Possibilities to integrate wearable biomonitoring sensors into adaptive lighting systems

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Abstract. There are two trends in modern lighting: the first one is lighting intelligence and adaptability, and the other is an orientation on the biological effects of light on the human body. This article analyzes the possibilities for further development of adaptive lighting systems from human biomonitoring data integration point of view. A review of wearable medical devices, which in the future could work as sensors of an adaptive lighting system, is presented.

1. Introduction

Modern lighting is no longer limited only by its functionality, such as combating darkness and prolonging daylight hours. Lighting has become an important part of a smart home, features adaptability, and can work with a person’s state. The concept of «adaptive lighting» is usually defined as an intelligent system, where lighting dynamically adapts to the presence of people or current environmental conditions through data transmitted by different sensors [1]. Lighting systems do not include modules that work with objectively obtained data about a person. At the same time, due to the development of distance medicine, the first devices that work directly with a person in real-time have already appeared. This paper analyzes the possibilities for further development of adaptive lighting systems, taking into account the development trends of wearable medical devices as sources of biomonitoring data about a person.

The reason for such discourse may be the trend to develop medical devices that are becoming smaller, more convenient, and portable, and provide the opportunity to obtain reliable data outside large laboratories. According to analysts, the market of wearable medical devices is destined to grow from USD 6,231.7 million in 2017 to USD 23,310.9 million by the year 2025 [2], while smart lighting is expected to grow from USD 7.93 billion in 2018 to USD 20.98 billion by 2023 [3]. There is also a notable trend to create a human-oriented environment.

The eye is a sensory organ that reacts to light and provides vision. However, at the beginning of the 21st-century studies showed that parts of the visual system (eyes and nerve channels) are used not only to provide visual functions. The so-called non-image-forming effects of light were discovered. The non-visual effect of light also impacts our mood, concentration, vigor, alertness, mental and physical performance [4]. In other words, 3 types of light exposure on the human body are distinguished: circadian, cognitive, and emotional.

Lighting control systems were much more expensive and complicated just 15-20 years ago and are fast developing. Previously, there were a large number of restrictions in lighting systems related to the number of lighting devices, their compatibility, and control units. A big number of luminaires is no
longer a problem since there are solutions for lighting control of entire cities now [5]. The indoor lighting control system usually works by receiving a signal from illuminance sensors. The rapid development of smartphones has allowed the replacement of sensors with mobile phones, which almost everyone has nowadays [6]. The number of publications about lighting control systems is growing; for example, in the journal “Energy and Buildings” the share of such publications is about 33%. This fact indicates a huge interest of professionals in various spheres in the development and integration of lighting control systems [7]. Lighting is not just light at this stage of technology development. Lighting is a monitoring tool of the system as a whole, which is a metering system for electricity consumption. This is a way of influencing human biological rhythms [8] and tracking customers’ position in a store as well [9].

The majority of modern adaptive lighting systems are based on external environmental parameters. The systems that react to the movements of a person, their presence, as well as climate change, day and night cycles are quite common. Lighting systems, which are positioned as biologically effective, are widely represented on the market. However, lighting settings that affect circadian rhythms (color temperature and luminous flux of luminaires) are changed per the programmed script [10], [11], or are adjusted by the user [12]. Adaptability in these systems is primarily associated with the use of presence/motion sensors, as well as photosensors. The adaptability, in this case, is aimed to reduce energy consumption.

As a transitional stage from external to internal parameters, there are systems that collect data from the external environment to influence the human condition. For example, an adaptive system can analyze the color of the sky to determine the correlated color temperature of natural light and bring artificial lighting closer to natural [13]. Thus, harmonization of the interaction of human circadian rhythms and artificial lighting is achieved. It is worth noting that such adaptive systems are still at the level of scientific development and have not been introduced into mass production.

There are also prototypes of adaptive lighting systems that work directly with human data received from wearable devices and sensors. In the Swedish Healthy Home project, the system collects the user's lighting history with the Daysimeter wearable device and supplements it with the necessary quantity and quality of artificial light ensuring the circadian effect. Achieved by the data integration system directly controls the lighting system or gives the users information about what kind of light they need [14].

These days scientists are considering options for integrating biomonitoring devices into adaptive lighting systems. For example, the ALADIN project aims to create a lighting system that will help older people live independently at home for a longer time and improve their quality of life. The prototype should help people achieve a state of mental activity or relaxation in specific situations by adjusting lighting [15]. Shifting the focus from external to internal parameters, a great potential is hidden in the possibilities of monitoring the human condition in real-time. The trends in the development of medical devices are wearability, miniaturization, as well as a combination of several sensors to read physiological and psychophysiological data in one device.

However, there are no examples of wearable sensors as devices that collect, process, and transmit information about a person on the smart homes market, especially on the market of smart lighting. At the same time, a large number of patents in human biomonitoring indicate the relevance and prospects of the combination of wearable monitoring devices and a controlled lighting system in one device. Patents describe lighting systems working with wearable sensors, that determine body temperature, pulse, user location, combined with external environmental factors, such as temperature and light [16]. Some biodynamic systems are described with a heartbeat sensor to control light devices when the user falls asleep and wakes up [17]. There are patents to adjust the color temperature of the source due to wearable sensors monitoring human condition [18].

To promote human health and well-being, the principles of how lighting works and its dynamic quality must include knowledge and data on the effects of light throughout the day, and light interaction with biological systems [14]. An intelligent lighting system based on biomonitoring can cope with this better than manual control, since it can perform complex human condition tracking.
around the clock in real-time, and the control algorithms are based on scientifically proven patterns of light effect on the human body. Shortly (Figure 1) one small sensor, a finger patch (already developed by scientists), can become a “receptor” of the lighting system for a home or an office and provide information about a person’s psychophysiological state: level of arousal and stress, circadian rhythm, concentration and performance, emotional and cognitive fatigue. At the same time, the adaptive system monitors a person through surveillance cameras and can identify complex and nuanced emotional and cognitive states when analyzing their behavioral patterns. This real-time data has not only the potential to determine the psychophysiological state of a person but also to correct or maintain it through light.

Figure 1. The lighting system monitors and reacts to a human’s psychophysiological state via the “receptor” finger patch.

2. Materials and methods
The criteria to analyze wearable biomonitoring devices to select gadgets are presented:
1. Functionality. Devices should read only the psychophysiological parameters affected by light. Psychophysiological parameters, which can change when exposed to light, are:

- hormone level;
- brain signal;
- heart rate;
- electrodermal activity.

2. Portability of sensors.
3. Independence from medical centers. Mandatory data analysis and decoding by a medical institution can create a large delay in the reaction of the light system.

3. Results
Based on market analysis wearable sensors are divided into 3 groups: devices to study circadian rhythms, cognitive and emotional states of a person. The development of technologies in each group is described. The existing wearable sensors presented in the analysis can be integrated into lighting systems to collect and analyze biomonitoring data in these groups.

3.1. Circadian rhythms
The objective methods to analyze the state of a person undergo significant changes. Until recently, to analyze a person’s hormonal balance when studying circadian rhythms, it was necessary to conduct
research and process data only in specialized medical centers. Now electrochemical patches (portable wearable patches measuring hormone levels) can determine the effect of various light characteristics on the sleep-wake cycle of a person.

![Figure 2. Evolution of circadian rhythms research methods.](image)

3.2. Cognitive state
Currently, there are many devices from completely different industries to research a person’s level of attention and concentration under certain environmental conditions. Studying the effect of specific light characteristics on human cognitive activity is becoming easier and more widespread. Today a researcher does not depend on huge non-portable machines, can conduct tests in the natural environment, and provide subjects with a wider field of action.
OBELAB has created the NIRSIT, portable functional magnetic resonance imaging (fMRI) [22]. It visualizes the processes in the brain, tracks the progress and level of depression, checks the signs of emotional reactions to specific stimulations, and monitors the learning process. This tool can be used to determine the effects of light on psychological processes such as learning, memory, depression, and anxiety. This device is not unique on the market right now. OPENWATER has made the same wearable device disguised as a regular hat [23].

Another perspective tool is a surveillance camera that allows to evaluate the behavior of people on the street. Affectiva is a platform for reading the cognitive and emotional biomarkers of the human face in real-time. It can serve as a tool to determine the influence of light characteristics on the cognitive functions of a person and allows working with several subjects in parallel [24]. The authors of BrainWaveBank emphasized the possibility of measuring the cognitive states of a person based on the health study of older people [25].

### 3.3. Emotional state

Another set of studies of interest to light designers is the emotional impact of lighting solution or its specific characteristics on the user. Modern science helps the researchers allowing studying the human condition easily and conveniently. Sensors combine several types of data collection functions (for example, measuring the electrodermal activity of skin and pulse) and are completely portable.

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**Figure 3.** Evolution of cognitive state research methods.

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**Figure 4.** Evolution of emotion state research methods.
Portable electroencephalography (EEG) or fMRI devices like the aforementioned NIRSIT and OPENWATER hat can become one of the tools for obtaining data on a person’s emotional state. OPENWATER provides an opportunity to study the influence of light on such psychological processes as depression and anxiety.

Feel is a gadget bracelet, integrates several biomonitoring sensors. It measures skin electrodermal activity and heart rate, which give objective data of a person’s emotional state [26]. The Spire device takes into account the respiration rate, heart rate, sleep quality, and displays a person's stress level, which can be applied directly to adaptive systems.

Market analysis of portable biomonitoring devices shows that modern medical technologies provide comprehensive monitoring of a person’s state in real-time. Their integration as sensors of adaptive lighting systems allows a more accurate effect on the human body, based on scientifically proven laws, and result monitoring.

| State                          | Indicator          | Type of device          | Example                  |
|-------------------------------|--------------------|-------------------------|--------------------------|
| Circadian rhythm              | hormone level      | patch                   | Stanford’s sensor        |
|                               |                    | bracelet                | Sweatronics              |
|                               | brain activity (fMRI) | headset                | NIRSIT by OBELAB, OPENWATER |
| Cognitive and emotional statement | brain activity (EEG) | headset                | BrainWaveBank            |
|                               | facial expressions | platform for computing vision | Affectiva                |
| Emotional statement           | electrodermal activity of the skin | bracelet | Feel                     |
|                               | heart rate         |                         |                          |

### 4. Discussion

Being aware of the problems and threats associated with artificial intelligence, artificial intelligence sphere continues evolving, and we are entering the sphere of ubiquitous sensors. The design of such systems requires an understanding of both functional and ethical issues. Specific sensor properties impose certain restrictions on them. For example, they are hyper-personalized: if a system adapts to the psychophysiological state of several people, it will have to average the results that refute the existence of an adaptive system. Hence, the area of application is limited to indoor space.

Medical portable devices may collect various personal data. It is important to note that all medical personal data must be protected from theft and alteration, therefore data protection is a crucial point in the development of such systems. Software and data transfer systems must protect personal data and portable medical devices from hacker attacks. Hacking a diabetic's smart contact lenses to get erroneous readings can lead to their owner either not receiving warning signals or overreacting to the exaggerated glucose readings. This can not only have serious consequences but also be fatal [27]. There are several difficulties for fully running adaptive lighting systems that work with a person's medical data:

1. Portable medical devices often need to send data to a smartphone or control unit for the correct operation of adaptive lighting systems. To do this, a significant increase in the battery capacity of the device or a constant device charging is required.
2. Portable devices may have difficulty in positioning a person in an apartment. Considering the smart home concept, where the lighting varies depending on a person’s medical indicators, the positioning will be easier to organize using special cameras than with portable devices.

3. There may be a delay in transmitting a large amount of information between a device, a smartphone/control unit, or a lamp since the mathematical capabilities of the device are limited. Then, the sense of adaptability is lost in principle, and the device with a long delay will not be in demand.

4. Another challenge is the construction of a “psychological” relationship between a person and the system. The possibility of choice (or its illusion) is a natural need in human life. Depriving a user of this opportunity, transferring to the algorithm the right to dictate living conditions, there is a risk of putting a person in a subordinate state, which will cause an internal (and then external) protest. The system, first of all, should not be a dictator for a person, but an adviser.

To avoid negative emotional manifestations, a person must be aware of the causal relationship between their psychophysiological state and the recommended parameters of the light environment and be able to follow or not follow the recommendations received.

5. Conclusions
The development of technology leads to a constant change in the relationship between a man and a machine. Adaptive lighting systems might be created with the integration of sensor types analyzed in this paper. Such systems have a lot of opportunities and challenges. Adaptive lighting systems with human health monitoring will develop further despite all technical and ethical problems. A balanced and skillful approach to their development with the integration of medical sensors makes lighting an efficient assistant of the person in the near future.

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