z^3

Discover what affects your sleep and how to improve it.

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Abstract— **Sleep is a natural process which is essential to human beings, and lack of sleep or bad sleep hygiene can have profound effects on an individual's well-being. In this report we investigate the various factors that can influence sleep, reviewing some of the currently available technology and propose a system, "z^3", based around an smart phone application and external sensors to collect data from the user and their sleeping environment, to provide personalised advice in order to help the user get a better night's sleep.**

I. INTRODUCTION

Sleep is incredibly important for both psychological and physiological health and yet people often struggle to get enough sleep. Reasons for lack of sleep can be due to a variety of factors including sleeping in an unsuitable environment or engaging in unhelpful behaviours in the hours leading to sleep. These factors can affect different people in different ways and so advice that helps one person may not help another.

Our research suggests the existence of a niche in the market for a system that provides users with clear, personalised advice to promote better sleep hygiene, with the hope that this will improve alertness and mood during the day. We plan to develop this system using a multi-sensor wireless device (TI SensorTag 2.0) to monitor the user's sleeping environment and habits. We will continuously measure temperature, brightness and humidity throughout the night, and combine this with qualitative user input data. Using machine learning on initial data collected from a variety of different people to produce generalised conclusions about the main factors affecting a user's sleep, we will identify factors of interest to set generic advice which will be the starting point for the app on installation. On using the app, the user's data will be analysed using component analysis algorithms to identify the amount that each factor affects the user's sleep and to suggest personalised improvements to be made. The system will be quantitatively evaluated through a two week trial, demonstrating the changes in each user's factor weightings and comparing the change in factor weighting against an existing sleep cycle measurement applications to measure it's prediction accuracy, and qualitatively through user feedback. We will compare results against a standard sleep cycle monitoring application to compare perceived improvements versus actual improvements in sleep patterns.

Finally, we outline our method for evaluating the system in order to determine it's efficacy both in the short-term and long-term.

II. RESEARCH HYPOTHESIS

With our system composed of both a mobile application and an external multi-sensor device, we expect to improve sleep quality in two ways:

1) Short-term - By understanding what factors affect sleep quality generally, our system will help users to improve their sleeping environment as well as their sleep cycles through providing advice to the user.
2) Long-term - Using machine learning algorithms to weight the different factors affecting sleep in order to personalise advice, the user will develop the optimal sleeping routine for themselves to carry out before and after every night.

In both these cases, we expect the application to engage users in actively improving the quality of their nights and to help them feel energised at the start of every day.

III. BACKGROUND

This section will examine the background research into sleep and current technologies aimed at improving sleep hygiene.

Sleep has been shown to be vitally important to our lives, affecting our ability to remember, process and act on information as well as our mood and physiological well-being. The necessity of sleep is highlighted by a study conducted on rats that found that sleep deprivation ultimately resulted in death, following various different physiological deteriorations, although there was not one uniform cause of death [1]. This shows that sleep plays an important role in maintaining a healthy physiological condition, even if we have not determined precisely how this happens. One does not have to undergo extreme sleep deprivation, however, to experience negative symptoms: one meta-analysis of sleep deprivation studies found that sleep deprivation affects mood, cognitive and motor performance, with mood being the most affected [2]. Moreover, this study surprisingly showed that partial sleep deprivation, which is the result of getting less than 5 hours of sleep in a 24 hour period, has the greatest consequence on these factors, even above short and long term total sleep deprivation. This finding highlights how important it is for everyone, and not just those at risk of carrying out total sleep deprivation, to consider how their sleep patterns can be affecting their daily lives.

The environment has been shown to have an effect on the quality of sleep, with some factors having more impact than others. One study, for example, found that humid heat exposure leads to worse sleep [3], whilst another study found that brighter ambient light increased alertness in workers [4]. Another found some correlation between noise and awakenings in ICU (Intensive Care Unit) patients, however found it to be a less significant factor in reducing sleep quality than had been previously suggested [5]. Other external factors, such as technology and substance use, also have been identified as affecting sleep of college students [6].

Naturally, there have been many technologies developed in an attempt to improve sleep quality: many of these are purely mobile applications, which do not monitor the environment. Since a major aim of our system is to make users aware of the effect environmental factors have on their sleep, we will review the technologies that extend beyond apps and that measure these factors.

One such system uses a sensor placed across the top of a bed, which measures sleep activity through movement [7]. The researchers, Paalasmaa et. al., argue that the system is suitable for long-term monitoring of sleep because it is unobtrusive, as opposed to any wearable devices. We agree with them, so have strived to design a system to be unobtrusive as well. This paper supports a commercially available technology, Beddit [8], which measures factors in the environment such as temperature, humidity and noise. The companion mobile application shows you how your sleep quality differs as a percentage for user- and app-defined notes attached to that night, so "#reading" may improve sleep by 29% whereas "#tuesday" may worsen sleep by 17%, for instance. Sleep quality is measured solely through user movement measured by the bed sensor and not through any user confirmation.

This may prove to be an issue when the sensors do not report 100% reliable and accurate data. One study, conducted by Draganich et. al., reported the effects of "placebo sleep" [9] on performance in cognitive tests. The researchers found that if participants were told that they had slept well or badly, according to sensors that supposedly measured their REM sleep, their performance in tests will increase or decrease accordingly, independently of how well rested they had initially reported they felt. We do not want to introduce this bias into our user feedback by attempting to judge sleep quality on sensors. Instead, we will ask the user to rate their perceived quality of sleep and our system will learn directly from the user what the ideal environment is for them.

Another commercially available sensor, CubeSensors [10], measures air quality, humidity, temperature, noise, light and pressure. To interact with it you can shake it to make it glow, with the colour of the light indicating the quality of the current environment. The company behind CubeSensors claims that through monitoring of the home environment and giving the user timely updates, they will be able to adapt their living situation, thus improving their and their family's sleep and general health. CubeSensors does not appear take into account the fact that everyone may have different preferences to their home environment.

Through understanding research and assessing the market, we have found a niche for a solution that will allow users to learn what does or doesn't help them sleep well. Clearly there are many factors that have some affect on sleep, but because of individual variation likely due to genetic and cultural factors [11], we do not simply want to add to the body of general sleep hygiene advice. This is why we believe there is value in creating a system that gives personalised, clear suggestions, as opposed to simply repeating the same advice that can be found online. Some current technologies, as discussed, began to consider this by showing the user percentage scores to various influences on sleep quality, but they have not turned this data into straight-forward advice as to what actions the user may be able to take. Additionally, we do not want to mistakenly tell the user they slept poorly when they believed they had slept well, therefore we will mostly rely on a self-reporting measure in the morning, with immediate suggestions for changes only being given by the application if their assessment falls below a certain level.

IV. SYSTEM DESIGN

A. *System Overview*

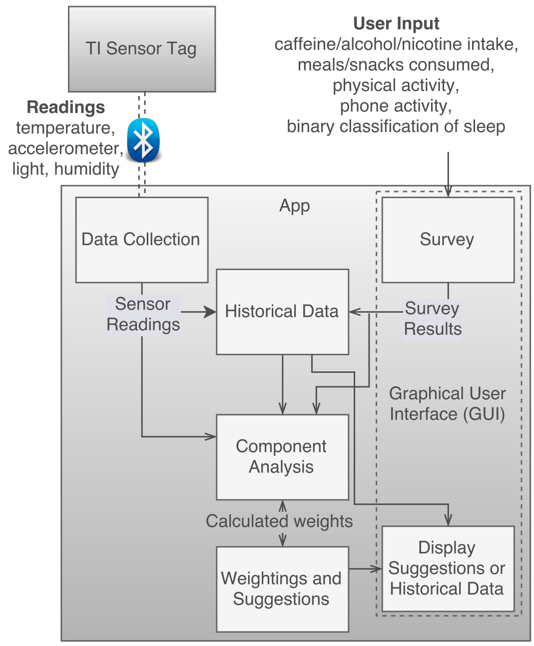

Fig. 1. System Diagram

The proposed system will collect data related to the user's sleeping environment using a Texas Instruments SensorTag. This device can monitor various quantities such as temperature, brightness and humidity, which altogether will allow us to judge how long and how well the user slept. This data will be relayed to an iOS application via a Bluetooth Low Energy connection, and fed into into a component analysis algorithm embedded into the mobile application, along with the answers supplied by the user to regular survey questions. The component analysis software will calculate weights for the environmental factors and user habits, as well as the generalised factor weighting resulting from machine learning carried out on initial data records, in order to provide customised suggestions to improve the user's sleep quality. A graphical user interface will communicate the suggestions, weightings and historical data through useful graphs and diagrams.

B. Hardware

In order to measure the environmental factors affecting sleep we will use a Texas Instruments SensorTag [12]. The use of the SensorTag simplifies the integration of hardware into the system, combining all of the sensors that we require to measure the sleeping environment into one small device. The CC2650STK SensorTag contains both infra-red and ambient temperature sensors, an ambient light sensor, a humidity sensor, a magnetic field sensor, a barometric pressure sensor and a microphone along with a 9-axis motion tracking device consisting of an accelerometer, gyroscope and compass [13]. Those of interest in our case are:

- The infra-red and ambient temperature sensors
- The ambient light sensor
- The humidity sensor
- The motion tracking device
- The microphone.

The first 3 sensors will help us understand and monitor the sleeping environment as well as the conditions prior to sleep. The other two can potentially help us track sleep cycles (and related events such as snoring) in order to infer sleep quality.

The SensorTag communicates the sensor readings to a smartphone using Blutooth Low Energy [14] which can then be processed by the smart phone or sent to the cloud to be processed by an Internet of Things platform, such as IBM Bluemix [15]. The multi-sensor device is small and ultra-low power, boasting a 1 year battery life which can be monitored by the Texas Instruments Simplelink SensorTag mobile application [16]. This makes it a practical choice for a product that targets users who may not have much technical knowledge.

C. Software

The hardware will be accompanied by a mobile application: in addition to handling the retrieval of sensor data from the TI Sensor Tag, it will also provide an intuitive interface to the user in order to communicate results as well as collect qualitative data.

Every evening prior to bedtime the user will be asked to quickly record any event or action which might affect his or her sleep, such as exercise, eating, sexual intercourse, alcohol/tobacco/caffeine intake. The application will also ask about personal habits, for example whether or not the user sleeps naked, if he/she drinks water just before going to bed, if he/she keeps electronic devices turned on in the bedroom and if he/she feels tired. Similarly, the next morning the user will be prompted to answer simple questions such as 'did you wake up to natural light?' or 'did you wake up to urinate during the night and/or did you turn the lights on?'.

Initially one night's worth of sleep data will be collected from multiple different people and machine learning will be used to identify contributing factors to difficulty sleeping. On initialisation of the application, using this generalised data and based on the user's answers to the short surveys, the software will be able to give general advice about life habits and bedroom-related factors which can affect one's sleep quality. In addition to that, the application will use component analysis to give personalised feedback. Every morning the user will be asked 'do you feel like you slept well?' and 'do you feel tired or energised?': if the user answered that they did not sleep well, the component analysis module will compare the sound amplitude readings with the environment data to identify the times at which their sleep was disturbed and whether it could be attributed to any other change in their environment. This data will also be compared with the survey answers and historical data to identify if a change in daily routine resulted in a bad night's sleep, such as drinking coffee within a number of hours before going to bed. If the user answered that they slept well, that night's environment data and survey answers will be compared to historical data to identify changes that have had a positive effect on their sleep. This analysis will be used to alter the weightings assigned to the different factors to identify which factors affect that user's sleep more.

The weightings calculated by the component analysis module will then be used to identify suitable suggestions to give to the user that may help improve their sleep hygiene. Through a simple and user-friendly graphical user interface, the user will be able to consult the customised suggestions inferred from the collected data, as well as diagrams and graphs showing the biggest factors that affect his/her sleep, or the data from a single night with identified points of interest.

The mobile application will initially be developed for Apple devices (iPhone/iPad). As a starting point we will use Apple's ResearchKit to implement the survey modules, in order to gather data to train the machine learning algorithm. Once that has been done, we will develop a full-featured iOS application including user-friendly surveys and simple yet useful diagrams. The next step would be to turn the app into an 'active aid' rather than a simple information platform, by adding modules such as meditation exercises, real-time suggestions regarding daily activities (coffee, exercise etc) and a smart alarm clock. We are also considering the possibility to allow pairing an Apple Watch which will provide heart rate data as well as the possibility to emit vibrations at night using haptic feedback, which will induce the user to lower his heart beat.

V. Evaluation

Initial data collection is necessary to develop and train our algorithm. This data collection will consist in both explicit and implicit feedback from the user. The implicit feedback will come from sensor data and the explicit feedback from a written survey the users will complete before going to sleep and once they wake up. The survey asks the users a range of questions on their activities during the day before going to bed, such as the time of their last meal and drink and whether they consumed alcohol or caffeine. In order to help us classify the data measured from our sensor as good or bad sleep, the user is asked whether they slept well or badly once they wake up.

Once this initial data has been clustered the performance of our application will be evaluated quantitatively in the short-term and qualitatively in the long-term. The quantitative evaluation will consist of a classification system called the Confusion Matrix. In a Confusion Matrix, the positive and negative scores for both predicated and real results are placed in a two by two matrix, from which several metrics can be determined. An example of such a matrix can be seen in figure 2.

		Predicted	
		Good sleep	Bad sleep
Real	Good sleep	a	b
	Bad sleep	c	d

Fig. 2. Confusion Matrix

One particularly interesting metric can be found from the confusion matrix: the accuracy. This is the amount of correct predictions over the total amount of predictions made, and can be calculated from the following equation, which will be the best indicator of our algorithm's performance in the short-term:

$$\frac{a+d}{a+b+c+d}$$

Fig. 3. Accuracy

Once the whole application has been built, a second round of data collection will take place with the objective of testing the algorithm. Using Imperial College London students as test subjects, we will qualitatively evaluate the long-term improvements of our application highlighted in our hypothesis. Similarly to the first round of data collection, our participants will place the sensor on their bedside table before going to sleep and will complete a short survey in the morning rating their sleep. Furthermore, a sleep tracking application on their mobile phone will measure their sleep cycle through the night.

The qualitative evaluation will assess the sleep improvement once the applications suggestions have been implemented by the user. A successful evaluation will show a positive progress over time on the users sleep by regulating their environment and routine before going to sleep. This can be measured by collecting explicit feedback from the user on a regular basis. By using a happy or sad smiley face to represent a good or bad night's sleep respectively, users can use this system to notify the application once they wake up. These results show the perceived sleep quality from the users, and will be compared to the sleep cycle results measured from the sleep tracking application that show the true nature of their sleep. Over time the results may be graphically displayed showing the progress in sleeping condition.

VI. CONCLUSION

In this design report we outlined our design for a system based around a iPhone app which uses sensor readings from a multi-sensor wireless device to identify factors that affect the user's sleep as well as the user's approach to sleep. This involves collecting temperature, brightness and humidity data over-night and obtaining user-input before and after sleeping regarding their daily activities and how well they slept. The data collected will be used to understand each individual's sleep patterns to create personalised advice to help the user improve their sleep hygiene. We will evaluate our system to determine it's efficacy for improving the user's sleep quality.

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