A Review of Recent Advances in Smart Homes for Improving Sleep Hygiene, and Sleep Quality

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Abstract- With the rising attention towards improving the quality of life and mental health, sleep hygiene and sleep quality have recently been the main topics of numerous studies. Quality of sleep not only affects our physical status but also plays a pivotal role in our psychological and emotional states. Sleep deprivation can increase the risk of cardiovascular and metabolic diseases along with the risk of impaired concentration and consequent road injury and accidents. As technology has become a main figure in our daily lives, technological advances have paid a great interest in improving the quality of sleep by enhancing the detection of sleep-related disorders and sleep abnormalities, particularly in the setting of smart homes and the Internet of Things (IoT). Smartphone applications, portable wearable gadgets, and devices along with more sophisticated and precise algorithms are now endeavoring to help us improve our quality of sleep and subsequently our quality of life. Hence, this review aims to illustrate a vivid picture of recent advancements in smart homes and their related technologies for improving sleep quality.

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Introduction

Sleep hygiene simply refers to those necessary and fundamental behaviors and environmental factors that promote and improve the quality of sleep and maintain healthy sleep (1). The quality and quantity of sleep can directly affect the social, physical, psychological, and biological functions of a human being (2,3). Hence, quality and quantity of sleep are the necessities of quality of life, and sleep deprivation or low-quality sleep, due to any causes such as sleep problems or a sleep-unfriendly environment, may harm us in every aspect of our lives (4). The prevalence of sleep problems has been rising during the last decades. According to population studies, 30% of the adult population suffers from insomnia, among which 10% suffer from chronic insomnia. Also, other estimates show that 9 to 21% of women and 24 to 31% of men suffer from sleep apnea. The cultural shift towards a "24/7 society" and an unusual increase in night-time activities such as watching TV and the use of mobile phones and the internet has severely compromised our quality of sleep (5).

Internet of Things (IoT) has become one of the significant components of smart homes which is a form of assisted living technology that includes several communication and network devices, which enhances the quality of life, energy management, and safety of its residents (6). Smart homes have become advanced to the extent that they gather information and can actively

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control several in-door functions of the house without any human intervention (7). The use of this technology has been rigorously investigated in recent literature and among its numerous applications towards enhancing well-being, sleep aid systems have gained great interest. These systems aim to improve the sleep quality of their users by gathering relevant data regarding daily routines and behavior patterns (8). These systems can also detect stress levels and use relaxing techniques to reduce these stresses. Sleep gadgets, sleep monitoring systems, and sleep-enhancing devices can also build an effective communication interface for patients, caregivers, and physicians (9).

Sleep disorders are defined as any condition disturbing normal sleep patterns. Although, about 80 different sleep disorders have been identified (10,11), however, the most prevalent and clinically significant sleep disorders are insomnia, sleep-related breathing disorders (such as sleep apnea), narcolepsy, and restless leg syndrome (12). With the rise and advancement of smart gadgets in intelligent home settings, various algorithms, systems, and programs have been introduced for the detection of sleep disorders and disturbances at home. Hence, while the prevalence of sleep problems is increasing, with the help of assistive sleep technology, this problem can be tackled. This review aims to illustrate a vivid picture of recent advancements in smart homes and their related technologies for improving sleep quality. This review initially examines the framework of research in sleep quality regarding IoT and smart homes. Further, it thoroughly discusses examples of these technological advances, and finally introduces the concept of human-centric lighting and its future potential and applications.

The framework of sleep systems

The framework of sleep systems can simply be depicted in three stages. The first step is data gathering via various sensors such as traditional polysomnography (PSG) videosomnography (VSG), sleep diaries, and accelerometry (13). The data will then be cleaned, transformed, and analyzed using machine learning or statistical models. This processing will finally provide personalized recommendations for the users and real-time changes controlled by smart devices.

PSG is the diagnostic tool that is used for detecting sleep disorders and sleep disturbances which records various physiological signals such as brain waves, heart rate variability, rapid eye movement (REM), and muscle contractions. Despite being the gold standard tool for diagnosing sleep disorders, PSG needs to be performed in clinical settings and sleep clinics (14). VSG is another method for evaluating sleep disturbances, by recording a person's movements during sleep. These recordings will be scored by an expert afterward. The main problem regarding the applicability of VSG in a smart home setting is the need for scoring by an expert. Typically, VSG and PSG are paired in clinical settings, however, recent advances have made it possible for this technique to be automatically scored. This scoring system uses an estimate of sleep duration, sleep onset and offset, and movements during sleep which is then transcribed into a summary score that classifies these patterns into sleep/awake cycles using existing algorithms (15).

Actigraphy and accelerometry are two methods that can be used in smart home settings for monitoring physical activities. Technological advances have made possible the potential for these methods to be used via wearable sensors such as smart watches, wristbands, and headbands. Other non-invasive methods for gathering data for sleep monitoring are bed sensors, ultrasound techniques, mobile phone applications, wireless electroencephalography (EEG) headbands, and radio frequency (RF) based sensors (16,17). Although numerous gadgets and devices are available on the market for sleep monitoring and improving sleep quality, few studies have assessed the efficacy and efficiency of their performance in comparison with standard techniques (13). Also, in recent years machine learning approaches have become more advanced in recognizing and analyzing sleep stages and sleep patterns. Novel methods such as convolutional neural networks and recurrent neural networks have been used to determine sleep cycles and sleep disorders (18-21). From here on, a detailed description of novel technologies regarding sleep quality and sleep monitoring will be given.

IoT architecture and its role in smart homes and health care

IoT consists of three main parts:

1. Field Devices (Sensors and Actuators)
2. Communication System
3. Management and Service Software and Systems (22)

In the Smart Home IoT application, sensors measure parameters like temperature, light level, air quality, consumed energy, etc. and actuators can control HVAC, light sources (both level and color), air fresheners, controllable home appliances, etc.

All sensors and actuators are accessible in the cloud-

based computing system via gateways and different communication media like Wi-Fi, GPRS, RF (point to point, point to multi-point or mesh), PLC, etc.

Many analytical software and systems are developed to run optimized algorithms, and control desired parameters like temperature, light, etc.

In conventional control systems, very simple control functions like on/off control are used to set the parameters like temperature, but using IoT-based control systems, very complicated control functions like PID, Fuzzy, or any AI-based algorithms may be used. Two main goals achieved by using this new control system are:

1. Controlled parameter (Like temperature) will be tuned very fine with less deviation from setpoint;

2. Some other parameters (Like user health parameters) may be involved in control functions and make the control system more flexible and oriented to user convenience.

Figure (1) shows a simple IoT architecture and how it could be consisting human health signals and analytical systems.

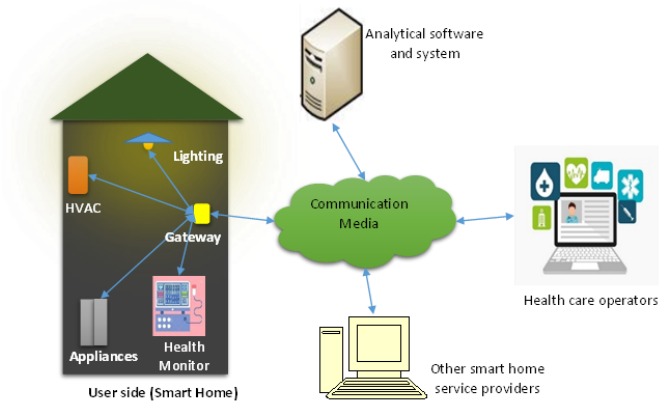

Figure 1. IoT architecture and smart home objects

Sleep quality and sleep monitoring systems in smart homes

Remote monitoring is one of IoT's benefits in the field of healthcare by maintaining and ensuring sound sleep, it can prevent chronic diseases, psychological problems, and accidents due to sleep deprivation or sleep disorders (23). Hence, with the increasing use of IoT, during the last two decades, numerous applications and artificial intelligent-based devices have been introduced to the market for monitoring sleep behaviors and patterns. The most important systems will be summarized below.

CaLmi

One of the intelligent systems is CaLmi, which utilizes the infrastructure of smart homes to reduce stress and therefore improve the sleep quality and mental well-being of its users. This system detects the stress level in its users and helps them to monitor their real-time stress levels. Afterward, it can either activate its automated stress-reducing processes or help the user choose one of its stress-reduction suggestions.

CaLmi gathers information regarding the daily activities, nutrition, health, and sleep quality of its users via an intelligent wristband. Physiological signals such as heart rate and heart rate variability, motions, nutrition intake, and body temperature are collected via responsive sensors. After processing the data, it identifies stress peaks and determines whether the stress reduction intervention is necessary or not. To compensate for individual differences regarding the appropriate stress reduction techniques, CaLmi offers different techniques to obtain maximum user satisfaction. This system also cooperates with other intelligent devices available in the user's smart home. After ensuring that the user is in a comfortable position, CaLmi initiates its stress reduction procedures. These procedures can be classified into four categories. One technique is exposure to nature via videos, images, and slideshows. In cooperation with other intelligent devices, CaLmi balances the lighting, colors, and sounds to simulate natural atmospheres such as forests, seashores, sunsets, etc. Another technique is mindfulness-based stress reduction (MBSR) which helps the user to practice meditation via yoga, body scan, or mindful sitting. With the help of other intelligent devices, CaLmi creates a meditating atmosphere such as balancing the

light and calming colors or diffusing appropriate aromas such as lavender. The third technique uses the available intelligent sound devices to play calming and relaxing songs while, again, the lighting and the aroma are appropriately adjusted by other devices. Expressive writing is also another novel technique that has been proven to be effective in reducing stress levels. While CaLmi provides appropriate questions for the user to express his/her feelings, the user's voice can be transformed into text, and simultaneously its thoughts are displayed with balanced lighting and aroma. Finally, CaLmi offers a customized stress reduction program that helps the user to adjust it according to his/her preferences and enables the use of the mentioned techniques in combination based on the user's current position (standing in the kitchen, lying on the sofa, etc). CaLmi analyses the stress level before, during, and after these programs which subsequently helps to maximize the effectiveness of these programs. According to a trial with real subjects, around 60% of the subjects felt less stressed and all of them reported that they felt sleepy, calmer, and satisfied (8,24).

HypnOS

HypnOS is another smart home-based system aiming at improving sleep quality by detecting sleep abnormalities and generating individualized sleep hygiene recommendations. Having various sensors and tracking gadgets, HypnOS can gather information regarding sleep activities and abnormalities, heart rate, pulse oximeter, respiratory rate, emotions, behaviors, and daily habits. It also detects nutritional and drinking habits such as alcohol or coffee consumption. The three main components of HypnOS are the smart wearable wristband (recording heart rate, sleep metrics, and physical activity), under-the-mattress sleep tracker (recording breathing rate, snoring during sleep, and night movements), and EEG headband (recording brain signals, and sleep metrics). HypnOS cooperates with AmIHomeOS, which is a collection of programs that controls other smart artifacts, makes an informed decision based on gathered contextual information, provides a more personalized experience for the user, and integrates other smart artifacts in the setting of the smart home. HypnOS takes into account numerous variables for monitoring sleep and providing sleep recommendations. Food intake and nutrition are observed to help the user consume sleep-friendly foods and beverages and prevent them from consuming substances that may lessen the sleep quality. It also detects sleep patterns, uncomfortable or irritative feelings, and stress levels. By cooperating with home control services, it balances the environmental factors that may affect the sleep quality of the users. Factors such as noise, room temperature, air conditioning, and level of brightness may adversely affect sleep quality, therefore, they are set to an optimal level to maximize the user's quality of sleep.

HypnOS also provides a personalized sleep diary for its users which takes into account different measures such as sleep duration, number of awakenings during the night, restful feeling after awakening, sleep quality, and caffeine or alcohol consumption. The HypnOS sleep diary follows other popular sleep diaries including; Consensus Sleep Diary, National Sleep Foundation, and Pittsburgh Sleep Diary. By gathering relevant information from the sleep diary and other sleep-tracking devices mentioned before, HypnOS can infer insightful deductions regarding the cause of the user's sleep disturbances and provide personalized sleep hygiene recommendations. For example, in cooperation with other intelligent artifacts, HypnOS understands the user is going to consume caffeine one hour before bedtime and notifies the user that consuming caffeine at this hour might adversely affect sleep quality (8,25).

SMARS

A novel Sleep Monitoring via Ambient Radio Signals (SMARS) has been recently designed by Zhang *et al*., SMARS is a radio frequency (RF) based statistical model that recognizes sleep stages and evaluates sleep quality along with recognizing wakefulness, REM, and non-REM. SMARS has been tested in a trial and it has been proven to be 88% accurate in detecting sleep stages. It also records respiratory rate even if the user is 10 meters away or behind a barrier such as a wall. As SMARS is an unobtrusive sleep quality monitoring system it can effectively be used in smart home settings for detection and management of sleep disorders (23).

Dream headband

The Dream headband (DH) is a wireless device that gathers and analyses real-time biological data that is used for sleep staging and introduced as a PSG alternative method. DH transfers the data via Bluetooth to a smartphone and the data is then sent to the sponsor's server via Wi-Fi connections. The type of biological data that is gathered by DH includes; 1) cortical brain activity via dry EEG electrodes, 2)

breathing per minute, motions, and user's position via a 3D accelerometer, and 3) pulse rate via an infrared pulse oximeter. The quality of EEG signals, heart rate and breathing variability, and sleep stage classification of DH have been compared with PSG. The EEG signals had a substantial agreement with PSG while breathing and heart rate variabilities and sleep stage classification showed excellent and soft agreement with PSG, respectively. The setting times for DH and PSG were approximately 5 minutes and 45 minutes, respectively. Due to high precision, lower cost, and ease of use, DH can be adapted for the detection of sleep disorders (26).

UpNEA and AeneA

UpNEA is a smart glove sensor for signals acquisition during the night together with a mobile application and a remote server called AeneA for cloud computing, used in an entire sleep monitoring system. This device detects accelerometer signals, photoplethysmography (PPG) signals, and peripheral oxygen saturation (SpO2) signals from the index finger. The device transmits the recordings made during the night to a smartphone app, which subsequently sends them to AeneA. Both the user and the clinician can view the results via a web application following cloud computing. Several functions are carried out by the AeneA sleep monitoring activity: classification of sleep stages, assessment of oxygen desaturation, estimation of heart rate and respiration rate, detection of tachycardia, bradycardia, atrial fibrillation, and premature ventricular contraction, and identification and classification of apnea and hypopnea.

The PPG breathing rate estimation algorithm showed an absolute median error of 0.5 breaths per minute for the 32 s window and 0.2 for the 64 s window. The apnea and hypopnea detection algorithm demonstrates an accuracy (Acc) of 75.1%. The classification task showed 92.6% Acc in distinguishing central from obstructive apnea, 83.7% in distinguishing central apnea from central hypopnea, and 82.7% in distinguishing obstructive apnea from obstructive hypopnea (27).

Xiaomi Mi Band 2

The Xiaomi Mi Band 2 is a wristband that defines light sleep, deep sleep, and awake time. It measures the number of steps, distance, and duration of sleep with clarity. It might be a useful technique for objectively evaluating adult sleep, particularly that of the elderly, and understanding how it affects many aspects of their health and well-being in assisted living facilities.

The Xiaomi Mi Band 2 was utilized together with the assessment instruments to demonstrate how sleep affects daily activities, cognitive function, quality of life, and degree of dependence on daily activities (28).

Phyjama: Physiological sensing via fiber-enhanced pyjamas

Phyjama was designed to introduce an agreeable textile-based sensor for sleep monitoring. Initially, a textile-based sensor that can measure heart rate and respiratory signals was needed. Two patches, a triboelectric patch, and a resistive patch were designed. These patches comprise the data-gathering system of Phyjama. The resistive patch can measure minuscule heart movement, and the triboelectric patch recognizes chest movements and respiratory rate. Since during night and sleep, different parts of our bodies are under pressure, the individual data of one sensor is unreliable to deduce body position, heart, and respiratory movement. Hence, the data is gathered from multiple sensors in different positions to accurately measure heart and respiratory rate along with body position and posture. The signal is initially retrieved from individual patches and undergoes pre-processing which eliminates useless and noisy signals. Afterwards, the signals from triboelectric and resistive patches undergo feature extraction and J-peak classification and the location of each J-peak is determined before fusion of these outputs. After quality assessment of these outputs using signal quality index (SQI), an accurate estimation of the J-peak is estimated. These patches can be used in the design of other wearable technologies as well. Pajamas can be used to improve the sleep quality of the geriatric population who commonly suffer from sleep disorders (29,30).

TagSleep

TagSleep is a radio frequency-based sleep monitoring system that recognizes snoring, coughing, and somniloquy during sleep. The TagSleep design comprises three radio frequency identification (RFID) tags and one RFID reader. TagSleep uses a two-layer sensing technique that initially gathers information to recognize respiration changes and through a second layer, analyses recognize coughing, snoring, and somniloquy. The sound pattern and chest movements of coughing, snoring, and somniloquy are unique. Three tags are placed near the user's chest and abdomen and an antenna near his/her head. TagSleep

uses the natural structure of an ordinary bedroom to enhance the signals by collecting signal reflections from walls and furniture. The collected data is pre-processed to eliminate unclear and noisy signals by removing the outlier signals. The next level of processing determines chest and abdomen movement to recognize sleep posture and respiration. Through a second-layer comparison of the results with snoring, coughing, and somniloquy, it recognizes these sleep activities. The results of the pilot study show high accuracy of sleep posture and the aforementioned sleep activity recognition. Due to its high accuracy, TagSleep is an applicable system for enhancing smart home automation (31).

Sleeppos

Sleeppos is an android-based application coupled with a pulse oximetry device that determines sleep position and can simultaneously intervene to correct sleep position and improve the quality of sleep during sleep. The smartphone is fixed on the chest using an elastic band. The accelerometery sensor in the smartphone gathers data regarding movements during the night and the sleep duration will also be recorded. The pulse oximetry allows the detection of oxygen desaturation (at least 3% in comparison with the baseline index) and the correlation between the occurrence of desaturation and sleep posture. By using the apnea-hypopnea index (AHI) severity classification, this application can categorize its users into mild, moderate, and severe sleep apnea patients. Upon detection of the supine sleep position, if activated, the app will make the smartphone vibrate every three seconds and help the user change his/her position to prevent oxygen desaturation. The pilot study showed that using this application reduced supine position sleeping in all subjects. This system can enhance better observation of sleep positions and sleep quality for those who are suffering from a sleep disorder related to sleep position (32).

SleepAge

A novel approach to qualitative assessment of sleep has been introduced by SleepAge. SleepAge is an Android-based application that estimates sleep quality and sleep patterns based on nocturnal sounds. It relies on the concept that body movement, bruxism, and snoring sounds can be used to estimate the sleep pattern. A smartphone records the sounds during the night, an actigraphy device recognizes movements and heart rate, and a room sensor determines the temperature and lighting of the room. A self-completed sleep questionnaire is filled by the user before sleep for assessment of the mental and physical status. Another self-completed questionnaire is filled out by the user after awakening regarding sleep quality and another questionnaire is filled out during daytime regarding dietary and other habits. A database of 111 subjects and 1572 nights of sleep was used to map a sound sleep pattern. The subjects were further divided into four age groups to determine the relationship between sleep quality and age pattern. Further studies should evaluate the accuracy and its application (33).

Other technological and machine-learning methods

Several recent studies have also introduced new methods for the recognition and assessment of sleep quality and sleep patterns in smart home settings. One study developed a face recognition sleep aid device that recognizes the user's mood during the night automatically plays soothing music and sets the room temperature (34). Another study aimed at developing a sleep monitoring device based on wrist movement, using a compact and portable processor and an integrated accelerometer. It can detect awake and sleep states and classifies the sleep stages into four categories; "awake," "light sleep", "deep sleep", and "REM". Being a non-invasive measurement of sleep stages, further studies can investigate its applicability for healthcare workers to monitor their patients in a smart home setting (35). Helena is another sleep aid device that recognizes sleep activities such as entering and exiting the bed, sleep position changes, and other movement along with vital signs and falls from bed. This system determines this movement based on bed vibration and a novel machine-learning method with an accuracy of more than 90%. Due to the detection of falls from bed, this device can have a great application for geriatric patients who are suffering from mental disorders. Several studies have investigated the potential of monitoring and supporting sleep apnea patients, sleep performance, bruxism, and other sleep disorders (36-42). Table 1 summarizes the clinical measurements, interventions, or outcomes of the aforementioned sleep monitoring systems.

Human-centric lighting (HCL): Introduction and potential for future application

Humans respond to lighting both visually and non-visually, psychologically and physically. Attention, visual discomfort, pupil changes, melatonin suppression, cognitive changes, circadian rhythm, and

sleep quality are among a few responses that lighting can affect (43). Circadian rhythm is the human's biological clock that recognizes light/dark patterns and is responsible for numerous physiological responses such as regulation of hormone secretion, autonomous nervous system, sleepiness, quality of sleep, etc (44). This clock works by the amount of light that it receives during the day (45). With the rise of IoT and technological advances in LED light sources and lamps that can prepare any combination of the visible light spectrum and emulate natural sunrise or sunset light patterns, several endeavors have been made to make tailored lighting. Lighting enhances physical and mental activities and improves sleep quality. Human-centric lighting (HCL) which has recently been introduced, encompasses different solutions that consider light as a biological mediator that can trigger visual and non-visual responses (44). Although upon its introduction, several scholars have met its concept with skepticism (43,46), however, the integration of HCL in home environments and healthcare facilities has been approved and implemented. A recent study aimed successfully at improving the sleep quality of older adults in residential communities by tuning environmental lighting (47), while another study improved and supported the circadian rhythm in patients who were hospitalized in an intensive care unit (ICU) (48). Smart human-centric lighting dramatically decreases sleep disruptions and enhances the quality of patients' sleep in nursing homes, according to a prior study by Park KS *et al*., (49). A technique called Tunable White Light for Elders (TWLITE) was developed to assess the effects of home-based lighting interventions on older adults. The TWLITE findings lend credence to the idea that, particularly for older adults, tunable whole-home lighting systems are very acceptable and practically implementable when employing an automated platform for continuous data collecting (50). The true potential and applicability of HCL in influencing and improving sleep quality are yet to be further investigated.

Sleep hygiene and sleep quality play a crucial role in a human's physical, mental, and emotional status. A great part of recent advances in IoT dedicated itself to facilitating the detection of sleep disorders and sleep abnormalities to further eliminate those factors that adversely influence the quality of sleep. The body of research encompasses two major parts; theoretical and practical implications. While new theoretical approaches have been introduced at a significant pace in the recent past, further studies should search for the capacity of their practical application regarding sleep hygiene and sleep quality. Numerous smart home-based applications and technologies have been introduced, and in this review, several important examples have been thoroughly discussed. Facilitation of the integration of these technological devices in smart homes can effectively improve not only the quality of sleep but also the quality of life of present and future generations. After all, that should be the sole purpose of technology itself.

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