A Biofeedback System for Sleep Management

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***Abstract*—Sleep is state of rest necessary for human wellbeing and survival. Low quality sleep during the night affects human performance during the day and can lead to serious illnesses and disorders. In this paper we propose a multimodal system that monitors the quality of sleep and adapts the ambient environment where user sleeps in order to optimize the sleeping conditions and eventually the quality of sleep. The system generates a sleep record that contains a sleep quality index based on multiple biofeedback measurement from user. A feasibly study with sixty subjects is conducted to shape the system requirements and meet user expectations. The results showed that more than eighty percent of the participants realize the need for the proposed system and want the system to generate a sleep record and to control the ambient environment. Only five percent of the participants disagree that the system would improve the quality of sleep.**

Keywords:* *biofeedback system, ambient intelligence, sleep management, sleep index, wellbeing.

I. INTRODUCTION

According to the National Sleep Foundation (NSF), sleep is a physical and mental resting state that is essential for a person's health and wellbeing [1]. An average person spends about one third of her/his life in sleep where the efficiency of human performance is proportional to the amount and quality of sleep she/he gets in the previous night. Irritability, moodiness, daily sleepiness, and disinhibition are some of the first signs a person experiences from lack of sleep [2]. Furthermore, the degradation in sleep quality is associated with long-term health consequences such as chronic medical conditions including diabetes, high blood pressure, and heart disease, among others [3].

Researchers have identified three classes of causes of sleep abnormalities: psychological, physiological, and environmental [4]. Psychological causes of sleeping difficulties are mental and usually short-term, with stress being the number one cause [4]. Common triggers include school or job related pressure and social complications (such as the death in the family, etc.). Physiological causes are changes in the physiological system that deprive healthy sleep and results from discrepancies in the brain and nervous system, the cardiovascular system, metabolic functions, immunity system, etc. Finally, environmental factors include the setup of the ambient conditions such as a room that is too hot or cold, too noisy or too brightly lit, comfort and size of bed, etc. This research addresses the second and third classes of sleep abnormalities (physiological and environmental) as they are easier and more convenient and practical to measure and control, as will be explained later.

Nowadays there exist several methods to analyze and quantize the quality of sleep such as the polysomnography (PSG) procedure [5], self-rated questionnaires instruments such as Pittsburgh Sleep Quality Index (PSQI) [6], and biofeedback [7]. Although PSG provides accurate monitoring and assessment of sleep quality, it is highly expensive, intrusive, and requires specialized centers [5]. PSQI is commonly used, however, is subjective by nature and thus provides the least reliability [6].

Biofeedback technology is an emerging field involving the measurement of physiological functions of the human body and displaying the information to the user with the aim of enhancing the user awareness of their body performance and promoting wellbeing [7]. Meanwhile, another interesting technology, named Ambient Intelligence (AmI), has recently evolved to enhance the ambient environment awareness of the user need and react accordingly [8]. Combining biofeedback technologies with AmI systems has led to several interesting research and applications [9].

In this paper, we propose the use of biofeedback systems to measure and quantize the quality of sleep and the utilization of ambient intelligence technologies to adapt the ambient environment to maximize the quality of sleep and eventually enhance the general wellbeing. The proposed system uses pervasive biofeedback sensory devices (such as oxygen saturation, accelerometer, etc.) to detect different phases of human sleep and quantize the sleep index during each phase. These devices are non-intrusive and thus do not disturb the users' usual sleep. Furthermore, the system uses transparent actuation technologies to manipulate the ambient environment to improve the sleep conditions and enhance the quality of sleep (examples include changing the light intensity, changing the room temperature, closing a window, etc.)

The rest of this paper is arranged as follows: section II presents a related work for measuring the quality of sleep using biofeedback technologies and existing responses to enhance it. Section III describes the proposed system merits and details its comprising components. In section IV, we present a feasibility study to confirm the user's interest in the proposed system and derive requirements based on user feedback, along with a discussion about the user's feedback. Finally, section V summarizes the contents of the paper and provides perspectives for immediate future work.

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II. RELATED WORK

There exist several procedures for measuring the quality of sleep. The most common and simple one is using actimeter/actigraph [16-17], a watch shaped accelerometer worn on the wrist to measure the user activity during sleep. There are strong correlation between wrist activity and detection of sleep/awake status [18]. Researchers in [19] reported that more than 90% agreement between actimeter and PSG can be achieved. Although the total sleep time can be measured using an actimeter, it cannot give a trustworthy measurement for the sleep quality, rather it measures the sleep efficiency that is defined based on parameters such as sleep time or total time in bed [15].

In [10], Heart rate variability (HRV) and respiratory signals, captured using an Electrocardiography (ECG) sensor, are used to detect sleep apnea as well as sleep fragmentations (number of sleep micro-arousals). The authors were able to differentiate Rapid Eye Movement (REM) stage from Non-Rapid Eye Movement (NREM) stages with accuracy of 89.9% compared to the traditional PSG method, nonetheless there is no clear score scale or index for quality of sleep measurement.

In [11], only ECG signals are used to differentiate between sleep/awake, REM/NREM, light/deep sleep. The sleep quality is assessed using three factors: 1-sleep time vs. time in bed, 2-deep (delta) sleep time vs. total sleep time, and 3- Sleep latency (time from lights off to sleep). In [12] audio, video, heart rate, Passive Infra-Red (PIR) are the modalities used to detect sleep/awake status during sleep. Only video and PIR are tested and showed around 0.9 correlation with actigraph data (wrist movement).

The aim of the project in [13] is to create a set of wearable sensors that are intended to be used for continuous and long term monitoring of sleep and activity for stressed people, without the need for recharging the battery or replacing components. The factors that are monitored are: HRV that identifies the stress level and a motion sensor that measures physical activity, both sensors are place on the chest. No testing has been done on users to identify the accuracy of the sleep quality measurement. Also placing sensors on the chest makes them intrusive and can interfere with normal sleep of users.

In [14] a two axes accelerometer worn on the upper arm is used to detect roll-overs during sleep. Roll-overs differentiate light sleep from deep sleep, and then the sleep quality is calculated as the ratio deep sleep time divided by the total sleep time. In [15] three sources of data are collected for sleep duration and sleep quality: user log (subjective), actimeter and pressure sensor on the mattress (objective). There were a weak correlation between visually analyzed sleep quality and bed occupancy time, and a clear correlation between visually analyzed sleep quality and actimeter data. Again sleep quality is only based on total sleep time/time in bed.

In summary most of the existing solutions use a single source of data to measure sleep efficiency. However in PSG [5] many parameters contribute to the quality of sleep: limbs movements, sleep efficiency, sleep onset time, number of arousals across the night, breathing irregularities (sleep apnea), percentage of deep sleep time, percentage of REM time, among others. Therefore multiple parameters need to be simultaneously measured from the user body and correlated in order to provide a highly accurate measure of the sleep quality (referred to as the sleep index). ECG, oxygen saturation and limbs movements are few examples.

Furthermore, to the best of our knowledge, none of the existing work attempts to control the ambient environment with the objective to improve the quality of sleep. In this paper, we propose to use biofeedback technology to develop a system for sleep management, including measuring the quality of sleep using biofeedback sensors as well as controlling the ambient environment to enhance the quality of sleep using ambient intelligence technologies. The proposed system incorporates multi-modal interactions in order to control the environment parameters that affect the quality of sleep and to communicate the sleep management information to the user or any other interested party (such as a parent or a specialist).

III. THE PROPOSED SYSTEM

The sleep management system helps people stay aware of their body during the hours when they are not conscious. The system provides an objective assessment of the quality of sleep during the sleeping phase using biofeedback data.

In addition, the system manipulates the ambient environment so that it becomes ideal for a better and healthy sleep. Different types of responses are applied on the environment and on the user for the purpose of enhancing the quality of sleep.

In contrast of the polysomnography clinical test which is used for patients and is usually intrusive, the proposed system aim is to design a system that can be used by healthy non-patient users at their homes to measure and improve the quality of sleep. Therefore biofeedback data that can be recorded using non-intrusive sensors and do not interfere with users' sleep will be considered.

A. System Architecture

The proposed system architecture is shown in Figure 1. The architecture is composed of four modules: (1) Input Interfaces Module, (2) Sleep Management Center, (3) Data Center, and (4) Output Interfaces Module. Various input interfacing devices are used to capture data related to the sleep experience of the user. The collected data will be forwarded to the Sleep Management Center that performs signal conditioning and makes a decision about an appropriate response. The corresponding response will be sent to the Output Interface Module to control the ambient environment. In addition, the Sleep Management Center generates a Sleep Record after a sleep period and presents it to the user, a medical staff or a third party such as parents. The collected data is logged into the Data Center and can be used to generate a sleep record or to perform offline or long term analysis.

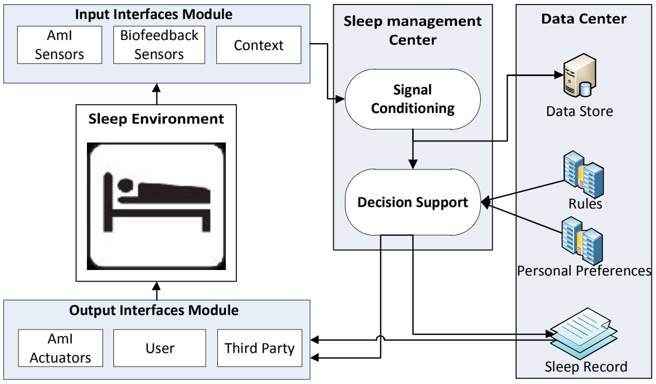

Figure 1. Sleep Management System Architecture

B. System Components

1) *Input Interfaces Module:* The input interface module acquires data that indicate or affect the quality of sleep. There are at least three types of input interfaces: AmI sensors, biofeedback sensors, and context sources.

a) AmI Sensors: Capture information about the ambient environment (for example the sleeping room) that can affect the quality of sleep. Examples of ambient information include the room temperature, the light intensity, ambient noise, and state of home appliances (such as if a door is open or not or if a TV is on or off, etc.). Another potential ambient source is the presence of another human in the same room which can be captured using an IR camera.

b) Biofeedback Sensors: Capture physiological functions of the sleeping person. Several physiological parameters are valid indicators of the quality of sleep. Examples of physiological parameters are human skin temperature, heart rate, oxygen saturation, respiration rate, blood pressure, and body movements.

c) Context: Contextual information enhances the system awareness of the sleeping environment and settings. For instance, knowing about the time when the person is sleeping might correlate to the quality of sleep. Other examples of context information include user calendar and user preferences.

2) *Sleep Management Center:* The sleep management system is comprised of two components: the Signal Conditioning Component and the Decision Support Component.

a) Signal Conditioning Component: performs various signal conditioning and analysis such as analog-to-digital conversion, data filtration, amplification, scaling, etc.

b) Decision Support Component: The resulting signals are consumed by the decision support component that performs data fusion and correlation to compute the parameters that contribute to the quality of sleep index (such as sleep latency, sleep efficiency, REM latency, etc.). The derived results are also stored in the Sleep Record for further analysis and references. The decision support component generates a response that can cope with the degradation with the quality of sleep and eventually improving the sleeping conditions.

3) *Data Center:* The Data Center is the main repository for the proposed system. It stores three types of related data: Personal Preferences, Rules, Sleep Database, and the Sleep Record.

a) Personal Preferences: Personal preferences strive to personalize the sleep management system by incorporating user feedback into the decision making. For example, the user can specify her/his preferred sleeping room condition (such as room temperature, light intensity, and maximum level of noise, etc.).

b) Rules: The rules define the knowledge based in the form of IF_THEN production and are utilized by the decision support component. For example when the room temperature goes below a threshold set for good sleep, the heater system will be activated to increase the room temperature to what is preferable to the user.

c) Data Store: The Sleep Database logs the data related to sleep quality that are captured by the sleep monitoring system. This data can be used for offline and/or long term analysis to study the user sleep behavior and disorders.

d) Sleep Record: At the end of each sleep session the system generates a report that evaluates the score of the overall quality of sleep, the specific score for every contributing factor, and highlights any issue that could have affected the quality of sleep during the previous night. According to polysomnography – the clinical gold standard for studying the sleep quality – we used the following parameters to compute the total sleep index (TSI):

- Sleep efficiency (SE)
- Sleep latency (SL)
- Number of awakenings (NA)
- Wake after sleep onset (WASO)
- Periodic limb movements index (PLMI)
- Stage 1 percentage (S1)
- Stage 2 (light sleep) percentage (S2)
- Stage 3 and 4 (deep sleep) Percentage (S34)
- REM percentage (RP)
- REM latency (RL)
- Respiratory Disturbance Index (RDI)
- Snoring index (SI)

Total Sleep Index (TSI) indicates the overall quality of sleep and is measured based on the parameters 1 to 12. Table 1 lists these parameters along with their optimal values in healthy users, their descriptions and sensors that can be used to capture and/or derive them from.

TABLE I. PARAMETERS USED IN COMPUTING TSI

Parameters	Optimal Value [20]	Description [21]	Sensors
SE	> 95%	Total sleep time*100/total time in bed	ECG, Actimeter
SL	< 15 minutes	Time from lights off till beginning of sleep	ECG, Actimeter
NA	< 10	Number of awakenings during night	ECG, Actimeter
WASO	< 15 minutes	The total time spent awake during sleep period time	ECG, Actimeter
PLMI	< 30/h	Average number of limb movements per hour	Actimeter
S1	1-5% of total sleep time	Stage 1 time/total sleep time	ECG
S2	50% of total sleep time	Stage 2 time/total sleep time	ECG
S34	10-20% of total sleep time	Stage 3and 4 time/total sleep time	ECG
PR	20-25% of total sleep time	Stage REM time/total sleep time	ECG
RL [22]	90 minutes	Time from beginning of sleep until appearance of first REM sleep	ECG
RDI	< 5/h	Average number of respiratory disturbances (cessation of breathing lasting more than 10 seconds)/total sleep time	Oximeter
SI	< 5/h	Number of snoring breaths per hour of sleep	Microphone

4) Output Interfaces Module: The Output Interfaces Module provides the means to display and execute the responses generated by the Sleep Management Center. This module is composed of the following elements: AmI actuators, the User, and a Third Party.

a) AmI Actuators: The AmI actuators are used to manipulate the ambient environment to enhance the sleep conditions. This includes controlling the air conditioning system, the light intensity, home appliances (such as speakers or TV), and room setup (such as opening or closing a door or window).

b) User: The system can communicate its finding with the user. This is only possible offline (before or after sleep) and gives feedback about the quality of user sleep. This helps users raise awareness about the quality of sleep they are getting as well as issues raising such sleep disorders.

c) Third party: The system can also communicate the collected information and responses to a third part user (such as a specialist or a parent in case of children sleep management). For example, if a new born is not having a good quality of sleep, the system will alert the parent(s) about it and provide recommendations for improving the sleep quality.

IV. FEASIBILITY STUDY

To prove the merit of the proposed system, we have conducted a feasibility study. Sixty (60) subjects of different age groups (25 females and 35 males) participated in the study. After describing the proposed system, the subjects we asked to complete a questionnaire. The results are presented and discussed in this section.

A. Results

Table 2 shows the four most important questions in the questionnaire. Sixty two percent (62%) of the subjects agreed to wear the hardware during sleep. Only one participant suggested that the system would compromise her/his privacy, 31 participants were neutral, and 28 participants did not have privacy issue when using the system. More than three quarter of participants preferred that the system generate a report about their quality of sleep and control the ambient environment. Only 5% of participants disagreed that the system would improve the quality of sleep. These results are shown in Fig. 2.

TABLE II. IMPORTANT QUESTIONS FROM FEASIBILITY STUDY QUESTIONNAIRE

Q1	Are you OK if you (and your children if applicable) wear the device (watch) on your wrist while sleeping?
Q2	Do you think the proposed system would compromise your personal privacy?
Q3	Would you prefer having just a report of your quality of sleep? Or report of quality of sleep PLUS Controlling the ambient environment? Or none?
Q4	Do you think this system would improve the quality of sleep?

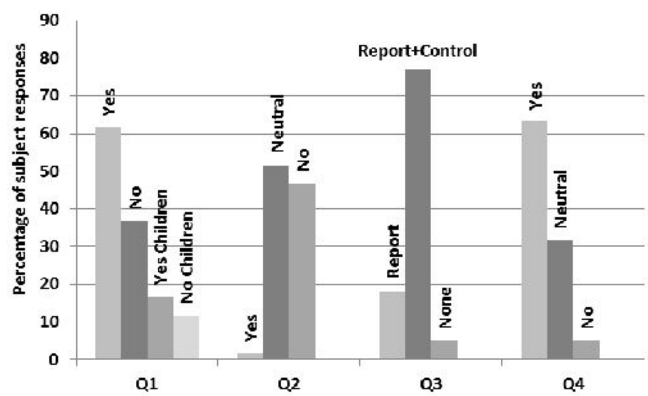

Figure 2. Results for answers of questions in Table 2

In order to design an appropriate response and control for the ambient environment, the subjects were also asked about the main causes for sleep discomfort or disorders. Figure 3 lists the most important causes of sleep discomfort. Participants can select more than one answer. The first common cause of sleep discomfort is temperature (low or high) selected by 62% of participants. The second cause is strong light for 58% of participants. The third is high noise for 53% of participants.

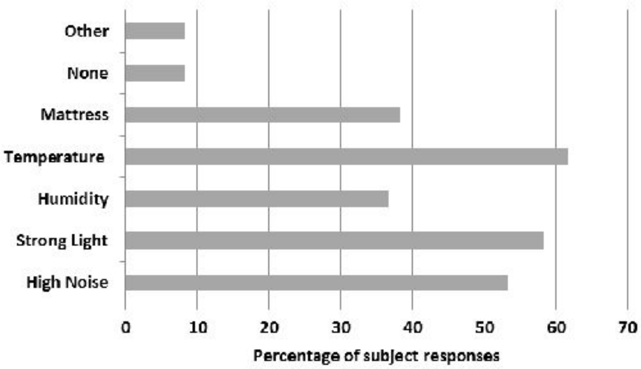

Figure 3. Most common causes of sleep discomfort

B. Discussion

Based on the results of the survey, the device – that users wear during night sleep – has to be none- or at least minimally-invasive. As mentioned in question 1, if the device is similar to a watch worn on the wrist it would be acceptable by almost two third of users. Therefore only sensors that do not interfere with user's comfort will be considered in the system design and implementation. All sensors will be placed in the watch (actimeter) or attached to it (fingertip oximeter). Cameras and passive infrared sensors [12] will not be considered since they compromise user privacy especially during sleep. Also sharing the sleep record with a third party such as specialist will only be available after user approval.

Based on the responses of participants in Figure 3, the most important ambient information that will be monitored and controlled during the night will be, in order: room temperature, ambient light, and ambient noise. Amongst the responses two users mentioned mental load as a reason for poor quality of sleep. We will investigate adding soft audio, natural scenes pictures or lighting effects to reduce the mental stress before falling asleep.

V. Conclusion

A biofeedback system for sleep management is presented in this paper. The objective is to promote the wellbeing of healthy users through monitoring their sleep quality objectively and controlling the ambient environment so it becomes ideal for better sleep. A sleep record is generated by the system based on the captured biofeedback sensory data and the sleep quality index is calculated; this record is available for experts to perform more in-depth analysis of sleep behaviors and diagnoses sleep disorders. The feasibility study gave us an insight on what factors need to be controlled on the ambient environment, and showed users' strong interest in our system for promoting wellbeing.

Our immediate future work is to implement the system, to bring forth a mathematical model to compute the sleep quality index and generate multimodal responses. Finally, experimental studies will be performed to ascertain the ability of the system to improve the quality of sleep.

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