 10 of them are common. HypnOS has the ability to answer all of them through HSD which is offered by HypnOS mobile application. HSD is completed on a daily basis and it consists of two sections: one completed in the morning after waking up (post-sleep diary) and one before going to bed (pre-sleep diary) at night. The HypnOS system uses the sleep diary to collect information about the home residents' daily habits (e.g., caffeine and alcohol consumption, smoking) and their subjective perception about sleep (subjective sleep quality, restfulness sense after wake up). When a user completes the sleep diary, the HypnOS mobile application sends a request to the sleep monitor data bus in order to inform it that new data are available. Then, the sleep monitor data bus requests these data from the HypnOS mobile application and forwards them to the data collector in order to store them.

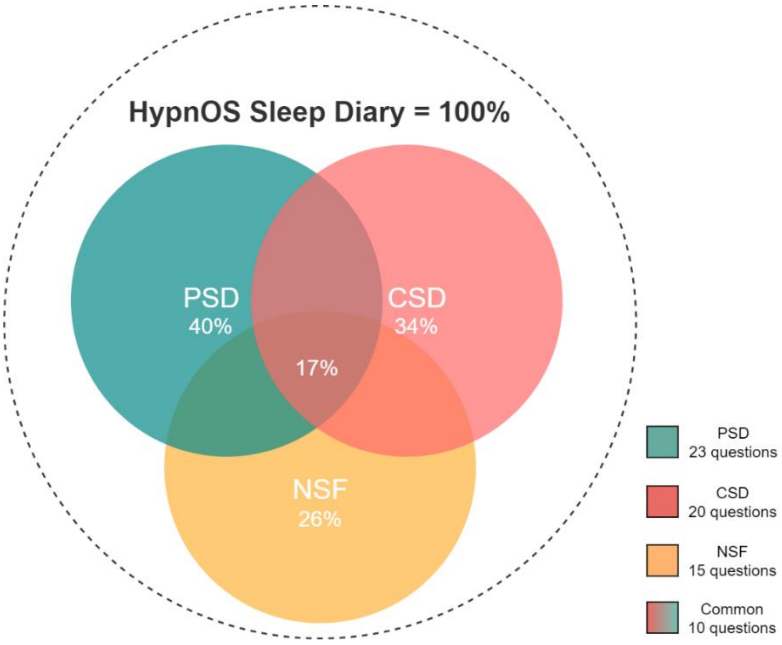


Figure 17: HypnOS Sleep Diary (HSD)

5.3.3 Ambient Monitoring Services of the Intelligent Home

Most research efforts so far have focused on sleep abnormalities detection from sleep measurements and bio-signals, but they do not take into account the context of the user. Still, context is an important source of information that can be exploited to gather additional information useful for sleep monitoring. Since this system targets an

Intelligent Home environment, a variety of sources is used to that end. More specifically, HypnOS introduces context-sensitive micro-services that are used to identify residents' behaviors in order to gain insights about the causes of their sleep-related issues and act accordingly.

The identification process is based on the analysis of data about the user's daily activities, habits and preferences, which has been retrieved from the ambient monitoring services of the Intelligent Home (Figure 18). It should be emphasized that, in the near future new ambient monitoring services will be created and integrated into the Intelligent Home. To that end, HypnOS has the ability to integrate any new ambient service that is deployed into the Intelligent Home and exploit it appropriately in order to gather additional contextual information from a new source.

Figure 18: Ambient Monitoring Services of the Intelligent Home

CaLmi (Stress Management)

Stress can impact daily life in many ways, including negatively affecting the quality of sleep. A very common phenomenon is when people lying in bed worry and feel anxious, which makes it almost impossible to relax and quiet their mind enough to fall asleep. In fact, all types of stress can harm sleep quality and sleep deprivation can

fuel further stress and irritability. While these are worrying trends, the good news is that there are ways to treat insomnia and better manage stress. In our context, CaLmi [96] – a micro-service of the Intelligent Home - detects residents' stress levels and offers personalized relaxation programs that are adaptable to the bedroom in order to manage their stress.

Nutrition

Eating habits can also affect sleep. More specifically, eating too close to bedtime may causes weight gain and disrupts sleep during the night. Moreover, certain foods (e.g., diets high in fat and junk foods) will have negative effects on sleep quality. On the other hand, foods rich in tryptophan (e.g., milk, cheese, crackers) - an amino acid that causes sleepiness - may lead to better sleep quality. In the Intelligent Home, a nutrition service collects all the information about inhabitants' daily nutrition habits (e.g., type of meal, calories). Accordingly, a micro-service consumes this information to make it meaningful for the HypnOS system. In more detail, HypnOS'S exploits a nutrition micro-service which log residents' meal timing to detect if it is very close to the usual bedtime. Furthermore, it logs the meal type and the calorie intake in order to identify if the meal is a light snack or a heavy one.

Home Control

Poor sleep quality or disrupted sleep could be caused due to environmental factors in the sleep environment. Ideally, the sleep environment should be a sanctuary for restful and restorative sleep. Environments which are noisy, bright, warm, full of moisture and bad air quality affect negatively the sleep and wake up process. Unfortunately, it is sometimes difficult for a person to assess which factors in the environment may be causing disrupted sleep. For that reason, an ambient service which is responsible for the control of the environmental aspects (e.g., temperature, humidity, lights) is deployed in the Intelligent Home. In the context of HypnOS system, a micro-service is responsible for the control of the environmental factors of the Intelligent Bedroom. In particular, it identifies in real time the environmental conditions of the bedroom and adjusts them according to the optimal conditions for a restful sleep (e.g., temperature for best sleep is between 60 and 67 °F, bedroom humidity level to 40%, light brightness to 30%).

User Activity Tracking

Furthermore, the current conditions at home and user behavior are inspected as well. Being awakened or out of bed (e.g., use of the bathroom several times), being irritated or uncomfortable due to others (e.g., bedpartner, pets or children), doing arousing and stressful activities (e.g., working, watching TV) before bedtime are some conditions that system is able to track in order to identify abnormal or unexpected user behaviors. Therefore, HypnOS exploits a micro-service which is deployed in the Intelligent Home in order to check the current home conditions. In particular, it detects residents' activities and checks their current location inside the house to identify any abnormal movements or other people being around them.

5.4 Data Collector

Data collector is the component which is responsible for gathering the different data into a centralized database and transforming them into one cohesive dataset (Figure 19).

As a first step, the aggregator requests the raw data from the sleep monitor data bus. When it receives the raw data, it stores them into a centralized database. Because raw data come from different sources, they are inconsistent, so they have to be pre-processed in order to be in the same format. For example, wearable activity trackers record heart rate values every 30 seconds while EEG headband record them every 60 seconds. To that end, the preprocessor requests these data from the aggregator and makes the appropriate transformations in order to make them consistent. More specifically, the preprocessor harmonizes and normalizes their values (e.g., mapping the timestamps so as values), completes missing values (e.g., replaces missing value with the average value of the other sleep trackers) and cleans erroneous data (e.g., correct or delete broken data).

Next, the sleep history recorder receives the preprocessed data and consolidates them to create a daily sleep record. In particular, it processes the data to elaborate some relevant information (e.g., finding median and average values, standard deviation from of the normal distribution). After this phase, the daily sleep record is

created and stored in a dedicated database. Similarly, the sleep profile builder uses the preprocessed data to build a sleep profile based on residents' past values.

Finally, the HypnOS data store saves all the valuable data sets in one centralized location. These datasets include sleep profiles, daily sleep records, subjective measurements and other external files (e.g., sleep hygiene rules). Furthermore, it has its own API, so that the sleep history recorder and the sleep profile builder are able to use it not only for requesting data, but also for sending data.

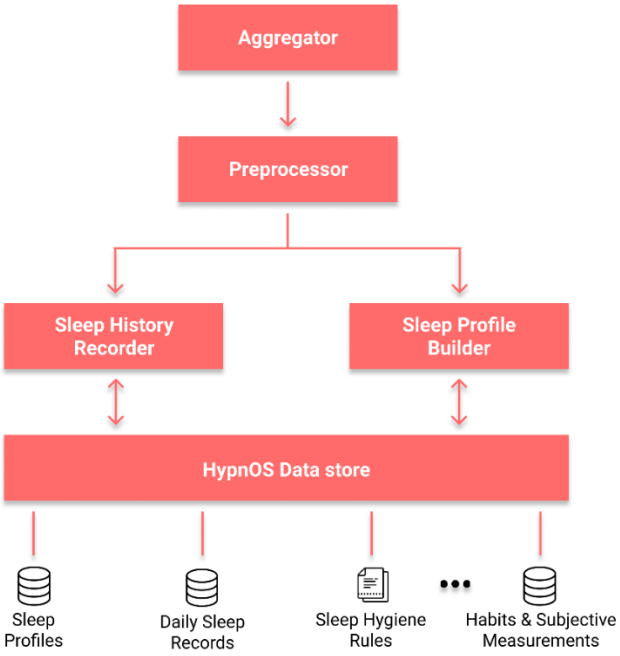


Figure 19: Data Collector decomposition

5.5 Intelligence Framework

The intelligence framework of HypnOS (Figure 20) aims to supports its overall decision-making process. In particular, it consists of intelligent tasks that run in parallel in order to interact with the end-user application. These functions consume data from the HypnOS data store and rely on Artificial Intelligent (AI) to perform tasks that are associated with the calculation of every night's personalized sleep score through the Sleep Score Calculator module, the generation of personalized sleep insights through the Sleep Insights Generator module, the scheduling of smart alarm

via the Smart Alarm Scheduler module, and the recommendation of relaxation programs for sleep through the Sleep Programs Recommender.

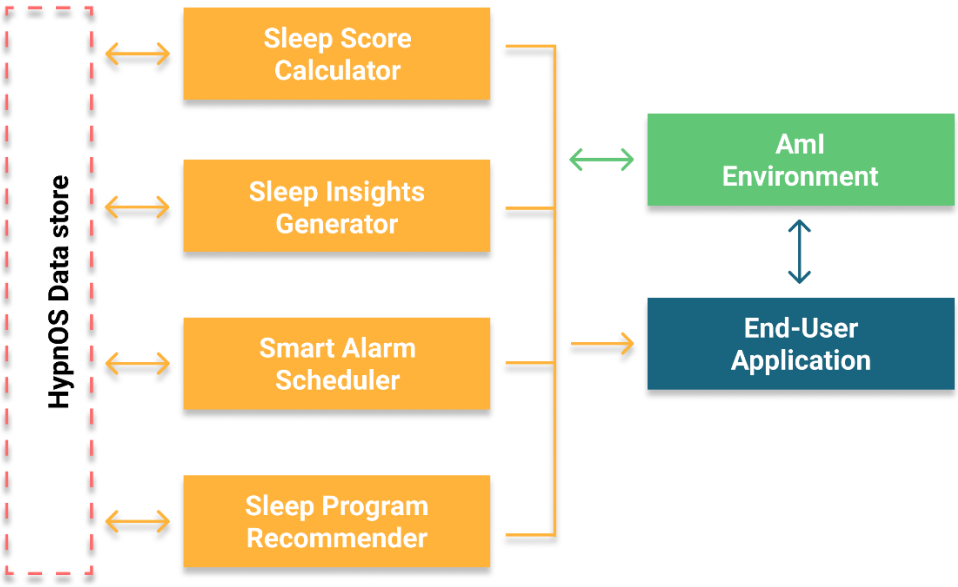


Figure 20: Intelligent Framework decomposition

It is worth noting that while the rest of the system architecture components (i.e., Sleep Monitor, Data Collector, End-User Application) are fully consolidated, the Intelligent Framework has been implemented following a decoupled approach, so as to allow new future integrations and/or replacements according to the findings of the two evaluation experiments that will be conducted in the near future: the 1st experiment will be a trial of the system in order to collect data, while the 2nd will be conducted in the Intelligent Home in order to examine the overall user experience of living in a home with such facilities and functionality.

Sleep Score Calculator

The Sleep Score Calculator predicts the “actual” sleep quality based on the monitored data received from the HypnOS data store. In particular, it detects sleep abnormalities in relation to the users’ sleep profile and daily history (e.g., increased bed movements, more awakenings after alcohol consumption) and outlines their potential causes (e.g. eating a heavy dinner before going to bed).

Overall, the Sleep Score Calculator module is based on a heuristic algorithm which takes into account (a) the individual sleep scores that are calculated from the different sleep trackers (e.g., wearable activity tracker/watch), (b) the individual sleep scores that are extracted from the PSQI and SHI sleep questionnaires, which combine different sleep-related parameters (e.g. awakenings, total sleep duration) and other external factors (e.g., drink coffee too close to bedtime, do important work before bedtime), (c) users' sleep history (average sleep duration, user slept close to his usual time, user woke up easily and close to his usual time) and (d) parameters that are extracted from the pre- and post-sleep diaries (provided by the HypnOS mobile application).

Sleep Insights Generator

The Sleep Insights Generator produces personalized sleep recommendations based on a collection of template sleep hygiene rules (see 2.4.1 section). Moreover, it takes advantage of daily sleep record data (e.g., time to fall asleep the previous night) and user profile information (e.g., drinking three cups of coffee in a single day) to extract personalized insights that encourage inhabitants to adopt healthier routines for the improvement of their sleep quality. In particular, it uses a decision tree classification approach that creates models to predict if daily routine factors (e.g., caffeine, alcohol, nicotine) could influence sleep quality negatively or not. In fact, for each of these factors, it creates a small decision tree to detect if there is a correlation between that particular factor and sleep quality.

For example, consider Table 4 below that presents how caffeine quantity and time of consumption affect sleep quality; using its data, a decision tree is built to predict if sleep quality is affected negatively (i.e. the decision column concerning sleep quality includes two classes: low and high).

Table 4: Dataset example

ATTRIBUTES		**DECISION**
Caffeine Quantity	**Caffeine Time**	**Sleep Quality**
0-2 cups	just before sleep	low
3-5 cups	2h before sleep	low

> 5 cups	just before sleep	low
3-5 cups	4h before sleep	high
0-2 cups	2h before sleep	high
> 5 cups	2h before sleep	low

The dataset is split on the different attributes using entropy calculation [154]. Figure 21 represents the decision tree used for the previous example. The rectangles indicate the splitting features, while the ovals represent leaf nodes that denote the classification results.

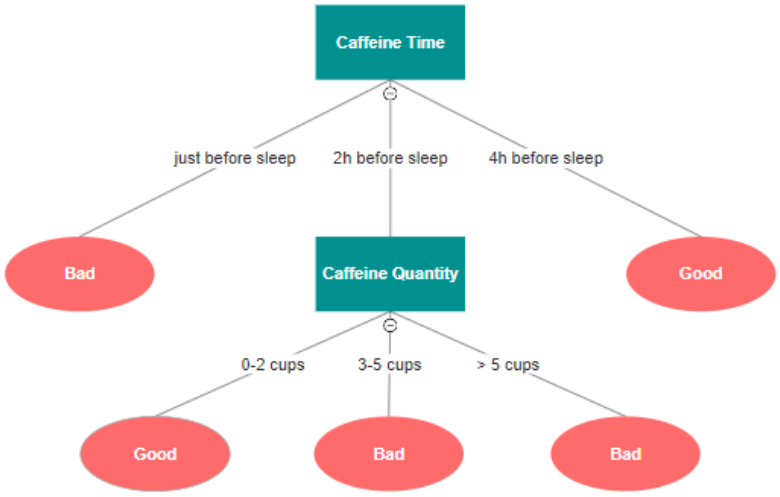


Figure 21: Decision tree example

Furthermore, sleep data of the previous night can be combined with other factors including: (a) user profile and sleep history information, (b) previous night's sleep score, and (c) the individual decision trees for the corresponding answers to the questions of the sleep diary, so that the system personalizes its sleep recommendations as much as possible. For example, if caffeine consumption does not affect the sleep quality of a specific user (which can be easily confirmed by his sleep history), then this user will not receive a recommendation regarding caffeine consumption (Figure 22).

```
function GetAllInsights() {
  return {
    "sleep_regularity": "Keep your sleep and wake times consistent",
    "high_caffeine": "Don't drink caffeine less than 2 hours before sleep",
    "intense_exercise": "Don't exercise intesively at least 3 hours before bedtime",
    "heavy_meal": "Heavy foods in the evening make it more difficult to sleep well",
    //...more insights with different wording...
  }
};

function GenerateInsights(user, last_night_data) {

var user_insights = [];
var hypnos_insights = GetAllInsights();

// Shortcut if last night's sleep was good
if (last_night_data.score >= user.history.avgSleepScore && last_night_data.
sleepQuality >= user.history.avgSleepQuality)
{
  return null;
}

// Logic for caffeine insight
if ((last_night_data ["Caffeine_Time"] == "BAD" || last_night_data
["Caffeine_Quantity"] == "BAD") && user.isAffectedByCaffeine)
{
  this.user_insigths.append(user_insights["high_caffeine"])
}
  return user_insights;
}
```

Figure 22: Sample code from the Sleep Insights Generator

Smart Alarm Scheduler

The Smart Alarm Scheduler estimates, using a set of heuristics, the optimal time to wake up residents (e.g., the lightest possible stage of sleep just before desirable wake up time) by exploiting the available data from residents' sleep profile (e.g., usual wake up time) and daily sleep record (e.g., light sleep). In addition, it takes into account the wake-up time that the users explicitly have set before they go to sleep. Next, it uses residents' preferences from their sleep profile to customize the bedroom environment in order to accommodate the "awakening" process and wake up residents in a gently way. In more details, it adjusts bedroom's ambient facilities (e.g., lights, sound, blinds, scent) according to users' preferences (e.g., user prefers to be awakened by birds singing sound) and at the same time, it tries to wake them up with the most efficient way for specific conditions (e.g., work vs weekend) based on their sleep history.

Sleep Program Recommender

This module recommends relaxation programs for sleep based on user preferences (e.g., user usually falls asleep with the “Rain Droplets” program) by utilizing information from the user profile. In more details, it is a tag-based recommender system which provides a dataset with keyword tags for each relaxation program for sleep. More specifically, every program is described by a list of attributes (e.g., duration, category, number of sessions), a list of keyword tags (e.g., sunset, tropical_beach, rain_sounds) that are related to its content, and a list of keyword tags that regard the most appropriate situation in order to activate a program (e.g., late_night, immediate_relaxation). For example, the Tropical Beach session in the Guided Imagery category offers tropical beach images and ocean waves sound and is suggested for situations when the user has difficulties in falling asleep.

Regarding the user profile, the user can set personal preferences about relaxation programs for sleep. Firstly, he is able to choose if he wants to receive sleep program recommendations or not. If yes, he selects some basic parameters that are related with the sleep programs according to his preferences (e.g., nature, summer). In addition, a list of programs that have been activated at least once, is stored in his sleep profile. Next, the effectiveness of each program is calculated by utilizing other program-related information (at a program was activated, how long the user was in bed trying to sleep, how long it took to fall asleep on average, other external factors that may have influenced sleep such as "heavy dinner just before sleep"). Finally, the user profile also includes information that is related to the user settings (i.e., light’s color, wall projector activity, sound, favorite scent) for each program in order to adjust it to his preferences.

To that end, HypnOS monitors user behavior and examines whether to suggest a relaxation program for sleep (e.g., HypnOS identifies that it takes more than usual for the user to fall sleep). In such a case, the sleep program recommender examines all the above data and suggests to the user the most appropriate sleep program according to the current conditions.

5.6 End-User Application

The HypnOS system monitors, collects, manages and creates large amounts of data on a daily basis. Some of that data contains useful information for users (e.g., sleep report, insights) and must be presented to them in an optimal way. Information visualization involves the visual disclosure of information behind the data in a proper display [155]. In order to achieve a usable and pleasant system which is easy to learn, users must understand visualizations in an effortless way and have a natural intuitive mapping with what they represent.

In recent years, mobile devices have become extremely popular and people believe there should be an app for everything [156]. Using applications, users can access various types of information and control different processes from everywhere and at any time. In particular, with regard to smartphones, according to IDC's research [157], 79% of owners keep their phone near them for all but two hours of their waking day. Moreover, in the last years, the use of mobile health (m-health), sleep monitoring and well-being apps has been growing rapidly [158]–[160]. For those reasons, HypnOS provides a user-friendly mobile application that has been developed to facilitate control over the system and assist users. In this section, snapshots of the current implementation of the mobile application are presented.

5.6.1 Report

The first page that users see when they enter the app is the report page and especially the daily report page, which contains a detailed analysis of last night's sleep (Figure 23a). Users can inspect a chart to learn about their sleep stages (e.g., duration of each stage). This chart is a doughnut chart which uses four colors to define the different sleep stages. Moreover, it represents details regarding sleep parameters (e.g., sleep duration, sleep score, time to fall asleep, snoring activity), bio-signals (e.g., nightly heart and breathing rate) and sleep patterns (e.g., sleep stages) which can be further inspected by clicking them. Furthermore, it shows an information window which contains sleep insights about the previous night This window is clickable and leads to the dedicated page for sleep insights for further information. Apart from a daily view, it offers weekly (Figure 23b) and monthly (Figure

23c) views where there is a bar chart that represents weekly and monthly average sleep duration respectively.

Figure 23: Sleep Report. (a) Daily view (b) Weekly view (c) Monthly view

Time to Sleep

As it was mentioned in the previous section, the report page includes details about time to fall asleep. When users click on the time to sleep parameter, they move to its dedicated page where they can inspect a horizontal bar chart to identify the time that it took them to fall asleep last night (Figure 24a).This chart has a gradient fill which consists of three colors, where each color represents the different classes that the value of time to fall asleep belongs to. In addition, it shows if this time is in normal range according to their usual time to fall asleep. Similarly with the sleep report page, it contains a weekly (Figure 24b) and a monthly (Figure 24c) view where there is also a bar chart and more details about their weekly and monthly time to fall asleep.

Figure 24: Time To Sleep. (a) Daily view (b) Weekly view (c) Monthly view

Snoring Activity

The sleep report page also includes details about users' snoring activity. When users click on the snoring activity parameter, they are navigated in a dedicated page where they can inspect two horizontal bar charts. The first one represents their snoring episodes during the night, while the second one represents the total snoring duration of last night (Figure 25a). Similarly with the previous pages, it contains a weekly (Figure 25b) and a monthly (Figure 25c) view, where there are two bar charts that represent snoring episodes and average snoring duration respectively.

Figure 25: Snoring Activity. (a) Daily view (b) Weekly view (c) Monthly view

Heart Rate

Next, the sleep report page includes details about heart rate during the night. When users click on the heart rate parameter, they are navigated to a dedicated page where they can inspect a spline chart. This chart represents last night's heart rate activity (Figure 26a). Furthermore, it shows the minimum, the maximum and the average value of heart rate during the previous night. Similarly with the sleep report page, it contains a weekly (Figure 26b) and a monthly (Figure 26c) view, where there is a bar chart that represents the average weekly and monthly heart rate activity as well as the minimum, maximum and average weekly and monthly heart rate values.

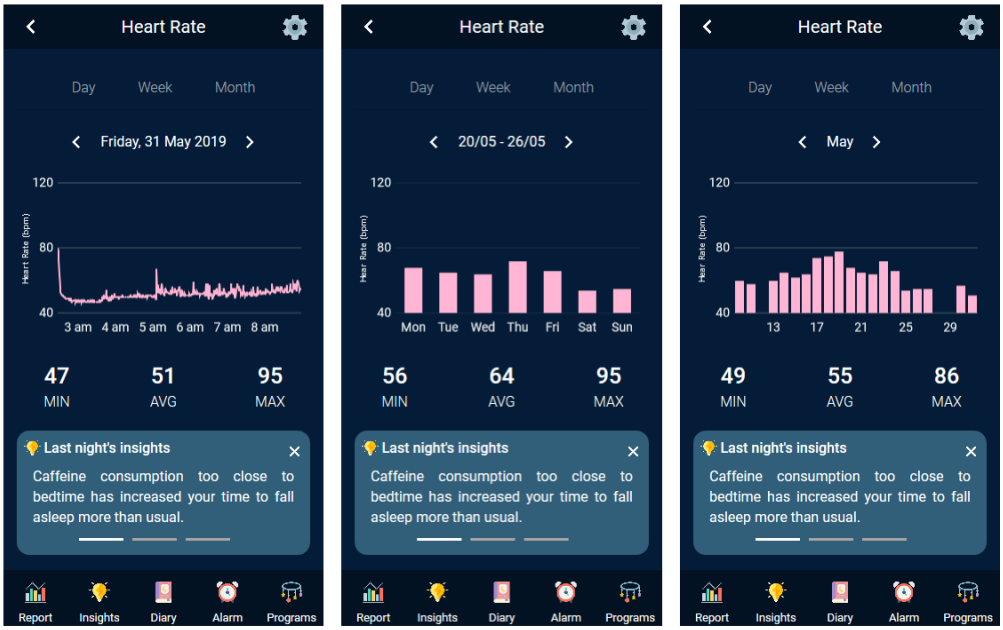


Figure 26: Heart Rate. (a) Daily view (b) Weekly view (c) Monthly view

Breathing Rate

Additionally, the sleep report page includes details about the breathing rate during the night. When users click on the breathing rate parameter, they are navigated to a dedicated page where they can inspect a spline chart which represents last night's breathing rate activity. Furthermore, it shows the minimum, the maximum and the average value of breathing during the previous night (Figure 27a). Moreover, it contains a weekly (Figure 27b) and a monthly (Figure 27c) view where there is a bar chart that represents the average weekly and monthly breathing rate activity, as well as the minimum, maximum and average weekly and monthly breathing rate values.

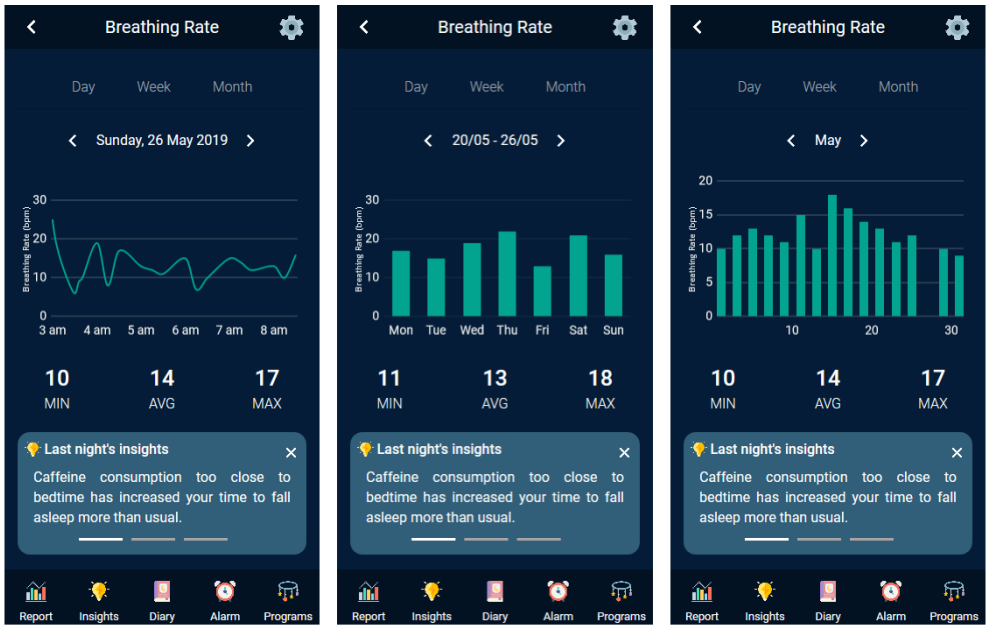


Figure 27: Breathing Rate. (a) Daily view (b) Weekly view (c) Monthly view

5.6.2 Insights

On the Sleep Insights page users are able to view personalized sleep insights on a daily basis. These insights are in the form of recommendations regarding users' daily habits that affect sleep (e.g. "Drinking coffee two hours before bed time might negatively affect your sleep"). On the top of the page there is a date picker where users can select the date that they want to view their sleep insights. Each insight is associated with a specific category (e.g., Caffeine). Users can vote if they like an insight or not. In this way, this kind of insight does not show up again by clicking the buttons that are on the bottom of the sleep insight's modal window (Figure 28).

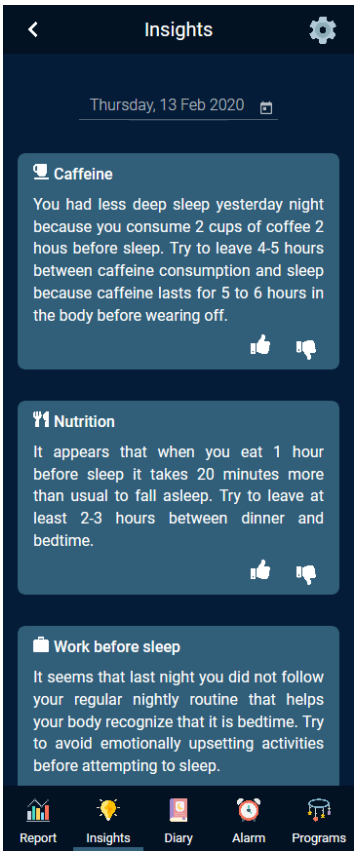


Figure 28: Insights

5.6.3 Diary

On diary page end users are able to view a calendar which shows their diary entries for every day of the current month. The calendar uses three colors to define the different diary entry states. The red color represents that they missed a diary entry, the orange represents that their diary entry was incomplete, and the green represents that they completed successfully the diary. At the bottom of the page, there is a button in order to add a new diary entry (Figure 29).

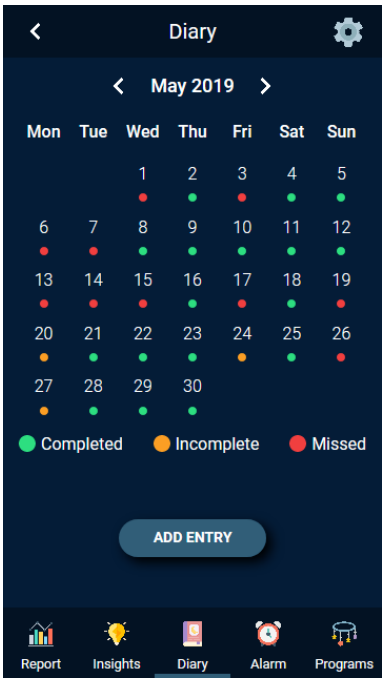


Figure 29: Diary

When they want to add a new entry, they are navigated to a page that consists of two sections: one completed in the morning after waking up (post-sleep morning diary) and one before going to bed (pre-sleep diary). Every day users receive two notification reminders to complete sleep diary: one after wake up and one before go to bed. If users forget one day to fill in the sleep diary, then they can select this day from the date picker that is on the top of the page and to complete it.

Pre-sleep Diary

In the Night Section, users answer questions regarding their habits and feelings during the current day. These questions include subjective ratings for mood and sleepiness feeling, as well as habits during the day such as caffeine and alcohol consumption (Figure 30).

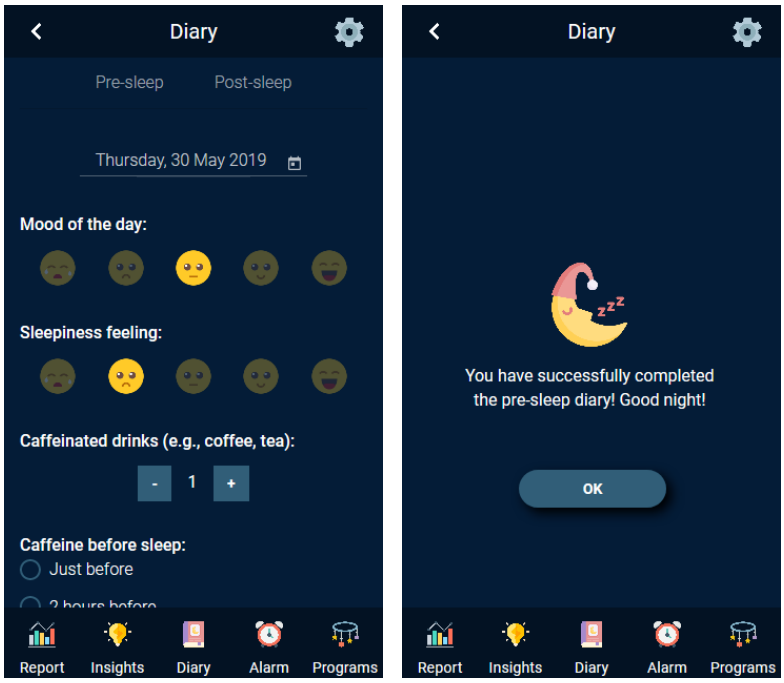


Figure 30: Pre-sleep Diary

Post-sleep Diary

In the Morning Section, users answer questions regarding their personal opinion about previous night's sleep. These questions include subjective ratings for sleep quality, restfulness sense and bedroom conditions (Figure 31).

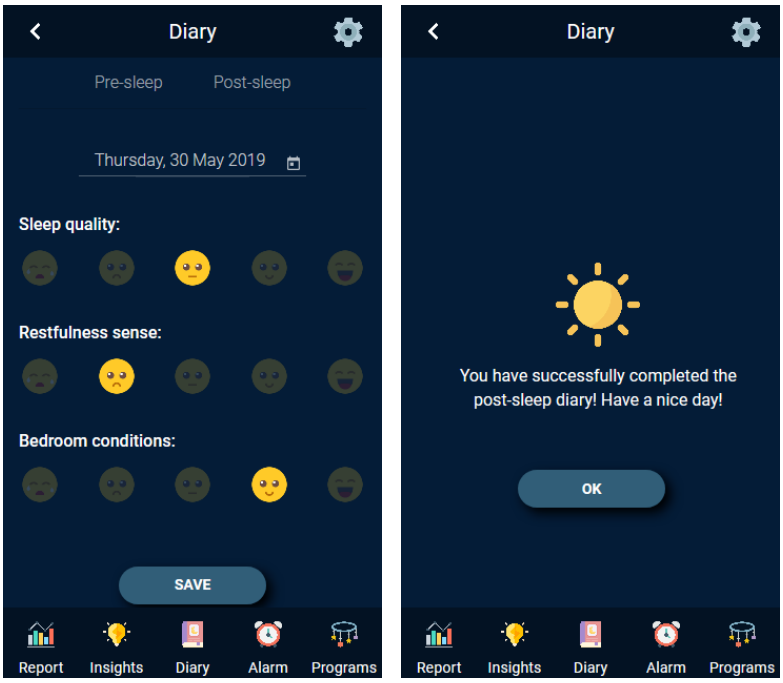
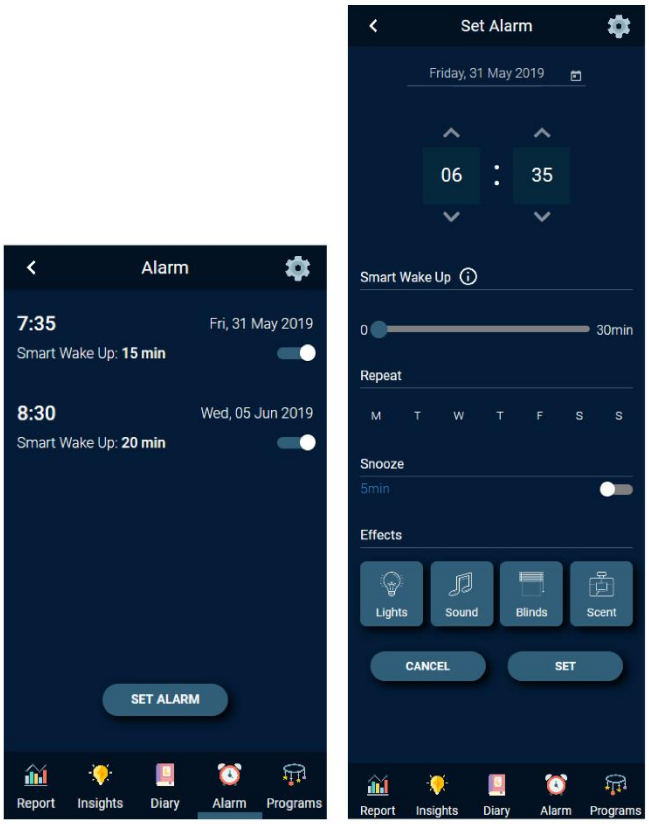


Figure 31: Post-sleep Diary

5.6.4 Alarm

On the Alarm Page end users can view their configured alarms if they have configured one or more (Figure 32a). If they don't have set an alarm, they can set one for the next morning according to their preferences by clicking the button that is placed at the bottom of the page.



(a) (b)

Figure 32: Alarm. (a) List (b) Settings

In more details, users are able to select the date and time for the alarm. In addition, they can also use the smart wake up option – a timeframe in which the best possible moment to wake them up is detected based on when they are in their lightest stage of sleep. Next, they can select the days that they want their alarm to repeat and they can enable snooze option. Moreover, they are able to adjust a variety of environmental factors (e.g. lights, sound, blinds, aroma scent) in order to facilitate their wake up process (Figure 32b).

5.6.5 Programs

On the Programs page, end users are able to select relaxation programs for sleep. In order to make the selection easier, for each program, the title and number of sessions

that are available are presented. The implemented programs are: Sound Relaxation, Breathing Relaxation and Guided Imagery (Figure 33).

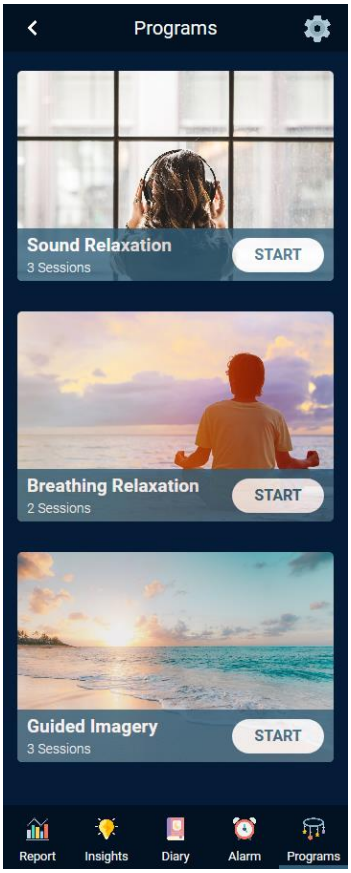


Figure 33: Programs

When users select one of these programs, a list of the available sessions for that program appears. For each session, the following information is displayed: title, duration, and if it is added to user's favorites. Users can choose to initiate any desired session from that list (Figure 34).

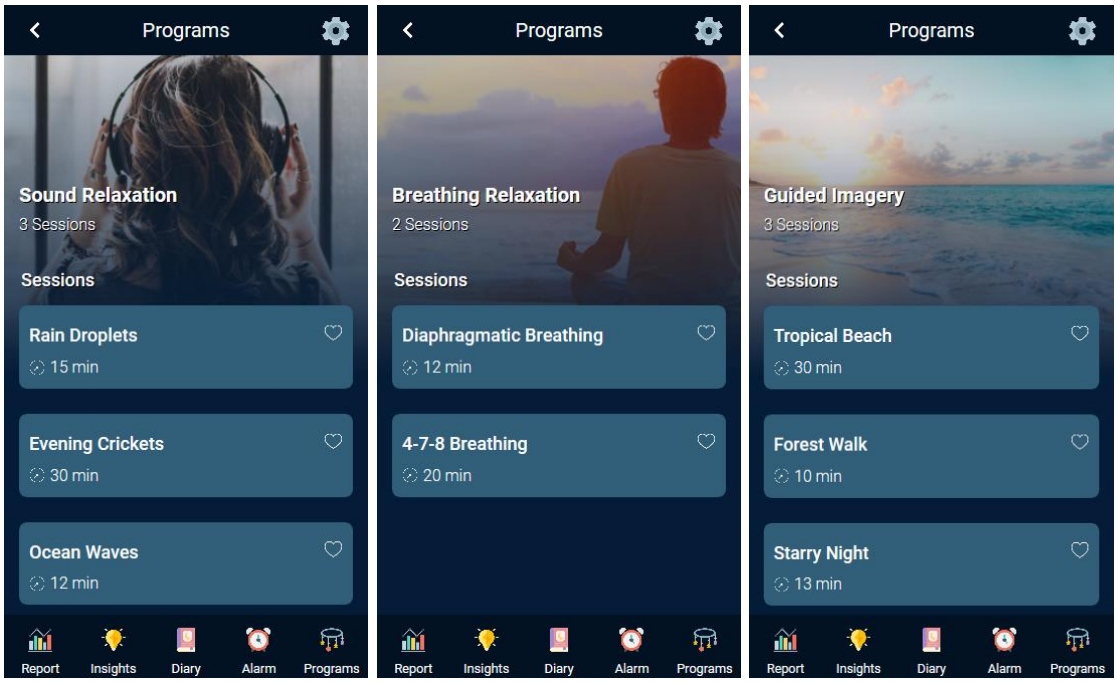


Figure 34: Available sessions for each program

The page of the selected session consists of audio content, a quick settings bar and a list of similar sessions that are in the same program (Figure 35). The audio content (e.g. rain droplets sound) is responsible for the promotion of users' relaxation. From the quick settings bar, users are able to stop the session at any time and to activate or deactivate the ambient light, sound, scent, and images displaying.

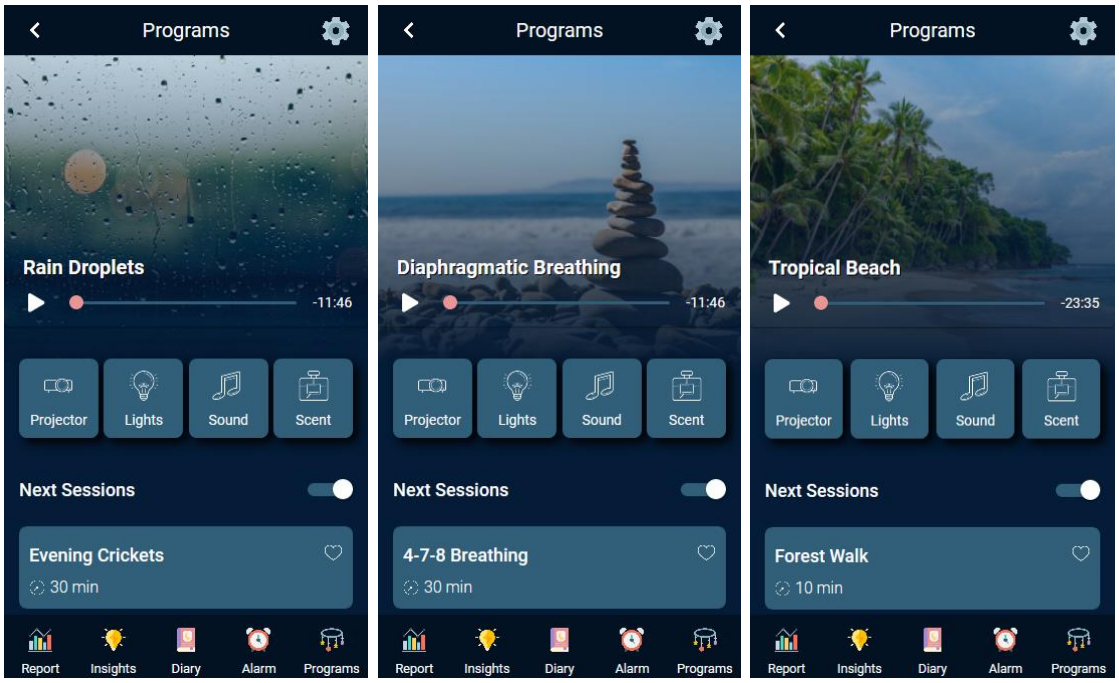


Figure 35: Snippets of sessions

5.6.6 Settings

In the settings page, users are able to access their profile and notification settings, and log out of their account (Figure 36).

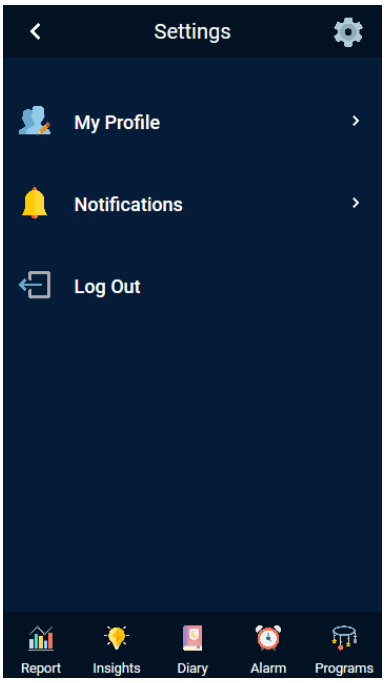
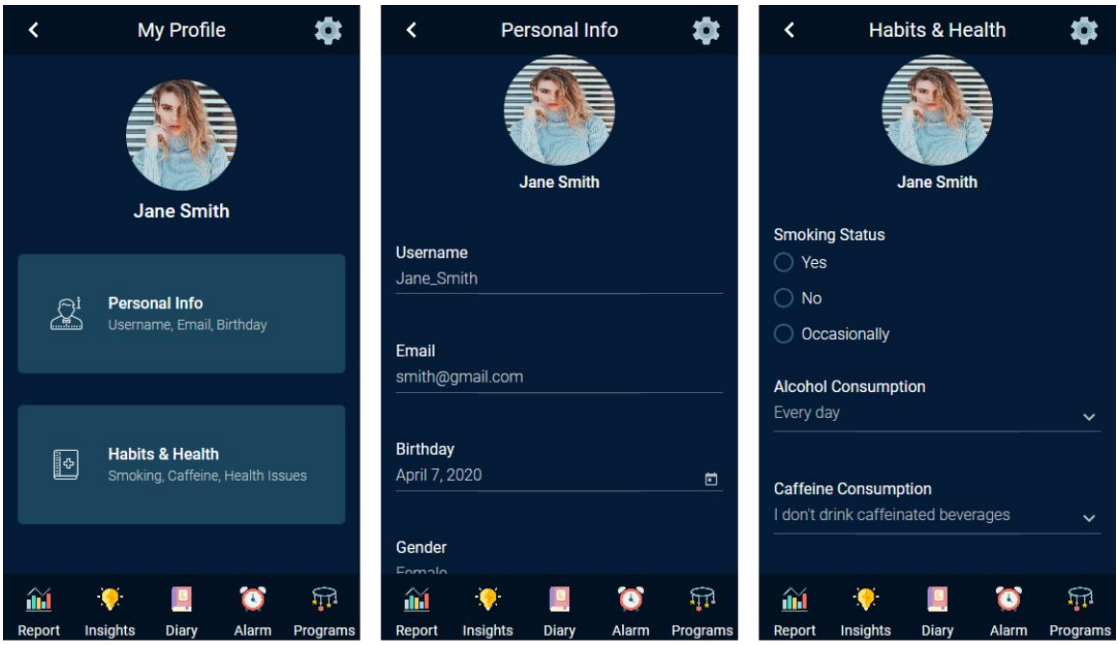


Figure 36: Settings

My profile

In the My Profile page, users can view or edit their profile information (Figure 37a). In more details, My Profile consists of personal information (e.g., username, sex, age, and birthday) (Figure 37b), habits' information (e.g., smoking status, alcohol consumption) and health information (e.g., possible health issues) (Figure 37c).



(a) (b) (c)

Figure 37: (a) My Profile (b) Personal Info (c) Habits & Health

Notifications

Notification settings allow users to turn on or off different types of notifications inside the application (e.g., sleep insights' notifications) and to enable ore disable quiet hours for each type of notification (Figure 38).

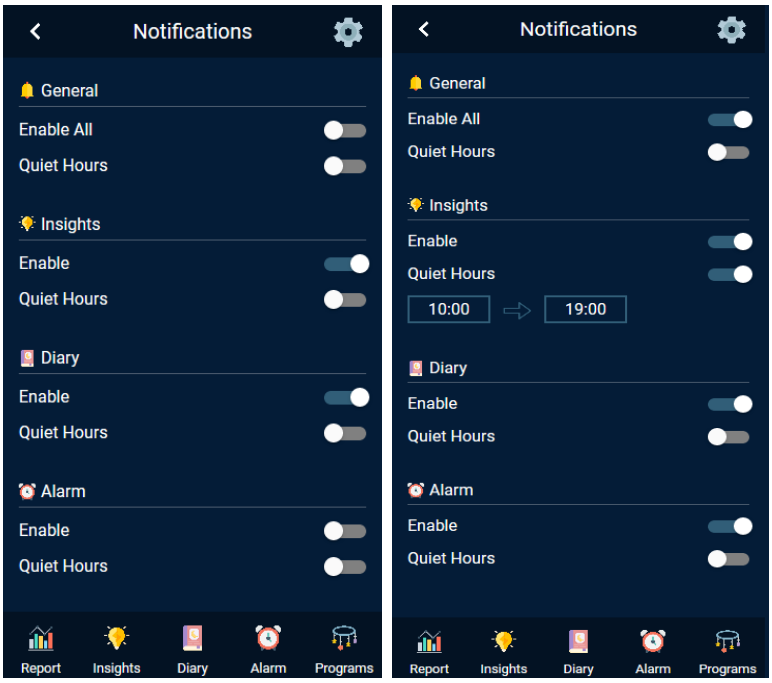


Figure 38: Notification Settings

Chapter 6

Evaluation

For the evaluation of the HypnOS system two methods were adopted: a heuristic evaluation on prototypes and a user-based evaluation on the implemented system. Both processes were coordinated by the Human-Computer Interaction Laboratory (HCI) of the Institute of Computer Science of the Foundation for Research and Technology – Hellas (ICS-FORTH).

6.1 Heuristic Evaluation on Prototypes

Before proceeding with testing HypnOS with actual users, an iterative heuristic evaluation experiment was necessary, in order to avoid any major usability errors. In general, a heuristic evaluation process includes the examination of the system's User Interface (UI) by a number of expert evaluators [161]. The HypnOS UI was examined by five (5) experts, who also judged its compliance with certain recognized usability principles [162]. The objective of this process was to investigate usability issues of the HypnOS UI such as interaction and comprehensibility problems.

6.1.1 Process

In order to efficiently conduct this experiment, a set of actual use case scenarios containing a number of tasks were created, which were given to five (5) expert evaluators. The main objective of the process is to extract identified findings by different experts and merge them into a list of usability issues. The evaluation experiment that was conducted was divided into five stages: (i) preparation, (ii) introduction, (iii) actual experiment, (iv) usability issue extraction and rating and (v) usability issue ease-of-fix rating.

As for the preparation stage, use case scenarios and tasks were created to lead users into interacting with the biggest part of HypnOS. These scenarios were written in an electronic format and given to the users one by one in a presentation-like format.

After the preparation stage was completed, the users were invited, one by one in separate sessions, and were introduced to the purpose of the experiment, as explained in the previous section, followed by a brief introduction to the system and its functionalities.

During the actual experiment, the scenarios were displayed so users could turn to read them again at their disposal. Since that was a heuristic-interaction evaluation experiment with experts in this domain, there was no need to offer hints or help and the session time was not restricted. However, all users were prompted to speak aloud during each session, since their comments constituted a basis for identifying more easily the usability issues of the system.

After finishing the session, each expert was asked to extract system's usability issues based on certain recognized usability principles. These issues were afterwards merged into one list, which contained all unique findings. Each expert was given a copy of this list to provide a severity rating to each issue, according to their preference. These ratings ranged from zero (0) to four (4), where the first is categorized as "not a usability problem" and the last as a "usability catastrophe". The final severity rating was produced by computing the average from each user rating.

Finally, the identified issues, along with the final severity rating, were forwarded to the development team, which ranked them according to the ease-of-fix scale – zero ("would be extremely easy to fix") to three ("would be difficult to fix")-, in order to designate the amount of effort needed to address them.

6.1.2 Heuristic Evaluation Findings

The experiment on HypnOS revealed forty-six (46) usability issues, which are categorized and sorted based on their severity ratings, as given by the expert evaluators. Table 5 presents the extracted issues, along with their severity and ease-of-fix ratings.

Table 5: Heuristic evaluation findings

Heuristic Comment	**Severity Rating**	**Ease-of-fix Score**
It is not clear that current day on sleep diary calendar is clickable	3	2
Users didn't like dropdown selection for possible health problems on User Profile	3	2
Sleep diary calendar should be more intuitive regarding completed and missed entries	3	2
Sleep insights should be higher on the page	3	2
There should be a prompt for the completion of sleep diary	3	2
Daily view for Time to Sleep should have a comparison with user's average Time to Sleep value	3	2
Date indication should appear on adding new diary entry	3	2
Alarm options should be better emphasized. For example, it is not clear whether days on the repeat option are clicked or not	2	2
Adding new entry to the diary seemed overwhelming for some users (e.g., contains a lot of text)	2	2
Sleep insights should be presented in a page dedicated to them (available through an extra menu item or a notification-like popup)	2	2

Sleep insights modal should be more interactive (e.g. prompt to schedule coffee time earlier)	2	2
Sleep Score information from monthly sleep report is missing	2	2
Terminology needs revision. For example, title for Programs doesn't describe exactly what kind of programs they refers to	2	2
Sleep stages should have a short description on click	2	2
Weekly view for Time to Sleep should have color indications below the bar chart to identify what the color means	2	2
Heart rate zones bar should have percentages on daily view	2	2
Icons on diagrams should have bigger size	2	2
Pink color on sleep watch should have higher contrast	2	2
Users didn't understand that sleep score and duration values represent average values on weekly and monthly sleep report	2	2
Average values should be presented at all diagrams	2	2
There should be an indication of the number of sleep diary questions at the top of the Sleep Diary page	2	2

Monthly view for Time to Sleep should be a bar chart diagram for better representation	2	2
Font size should be bigger in sleep insights modal window	2	2
Reports should offer more information (e.g., axis titles, measurement units, short descriptions)	2	2
More appropriate emoticons should be selected as an answer for the sleep diary question regarding restfulness	2	2
Sleep Score label under weekly and monthly sleep report is missing	2	1
Diagrams should have axis titles and labels	2	1
It is not clear which components are interactive (e.g., current day on calendar, programs)	2	1
The functionality of the customize button is not clear	2	1
It is not clear what is the use of the Light Effects option at Set Alarm clock page	2	1
More options for the Alarm should be provided (e.g., open the curtains when I wake up)	2	1
Selected alarm time should be more emphasized (e.g., bigger font size, bold fonts)	2	1
Sleep stages should be more emphasized (e.g., color indications, highlights, shape, color contrast)	2	1

Unit measurement in Heart Rate diagrams is missing	2	1
There are general interface inconsistencies (e.g., buttons size, tab menu position)	2	1
It is not clear that the offered Programs are interactive and offer more actions	2	1
More options for Programs should be provided (e.g., play button, add to favorites)	2	1
Sleep report should also have a yearly view	2	1
Title for Programs should be more explanatory	2	1
Users didn't like answering diary questions with sliders. For example, use selection box options or dropdown menu instead	2	1
Selected menu items should be indicated more distinctively	2	1
Daily view bar for Time to Sleep should have minimum and maximum values	2	1
Emoticons on sleep diary answers should be less transparent and use borders for the selected ones	1	1
Answering diary questions with emoticons may be confusing	1	0
It is not strongly indicated that the Alarm is on	1	0
Too big images for the offered Programs	1	0

The final severity score for each usability issue was obtained by combining and averaging individual scores provided by each expert. The final score ranges between one (1) and three (3). In more detail, four (4) issues were ranked as aesthetic cosmetic problems, thirty-five (35) as minor usability problems, and the remaining seven (7) were ranked as major issues. Most of them concerned general interface inconsistencies (e.g. variations in button sizes) and aesthetics (e.g. colors). Additionally, it was identified that some components did not communicate their functionality to the user (e.g., the current day on sleep diary calendar did not appear as clickable), while others missed easy access to functionality (e.g. play button for the available sleep programs). Finally, the most important finding was that users expected to find the Insights into a dedicated page. According to the development team most of them will require minimum to none effort to fix.

6.2 User-Based Evaluation of HypnOS mobile application

After completing the heuristic evaluation experiment of HypnOS's mobile application prototypes and resolving the issues identified, the system was implemented and a user-based usability experiment was conducted. User-based methods involve real users that attempt realistic activities in order to gain qualitative insights about how they use the system and what their exact problems are with the concrete interface being tested [163]. The experiment was conducted in the Intelligent Bedroom simulation space of the Intelligent Home in the ICS-FORTH AmI Research Facility, so as to make the users feel that they are indeed inside a bedroom, and that they use the application before and after going to bed.

6.2.1 Research Questions

The main objectives of the user-based evaluation experiment were mainly to identify any unsupported features, to uncover potential usability issues and to evaluate users' overall satisfaction before planning a large-scale experiment. In particular, the following research questions were addressed:

- **Research Question 1:** Is the HypnOS mobile application usable?

- **Research Question 2:** Is the HypnOS mobile application perceived as useful?
- **Research Question 3:** Can users get sleep recommendations and see the statistics of their sleep easily and effortlessly?
- **Research Question 4:** Are users willing to complete the pre- and post- sleep diaries?
- **Research Question 5:** Do users find the overall HypnOS system useful and promising?

6.2.2 Participants

A total of eight (8) users participated in the experiment, who were representative of the intended users of the system. The intended users of the system will be adults that belong to any age category. This number of users is appropriate for preliminary evaluations, as it can identify important usability problems and eliminate them before proceeding to large scale experiments [163].

The selected users meet different characteristics (e.g., age, gender, experience with sleep trackers or sleep monitoring applications). In particular, from the total of 8 users, the 75% were females, and the 25% were males (Figure 39). Moreover, users were selected in order to include an as wide as possible range of ages because according to many studies [33], [164], [165] sleep patterns change across the lifespan in various ways, including decreases in quantity and quality of sleep. To that end, participants were stratified into three subgroups (18-34, 35-49 and 50-64 years old) based on their age. In more details, half of the users (50%) were from 35 to 49 years old, the 37% were from 18 to 34 years old, while the 13% were from 50 to 64 years old (Figure 40).

None of the participants had experience with sleep monitoring applications or wearable sleep trackers, while the majority of them didn't experience sleep difficulties or sleep complaints. In this experiment there were no specific prerequisites for user participation. However, for future evaluation experiments, we intend to include users who experience sleep difficulties so as to record their comments and opinion as well.

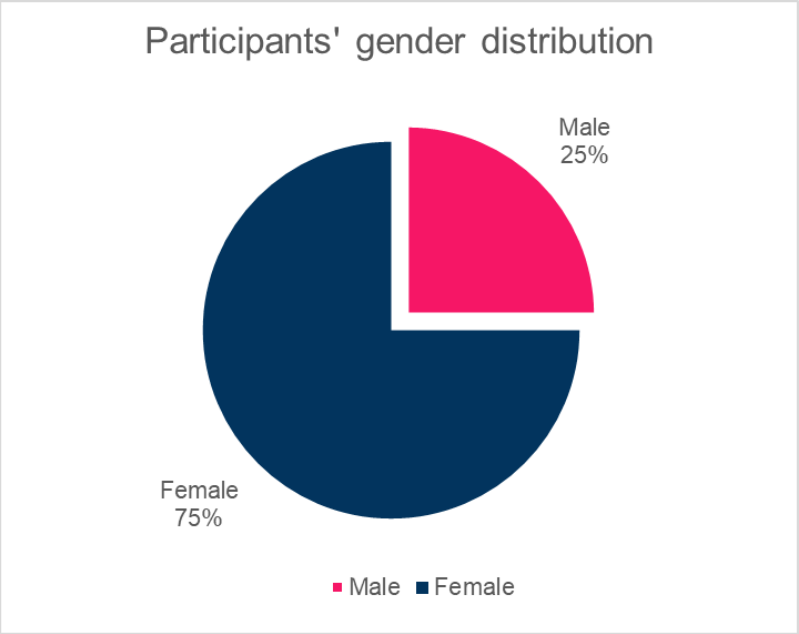


Figure 39: Evaluation participants' gender distribution

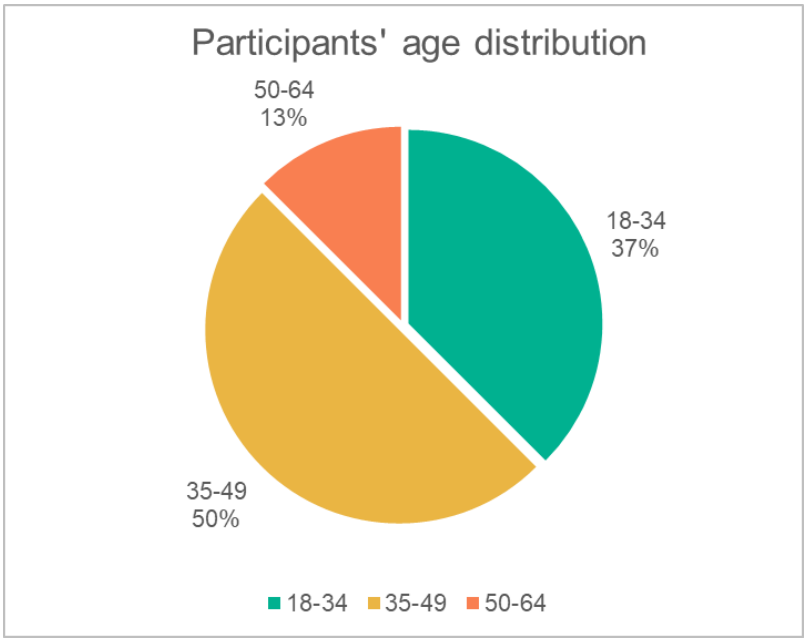


Figure 40: Evaluation participants' age distribution

6.2.3 Data Collection

In order to explore the aforementioned research questions, a pre-evaluation questionnaire, an observation grid and two post-evaluation questionnaires have been used.

Pre-evaluation Questionnaire

A pre-evaluation questionnaire has been used in order to collect participants' demographics and other user-related information and these were:

- The age of the participants
- The gender of the participants
- Sleep difficulties of the participants
- Experience with activity/fitness trackers
- Experience with sleep monitoring applications
- Experience with wearable sleep trackers
- Experience with relaxation applications for sleep
- Experience with other well-being applications in general

Observation Grid

A custom observation grid was used to collect qualitative and quantitative information:

- The overall duration of the running test
- The comments of users' during the test
- The number of users' errors during each task
- The time it took to users to complete each task
- The number of users' given helps during each task

Post-evaluation Questionnaires

Regarding the post-evaluation questionnaires, we employed two (2) different ones for the experiment, aiming to reveal the usability of the mobile application, as well as the overall user satisfaction. The first one was System Usability Scale (SUS) [166] -a subjective satisfaction questionnaire which included 10 questions, with five response options for respondents; from strongly agree to strongly disagree. The second one, was a custom questionnaire, which included 13 questions about users' overall impression regarding HypnOS and its mobile application.

6.2.4 Procedure

The usability evaluation experiment was divided into four stages: (i) preparation, (ii) introduction, (iii) running the test and (iv) debriefing [163]. In order to make participants feel comfortable and ensure that the experiment progressed as planned, a facilitator was responsible for orchestrating the entire process and assisting the users when required. In addition, an observer was responsible for recording information in the observation grid, while a member from the experimental team was outside the Intelligent Bedroom, in order to manage any possible technical difficulties.

Preparation

In the preparation stage, the facilitator made all the appropriate actions before the arrival of the participants in order to make sure that the experiment could be conducted. In particular, he tested the room to be ready for the experiment, and set the mobile device in the start state and ready for use. Moreover, he checked that all the materials required for the experiment (i.e., pre- and post- evaluation questionnaires, observation grid, scenarios and devices) are available and he switched off anything that could disrupt the experiment process.

Introduction

During the introduction stage, the facilitator welcomed the test participants, gave a brief explanation of the purpose of the experiment, and highlighted the importance of their participation. Next, the concept of the Intelligent Bedroom was described, followed by a short introduction to HypnOS and its mobile application. After that, participants were reassured that during the experiment they wouldn't wear any trackers and none of their biometrics would be recorded. Additionally, the facilitator clarified that their personal data would be anonymized, as described in the Informed Consent Form. After going through the Informed Consent form, they were asked to sign it prior to their participation in the experiment. Afterwards, the facilitator led the participants inside the Intelligent Bedroom and asked them to sit on the bed comfortably. Next, a demonstration of the bedroom's ambient facilities followed, while the participants had the ability to see the trackers employed by HypnOS. Finally, the facilitator told them that they could stop the experiment whenever they wanted and he encouraged them to follow the Think-Aloud protocol [167]. According to this

protocol, participants were asked to verbalize their thoughts as they moved through the User Interface so to give us valuable feedback regarding the difficulties that face during the execution of the tasks as well as their overall impression of the mobile application.

Running the test

After the introduction, participants interacted with the HypnOS mobile application by following the available scenario tasks. The scenario included six (6) tasks, which were given one by one to the participants in a presentation-like format, so they could turn to read them again as many times as needed. The scenario containing these tasks is available in APPENDIX B. During the test itself, the facilitator refrained from interacting with the participants and he didn't express any personal opinion when they were doing well or poorly. The only exception to this rule was made when participants were clearly stuck and were unhappy with the situation.

Debriefing

After the test was completed, the facilitator thanked the users for their participation in the experiment and offered them some treats. Next, the facilitator asked participants to fill in SUS before any other discussion regarding the system. Once all tasks were completed and the questionnaires were filled-in, participants were debriefed according to a set of questions (APPENDIX C) by the facilitator, who asked them about their overall impression and any other thoughts or suggestions that they had for improvement. After the user had left, the facilitator checked that all the results had been labeled with the test users' numbers, including questionnaires and forms as well as his own notes. Finally, the facilitator wrote a brief report while the events were still fresh in mind.

6.2.5 Results

In this section, the results of the user-based evaluation are presented in relation to the research questions have been posed previously.

Research Question 1 - Is the HypnOS mobile application usable?

"Usability is a quality attribute that assesses how easy user interfaces are to use" [168]. Usability is generally measured using a number of observable and quantifiable metrics. Task successfulness, number of help requests and number of user errors were used as indicators of usability when using the HypnOS mobile application. In particular, to indicate if the participants completed the tasks successfully or not, a binary variable (pass/fail) was employed. In more details, all the participants completed successfully the six tasks of the given use case scenario. Some minor errors where performed in some cases, which the users were able to overcome either by themselves or by acquiring hints from the facilitator.

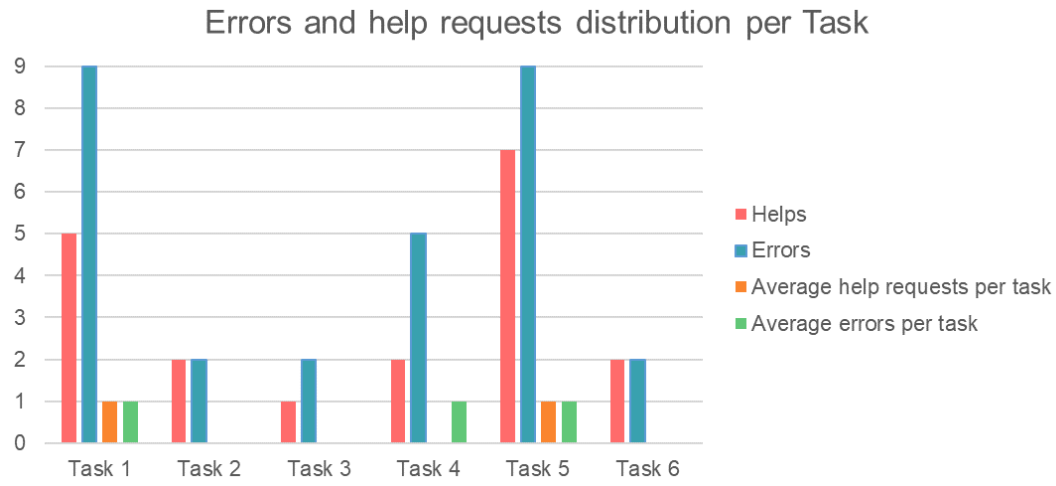


Figure 41: Errors and help requests distribution per Task

As illustrated in Figure 41 above, the majority of the tasks has only a small number of errors (on average zero or one error per task). The only tasks that exhibited an increased error rate were Tasks 1 and 5. In Task 1, users were asked to set an alarm for the next morning using smart wake up features, but it was observed that most of them tried to set an alarm from the diary page, which was not supported. This error can be partially justified by the wording of the scenario task; the task asked the users to set an alarm clock for the 30th of the month, however, at the same time the application was at the calendar view making the users think that they should click on the required date (30th).

In Task 5, where the participants were asked to view specific statistics from the daily sleep report, it was observed that the users had trouble finding some of them, especially the weekly snoring episodes. Similarly, this error can be justified, since the specific scenario task had two parts, one asking to check the weekly snoring activity and another to check the snoring episodes for Tuesday the 26th. In this case, users correctly found the snoring activity, but since the default view was the daily view, they tried to navigate to Tuesday by the existing previous and next day controls. So they managed to complete the second part of the scenario task, but forgot the first one, which required the facilitator to provide a hint.

Moreover, regarding help that participants required during the experiment, all the participants were offered at least one help for every task in the given scenario (Figure 41). It is therefore evident that for the majority of the tasks, only a small number of helps were needed (on average zero or one help request per task). The only tasks that exhibited an increased request for help are Tasks 1 and 5, for the reasons already mentioned above.

Furthermore, the SUS questionnaire has been used in order to measure the perceived usability. Generally, participants' responses were overall very positive. Figure 42 illustrates the SUS score individually (per user), as well as the overall SUS score for the HypnOS mobile application. The overall SUS score was 90.63, which is much higher than the average SUS score (68); a SUS score above a 68 would be considered above average and anything below 68 is below average. The SUS score and SUS average score are illustrated as two horizontal lines in the chart.

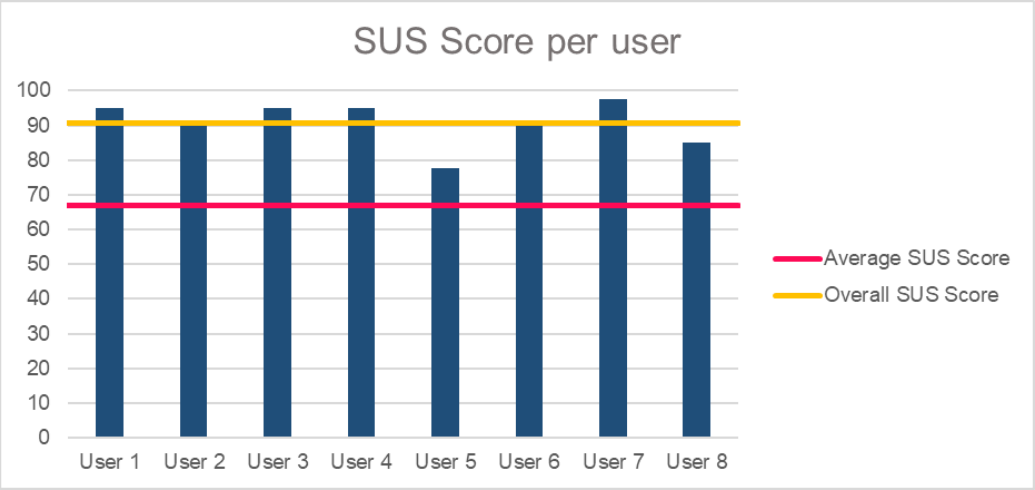


Figure 42: SUS score per user

Moreover, according to the curved grading scale for SUS [169] (Figure 43), the HypnOS mobile application received overall an A^{+} score. Further investigation of the individual SUS scores reveals that 87.5% of the users rated it with an A+ (ranging from 84.1 to 100) while the remaining 12.5% rated it with a B (ranging from 74.1 to 77.1).

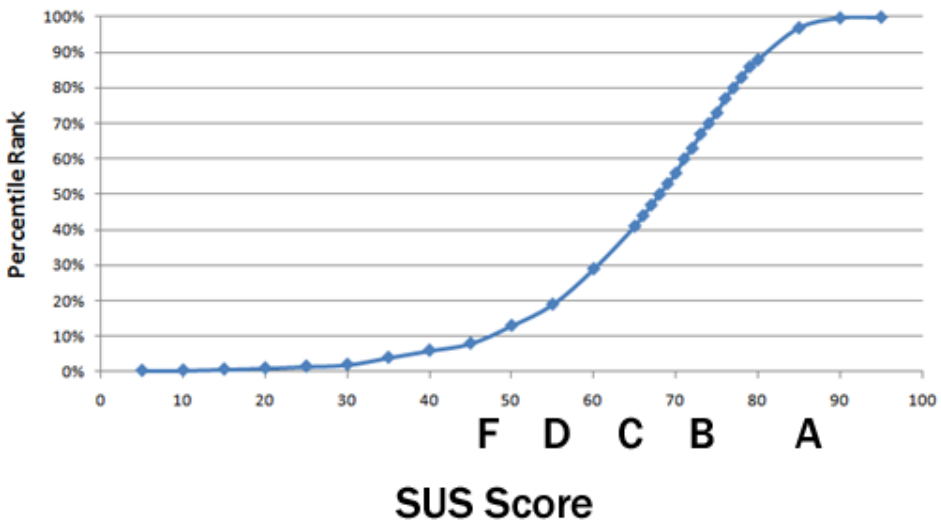


Figure 43: Curved grading scale for SUS [170]

To sum up, besides the minor errors and help requests, it can be concluded that users found the HypnOS mobile application to be really usable. At the same time, since no significant individual differences were observed in the in SUS scores, it can be concluded that users were really satisfied with HypnOS mobile application, giving it a very high average score (90.63), while almost all the users rated it with an A+ score.

Research Question 2 – Is the HypnOS mobile application perceived as useful?

Usefulness can be defined as “the degree to which a product enables a user to achieve his or her goals, and is an assessment of the user's willingness to use the product at all" [171]. In the current study, user comments and responses in the debriefing questionnaire were used as indicators of usefulness.

In general, user comments about the overall impression of the HypnOS mobile application were very positive. In more details, all the participants found that the application was very friendly, easy to use and simple enough (“Found the UI of the application very user-friendly!”, “I believe that the mobile application is clear and practical especially in relation with a computer application!”). In addition, participants reported that the HypnOS mobile application will be really helpful in cases where someone has sleep difficulties or complaints about sleep (“Found the application very interesting and helpful, especially for those who have sleep issues!”).

Additionally, participants’ reactions about the smart alarm and sleep programs functionality were positive (“Found the Programs very useful and especially their ability to adjust bedroom conditions!” “I like Programs and mostly the wall projecting feature!”, “I found smart alarm feature very interesting and useful!”). Finally, participants emphasized the HypnOS mobile application’s potential for viewing sleep statistics and getting personalized sleep recommendations (“I would use the mobile application to view my sleep statistics on a daily basis!”, “I like the concept of getting sleep insights!”, “I would definitely use the mobile application to get personalized sleep recommendations!”).

To conclude, the overall impression about the usefulness of the mobile application, was positive regarding its potential to assist those that may have sleep difficulties and to provide sleep statistics and personalized sleep recommendations.

Research Question 3 - Can users get sleep recommendations and see the statistics of their sleep easily and effortlessly?

The experiment that was conducted explored if users could successfully view sleep insights and statistics with the minimum possible effort. In order to examine this, Tasks 5 and 6 were created. Task 5 asked the participants to check specific sleep statistics (i.e. sleep score, time to fall asleep, weekly snoring activity) from the daily sleep report, while Task 6 asked them to explore the factors that affected their sleep quality and to get some useful tips to improve it.

As for Task 5, all the participants managed to check the sleep score and time to fall asleep values. However, as for checking the weekly snoring episodes, many participants didn't notice at first glance the daily/weekly/monthly tabs on the top of the snoring activity page. As a result, they tried to find the weekly snoring episodes from the chart that shows that daily snoring episodes. This behavior can be justified, since the specific scenario task had two parts, one asking to check the weekly snoring activity and another to check the snoring episodes for Tuesday the 26th. In this case, users correctly found the snoring activity, but since the default view was the daily view, they tried to navigate to Tuesday by the existing previous and next day controls. So they managed to complete the second part of the scenario task, but forgot the first one, which required the facilitator to provide a hint.

In addition, it was observed that in the weekly snoring activity page, some users found the weekly snoring episodes directly from the chart, while others used the chart tooltip to view them. Moreover, a small number of participants tried to view sleep statistics from the sleep diary page instead of the sleep report page. To that end, it is concluded that for the most part, participants view their sleep statistics easily and without special effort.

Regarding getting sleep recommendations, it was observed that all the participants managed successfully to explore the causes that affects sleep quality and to get tips to overcome it. However, they also provided interesting suggestions in order to improve the interaction with this page and the overall aesthetics. In more detail, some participants reported that presenting a large block of text does not help the user find the information he wants quickly. So, it was suggested that tips should be presented separately from the cause of the sleep-related issues, and that important information

should be emphasized (e.g., use icons for every cause, bold text for the given tip, bigger gaps between causes and tip). Moreover, it was reported that the calendar-style date picker for the selection of the insight's date should be simpler and clearer. In fact, some users suggested to use left and right arrows in order to navigate to a specific date instead of using a calendar-style date picker.

Observations of the users during these tasks, as well as the comments users made during the think-aloud process, revealed that participants could easily get sleep recommendations and view sleep statistics, despite the fact that some of them made a few minor errors, which can be justified to some extent. At the same time, the overall impression was positive regarding the concept of the HypnOS mobile application to provide sleep statistics and personalized sleep insights.

Research Question 4 - Are users willing to complete the pre- and post- sleep diaries?

In order to answer this research question, during the Post-Evaluation session we asked users to express their personal opinion regarding their willingness to complete pre-sleep and post-sleep diaries.

It is worth noting that all participants liked the concept of HypnOS sleep diaries and specifically the ability of HypnOS to collect information about users' daily routine and habits, provided that their personal data will be secured. In fact, the 50% of the participants said that they would be willing to complete pre- and post-sleep diaries on a daily basis, especially if some fields were pre-selected. However, another 25% of participants reported that they would be bored to complete pre-sleep and post-sleep diaries on a daily basis, while the remaining 25% stated that they would complete them sometimes and not on a daily basis (Figure 44).

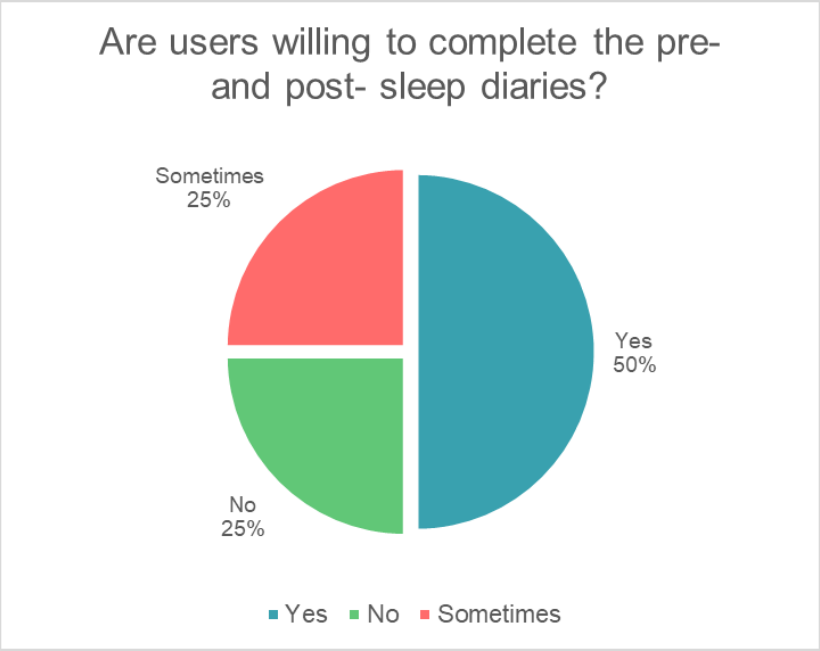


Figure 44: Evaluation participants' willingness to complete sleep diaries

In conclusion, it is very encouraging that a great number of the participants showed their willingness to complete sleep diaries.

Research Question 5 - Do users find the overall HypnOS system useful and promising?

User comments about the overall impression of the system were positive, emphasizing its potential for helping those who face sleep difficulties ("Found the concept of the system very interesting and helpful, especially for those that have sleep complaints!", "I like the concept - overall it is a very nice system!").

Moreover, there were positive impressions about HypnOS' ability to adjust the environment in order to create appropriate sleep-wake up conditions ("I would like this system to my bedroom!", "I like bedroom conditions created by HypnOS!", "Wall projector functionality is impressive! "Found smart wake up feature very useful!").

Furthermore, participants' responses provided valuable feedback about HypnOS' ability to provide a detailed sleep report and personalized sleep recommendations. In more details, participants emphasized that they would like to use the system mostly to view their sleep analytics ("I would use the system to view my sleep statistics on a

daily basis! “I like the concept of HypnOS to provide detailed sleep statistics!”). In addition, there were several positive responses regarding HypnOS’ ability to offer sleep insights that are personalized for each user. In particular, most of the participants reported that they would like to use the HypnOS system to get sleep tips that are personalized to them (“I would use the system to get sleep recommendations, especially if they would help me to make my sleep better!”, “I like the concept of the sleep insights, I find them very useful!”)

In brief, it can be concluded that the users found really useful the concept of the HypnOS system. At the same time, the overall impression was positive regarding the concept of a system that provides detailed sleep statistics and personalized sleep insights in order to help not only those that have sleep difficulties but also normal sleepers.

6.2.6 Discussion

The HypnOS mobile application was evaluated with 8 participants in the context of a preliminary user testing, aimed at identifying usability problems prior to a large-scale evaluation experiment. Moreover, a number of research questions were explored regarding usability, usefulness, user satisfaction with the mobile application as well as the overall usefulness about the HypnOS’ concept. The results were overall very positive, revealing that users – even first-time ones – can effectively use the application. Users were in their majority very satisfied with the mobile application as a means to view their sleep statistics and to get personalized sleep recommendations. Also, it was verified that users showed at the most part their willingness to complete post- and pre-sleep diaries.

It should be noticed that there were some limitations regarding this user experiment. In particular, we would probably receive different user feedback, if participants had sleep issues. In addition, the experiment conducted with simulated data, so the insights delivered to the users were not personalized to their measurements and daily habits. To this end, it is not certain that we have witnessed authentic reactions to them. However, we received useful feedback by observing the users and analyzing the evaluation findings, and we are able to provide a better and an improved version of the mobile application.

During this study we draw several useful insights:

- Users' impression of the Intelligent Bedroom was very positive. In particular, they were very enthusiastic about the sleep and wake up conditions that HypnOS is able to create (e.g. before sleep, bedroom's lights simulated the sunset colors). For example, a user stated "*I would like this system to my bedroom!*", while another one said "*The projected images on the wall next to the bed result in an impressive surrounding!*").
- Users found the concept of HypnOS very useful and helpful not only for those who have sleep issues, but also for those who do not face any sleep difficulties which gives us valuable hints about the potential users of the system. For example, a user stated *"Found the concept of the system helpful, especially for those who have sleep complaints!",* while another said *"I like the concept – I would use it to track my sleep even I didn't have sleep difficulties".*
- Users did not seem skeptical regarding HypnOS' ability to collect information about their daily routine and habits. On the contrary, the majority of them stated that it is a useful process, provided that their personal data will be safe ("I don't have problem that system has access to my personal data, provided that they are secured!").
- Most of the users are willing to enter data manually, if that means that the system will get useful information that result in personalized sleep insights ("I am willing to complete pre- and post-sleep diaries, especially if this gives valuable input to the system!"). A few users said they would complete sleep diaries sometimes but not on a daily basis which is also helpful for HypnOS. Only 2 users said that they would be bored to complete it.
- Users would be willing to wear / use all the sleep trackers (e.g., wearable activity tracker/watch, under-the-mattress sleep tracker) except from the EEG headband because they found it very obtrusive and irritating ("I would definitely use the under-the-mattress sleep tracker because it is very unobtrusive!", "I wear watch in my sleep anyway, so wearable activity tracker/watch wouldn't bother me!", "I wouldn't wear the EEG device on my head because I couldn't sleep!"). However, we feel that if users have real sleep issues, they won't have serious objections in wearing it in their sleep. For example, users that have

obstructive sleep apnea and wearing a CPAP device in their sleep may be more willing to use it than others that don’t have sleep issues.

6.2.7 Compliance with ethical standards

During the evaluation period, only the absolutely necessary data was collected and processed through a “pseudonymization” process, while participants' identities will remain confidential and not be revealed. More specifically, the following data was recorded:

- Personal data (e.g., age, gender, experience with similar systems)
- Experimenter’s comments and quantifiable usability measurements while users interact with the system (e.g., errors, help requests, observations).
- Comments and reactions during the experiment.
- Questionnaire and interview responses (not videotaped) after the experiment.

In the context of the evaluation process, the European Union (EU) regulation on General Data Protection (GTPR; 2016/679) has been properly taken into account and approval has been obtained from the FORTH Ethics Committee. In addition, participants were given information about the nature of the evaluation and all aspects of participation, and a consent form was signed, which has been prepared in collaboration with the Data Protection Officer (DPO) of FORTH.

Chapter 7

Conclusions & Future Work

Since good sleep quality is critical for good health and overall quality of life, it would be beneficial to have at our disposal a 24/7 sleep monitoring system that offers sleep hygiene recommendations for better sleep. This thesis has proposed a pervasive sleep monitoring and recommendation system for intelligent homes. In order to address the challenges of sleep monitoring, the system combines various sources of information, giving more emphasis to sleep-related parameters, bio-signals and contextual information. As an intervention step, it provides sleep insights that are personalized for each resident. The ultimate goals of the system are to: (i) guide people to change their daily habits that affect sleep in order to improve their sleep quality and (ii) help them to fall asleep effortlessly by activating any of the system's ubiquitous relaxation programs for sleep.

HypnOS is the first proposed sleep monitoring system that uses the minimum possible number of sleep tracker devices in order to monitor, as unobtrusively as possible, the sleep patterns of individuals. An important aspect of HypnOS system is that it relies on the existing intelligent home infrastructure and does not force users to move to an unfamiliar environment (e.g., sleep clinic) in order to monitor their sleep.

Furthermore, HypnOS fuses data from various sleep devices and combines them with contextual information revealing the resident’s daily habits. Such data are available through the ambient services of the “Intelligent Home”. To that end, the system exploits this kind of information to provide sleep recommendations that are personalized for each resident, so as underline the causes of sleep-related issues.

Additionally, based on the evaluation process, HypnOS seems to be a promising sleep monitoring and recommendation system for the Intelligent Homes. The reason is that sleep report and personalized sleep recommendations seemed to be very helpful and satisfying for the users.

When it comes to the discussion of future work, there are some improvements and additions that could be done. Apart from improvements on existing aspects of

HypnOS (e.g., the design of user interfaces, the precision of the sleep score calculation algorithm), future work can include new additions to the system.

Firstly, in the near future, the Intelligent Home of FORTH-ICS should be able to accommodate end-users, who can live in the house for short periods to intensively evaluate in-situ the HypnOS system. To that end, a longitudinal user-based study will be organized to take place, not only to assess the performance and the effectiveness of this approach but also to fully examine the user experience of living in a home with such ambient facilities.

Furthermore, a beneficial addition could be the ability of the system to collaborate with experts. In particular, sleep doctors and sleep experts could have access to sleep data on a 24/7 basis in order to provide better guidance to the users. An expert should be able to monitor users' sleep behaviors and patterns to enrich the existing sleep hygiene recommendations, determine when a relaxation program should be suggested to a specific user and advise users to see a doctor in case there are more complex issues (e.g., repeated breathing disturbances). With this in mind, the system could be further expanded in order to have a medical and health care scope.

Another extension of this work could be the integration of supplementary ambient monitoring services of the Intelligent Home (e.g., health and medication services) in order to gather additional information (e.g., diabetes disorder, sleep prescription or medication intake) about the context of the residents, so as to construct a more detailed sleep profile. Thus, it could be possible to provide residents more personalized and meaningful feedback regarding their sleep habits.

Finally, considering the fast-paced innovations in sleep technology, it could be possible to integrate new sleep technologies that monitor additional parameters (e.g., blood oxygen, muscle tone) during sleep in order to have a more thorough picture of sleep behaviors and patterns.

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APPENDIX A

HypnOS'S Different Data

	Parameters	Sleep Diaries			Sleep Trackers			Home	HypnOS
		PSD	CSD	NSF					
SLEEP-RELATED MEASUREMENTS	Time when user goes to bed initially	✓	✓	✓	×	✓	×	✓	✓
	Time when user leaves the bed definitively	✓	✓	✓	×	✓	×	✓	✓
	Time when sleep starts	✓	✓	×	✓	✓	✓	×	✓
	Time when sleep finishes	×	✓	×	✓	✓	✓	×	✓
	Time taken to fall sleep	✓	✓	✓	✓	✓	✓	×	✓
	Time taken to get up after final wake up	×	×	×	×	✓	✓	✓	✓
	Total awakenings	✓	✓	✓	×	✓	✓	×	✓
	Reason of awakening(s)	✓	×	✓	×	✓	×	✓	✓
	Total arousals	×	×	×	✓	✓	✓	×	✓
	Total time out of bed during the night	×	×	×	×	✓	×	✓	✓
	Total awake duration	✓	✓	✓	✓	✓	✓	×	✓
	Total time in light stage	×	×	×	✓	✓	✓	×	✓
	Total time in deep stage	×	×	×	✓	✓	✓	×	✓
	Total time in REM stage	×	×	×	✓	✓	✓	×	✓
	Total sleep time	✓	✓	✓	✓	✓	✓	×	✓
	Total time in bed	×	×	×	×	✓	×	✓	✓
	Sleep efficiency: Percentage of sleep of the total time in bed	×	×	×	✓	✓	✓	×	✓
	Sleep score: Sleep quality indicator that ranges from 0 to 100	×	×	×	✓	✓	✓	×	✓
	Total snoring time	×	×	×	×	✓	×	×	✓
	Snoring episodes	×	×	×	×	✓	×	×	✓
	Bed positions/toss n' turns	×	×	×	×	✓	✓	×	✓
	Total duration of nap(s)	✓	✓	✓	✓	✓	✓	×	✓
	Nap episodes	✓	✓	×	✓	✓	✓	×	✓
BIO - SIGNALS	Heart rate (min, max, avg)	×	×	×	✓	✓	✓	×	✓
	Breathing rate (min, max, avg)	×	×	×	×	✓	✓	×	✓
	EEG Brainwaves (frequency, amplitude)	×	×	×	×	×	×	×	✓
HABITUAL INFORMATION & SUBJECTIVE MEASUREMENTS	Caffeine consumption (quantity, time of consumption)	✓	✓	✓	×	×	×	×	✓
	Alcohol consumption (quantity, time of consumption)	✓	✓	✓	×	×	×	×	✓
	Nicotine products(quantity, time of usage)	✓	×	×	×	×	×	×	✓
	Exercise (type, intensity, duration)	✓	×	✓	✓	×	×	×	✓
	Medication Intake (name, dose, time of medication)	✓	✓	✓	×	×	×	✓	✓
	Subjective sleep quality	✓	✓	×	×	×	×	×	✓
	Restfulness sense after wake up	✓	✓	✓	×	×	×	×	✓
	Mood during the day	×	×	✓	×	×	×	×	✓
	Sleepiness sense during the day	×	×	✓	×	×	×	×	✓
CONTEXTUAL INFORMATION	Stress level	×	×	×	×	×	×	✓	✓
	Nutrition intake (type/heaviness, time)	✓	×	✓	×	×	×	✓	✓
	Bedroom conditions	×	×	×	×	×	×	✓	✓
	Activities before sleep	×	×	✓	×	×	×	✓	✓

APPENDIX B

User-based Evaluation Scenario

Task 1

Tonight, It's Thursday May 30th 2019. After watching an episode of your favorite TV show, you realize that is almost midnight and you must go to sleep since tomorrow you have a busy schedule. As soon as you lay in bed, you decide to set an alarm for the next morning through the HypnOS application.

- You want to wake up at 7:40 am with smart wake up window to 15 minutes and light and sound effects on wake up

Task 2

Since you just set your alarm for tomorrow morning, you are prompted to fill-in the pre-sleep diary.

- Fill out the pre-sleep diary with that in mind:
    - Today, you had a pretty tiring day. You drank a lot of cups of coffee work until late as you had a deadline for your work. After you finish your work late at night you order food from your favorite restaurant.

Task 3

After submitting the sleep diary, you go to sleep. 30 minutes later, you haven't slept yet, because you are stressed. So, you decide to use the application's features to help you fall asleep. You reminisced about your camping trips during summer, when you slept near the beach and you would like to get the feeling of 'being there' again.

- Start a relaxation program with images (beach-related).

After a few minutes, you feel that you are going to asleep.

- Turn off the projector.

Task 4

The night is over ... It's 7:50 am when the alarm goes off.

- Turn off the alarm.

You go to the bathroom and as soon as you return, you receive a notification prompting you to fill-in the post-sleep diary.

- Fill in the post-sleep diary as you want.

Task 5

After filling-in the post-sleep diary, you decide to:

- Check out the score and the duration of your sleep for the previous night.
- Check out how long it took you to sleep last night.

Because you feel that you snore quite a bit lately you decide to:

- Check out your snoring behavior for the current week.
- How many episodes of snoring did you have on Tuesday, May 28th?

Task 6

According to the app you saw that it took you enough time to fall asleep last night.

- Explore what factors may have affected your sleep quality to get some helpful tips on how to improve it.

APPENDIX C

Debriefing Questionnaire

1. Did you like the concept of HypnOS; a system that monitors your sleep and recommends you ways to improve it?
2. Would you like HypnOS to be installed in your bedroom?
3. Did you like HypnOS's ability to adjust the environment in order to create appropriate sleep/wake up conditions?
4. Would you be willing to use the sleep monitoring devices (wearable activity tracker/watch, under-the-mattress sleep tracker, EEG headband)?
5. What is your opinion about HypnOS's ability to collect information about user's daily routine? (e.g., from pre- and post-sleep diaries)?
6. What is your opinion regarding HypnOS mobile application?
7. Would you use HypnOS mobile application to view your sleep statistics?
8. Would you use HypnOS mobile application to get sleep recommendations?
9. What was the most difficult part for you regarding HypnOS mobile application?
10. What did you like most about HypnOS mobile application?
11. Was there something that you didn't like and would prefer to change?
12. Was there any functionality you would expect to find in the HypnOS mobile application but it wasn't there?
13. Would you complete the pre- and post- sleep diaries so as to help HypnOS in providing appropriate sleep recommendations?