Final Year Project

Bluetooth Light Sensor

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Abstract

The current document provides an in-depth analysis of the Bluetooth Light Sensor Project. The aim of this project is to develop a fully functional sensor that measures the intensity of light at different wavelengths within the visible spectrum. A mobile application then retrieves the data from the sensor, storing it both locally and in a database within a secure server. The sensor will be used as a proof of concept to develop a commercial product that will be used to perform studies at the Surrey Sleep Research Centre (SSRC) aimed at analysing the influence of light on human overall health and sleep quality. The design, optimisation, calibration and testing of both the initial and the final prototypes of the device, as well as the analysis of the data collected, are thoroughly described in this document together with the planning, risk assessment and cost for the project.

Acknowledgements

I would like to thank Professor Klaus Moessner from the 5G Innovation Centre (5GIG) [46] for his guidance and support throughout the entire project.

Moreover, I would like to thank Dr Imalka Jayawardena from the Advanced Institute for Technology (ATI) [45] for providing me with the necessary equipment and information to calibrate the sensor.

Additionally, I would like to thank Dr Victoria Revell from the Surrey Clinical Research Centre [48] for providing me with light sources and other equipment to collect preliminary sensor data and analyse it.

Finally, I would like to thank Stephen Mills, John Mouat and Laurence Drysdale from the Electronic Engineering Undergraduate Laboratories [47] for allowing me to use the laboratory equipment and assisting me with numerous hardware setbacks.

Disclosures, Author's Contribution and Constraints

This project was completed individually by Eva Esteban under the supervision of Professor Klaus Moessner as the Final Year Project for the Electronic Engineering with Computer Systems Bachelor of Engineering (BEng) degree.

The timeline for the project extends from October 2018 to May 2019, with the work being completed at the University of Surrey in Guildford, Surrey, United Kingdom. The budget for the project was initially set to £100 and extended three months into the project with the project supervisor's approval in order to satisfy the specification requirements of the hardware device.

The heart rate, steps and any other vital sign information collected during this project and presented on this report corresponds to Eva Esteban who, as the principal author of this project, authorised for her data to be used for this particular project.

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1 Introduction

Light plays a critical role in regulating many biological processes including sleep, circadian rhythms and the release of melatonin. The human visible spectrum of light is the range of the electromagnetic spectrum that the human eye can process. Typically, the wavelengths detected by the human eye range from 380 to 700 nanometres (nm) [60]. Different narrow bands of the visible spectrum i.e monochromatic light produce different colours which are known as the pure spectral colours. These are Violet (380–450 nm), Blue (450–495 nm), Green (495–570 nm), Yellow (570–590 nm), Orange (590–620 nm) and Red (620–750 nm). Their spectrum is continuous and presents no clear boundaries between the colours [7].

Research suggests that different colours of visible light have varying degrees of impact on our health and quality of sleep. For instance, it has been shown that blue light interacts with the human eye photoreceptor system, which is the one that triggers certain human body responses, such as resetting the internal circadian body clock and suppressing melatonin release, especially in old people [26]. As humans, we are exposed to blue light from both natural sources such as the sun and artificial sources such as Light Emitting Diodes (LEDs). The light emitted by most commercially available LEDs appears white to the observer but is in fact composed mostly of blue light with some yellow spectrum [1]. These LEDs are widely used in phones, television screens, computers and many other devices that constitute an vital part of many people's everyday lives, therefore increasing the likelihood of this light triggering responses in the human body. Additionally, new research shows that the cone photoreceptors in the human eye, which are mainly sensitive to green light, also encourage biological responses [23].

The Surrey Sleep Research Centre (SSRC) was established by Professor Derk-Jan Dijk in 2003 at the University of Surrey. The research undertaken by the centre includes studies on the regulation of human sleep by circadian rhythmicity, the effects of aging on sleep and circadian rhythms, and the effects of light on performance, sleep, and circadian rhythms, amongst others [59]. Currently, there are no available resources at the centre for measuring the intensity of light emitted at the wavelengths corresponding the different spectral colours in a standarised way.

The aim of this project is to design, develop and build a fully-functional electronic light sensor that can measure and store the intensity values of light at different levels within the visible spectrum. Moreover, the project must include the design and development of a mobile application which communicates with and retrieves the data from the light sensor. The application must time stamp the light data and include the Greenwich Mean Time (GMT) information to increase robustness by avoiding any time miscalculations should the study participants be travelling during the data collection process. The processed data must then be stored in a platform that is secure and accessible to the researchers at SSRC for analysis.

Being able to analyse the effect of visible light on humans both independently and in conjunction with other data will aid in the understanding of a number of sleep disorders, such as Seasonal Affective Disorder (SAD), insomnia and sleep apnea. This will, in turn, help to develop novel therapies that use light alone or in conjunction with other resources to successfully treat or lessen the detrimental effects of these and other sleep disorders. Furthermore, coloured light as a therapeutic approach could be extended to other disorders caused by the disruption of biological processes other than sleep in which light plays a role.

2 Literature Review

2.1 The Role of Light in Human Responses

Over the past few years, studies have shown that light plays an important role on a large number of human biological and behavioural processes. The findings highlight the importance of retinal illumination in decreasing fatigue, reducing depression, treating Seasonal Affective Disorder (SAD) and modulating circadian rhythms. These effects are caused by certain responses of the human body when exposed to light that do not seem to be related to specific patterns of exposure [53]. This has been proven by scientific studies that feature a group of blind humans who were incapable of forming images but could detect light to regulate melatonin secretion. Such biological responses have therefore been classified as non-visual or non-image forming [40].

One of the non-visual responses is the regulation of our internal circadian clock. This constitutes one of the most prominent effects of light on human health since circadian rhythmicity has been shown to have an impact on metabolism, brain and behaviour [32]. As a result, a number of light-based therapeutic approaches have been developed to treat different disorders including Seasonal Affective Disorder (SAD), depression, bullimia, dementia and chemotherapy secondary effects, among others. Moreover, many research studies highlight the effectiveness of timed light exposure as a therapy for different sleep disorders such as free-running disorder, shift work disorder, sleep-phase disorder and jet lag disorder [37].

2.2 The Human Eye

The human eye uses light and colour to form images that can be interpreted by the brain. In this process,light enters through the pupil, and several biological structures such as the crystalline work together to focus it on the retina, particularly on the fovea. The fovea is a depression on the retina that has the highest visual accuracy and contains the cones and rods of the eye [9]. The cones and rods are the photoreceptors that transform the photon energy received from light into electrical impulses. While rods are significantly sensitive and specialise in vision with low levels of light, cones showcase a lower sensitivity, therefore specialising in daylight vision. It is the retinal ganglion cells (RGCs) that then convey the electrical impulses to the brain for interpretation.

Recent studies have proven the existence of a different type of photoreceptive RGCs in the mammalian retina. This photoreceptive system is composed by the intrinsically photoreceptive retinal ganglion cells (ipRGCs), which present an opsin-like protein, known as melanopsin. Melanopsin is much less sensitive to light and responds more slowly. However, once its activation has been reached it is sustained over long periods of constant illumination [53]. Studies have shown that thresholds as low as illumination levels of 1 lux can activate this response [24]. Through different studies it has been shown that the ipRGC firing responsible for the human responses is caused by both the photoreception of melanopsin and the rod and cone signals [25].

2.3 Spectral Colours

The human visible spectrum ranges from 380 to 700 nanometres [60]. Even though the spectrum is continuous it can be divided into narrow bands that are known as monochromatic light. These bands correspond to the pure spectral colours, which are Violet, Blue, Green, Yellow, Orange and Red. A visual representation of the colours as well as their corresponding ranges can be found on Table 1.

Visible Spectrum	
Colour	**Wavelength (nm)**
Violet	380 to 450
Blue	450 to 495
Green	495 to 570
Yellow	570 to 590
Orange	590 to 620
Red	620 to 750

Table 1: Visible light spectrum bands with corresponding frequencies.

2.4 Spectral Sensitivity of the Human Eye

The light detection mechanisms showcased by human rods, cones and ipRGCs are dominated by different photopigments and thus manifest different spectral sensitivities. Rod opsin, which is the photopigment that characterises rods has its peak sensitivity around a wavelength of 550 nm. Cones can be divided into three types: S, M and L. S cones. S cones use an opsin known as cyanolabe, which has been shown to have peak sensitivity at around 420 nm. M cones use an opsin known as chlorolabe, which reaches its maximum sensitivity at 535 nm. The L cones opsin is erythrolabe and has peak sensitivity at 565 nm [53]. With regards to melanopsin in humans, research indicates that it has its peak spectral sensitivity at around 480 nm [52].

The wavelengths at which cones exhibit peak sensitivity are all within the visible range of colours previously explained in this document. Being able to record the biological and behavioural reaction of subjects when exposed to these particular wavelengths would be useful to understand the influence of coloured light on the regulation of circadian rhythms and how this, in turn, affects the sleep quality of subjects both healthy and with different medical conditions. The interaction between light wavelength and the non-visual responses triggered could aid in developing treatments to some of the above-mentioned health conditions. It could also help to explain why changes in the light environment, such as those associated with short winter days, working in shifts, and travelling between geographic zones are associated with changes in sleeping patterns, mood and cognitive function [61].

2.5 Measuring Light

There is a growing need in the scientific community to establish standarised methods of measuring the intensity of light. For a large number of years, research on the influence of light on the body's responses has relied on the use of lux meters. Lux meters are devices that measure the intensity at which the brightness of light appears to the human eye. However, in order to fully investigate the role of the recently discovered ipRGC photoreceptors in the physiological and behavioural state of human beings it is necessary to obtain more precise and discriminative measurements [53]. The approaches proposed by the research community on how to measure light for this purpose include independently measuring and quantifying the intensity of light at the wavelengths at which the different photoreceptive inputs of the human eye showcase sensitivity, which for this research work consist of 420, 480, 535, 550 and 565 nm, as mentioned in section 2.4 of this report.

2.6 Proposed Solution and Feasibility

In this project, a system is proposed as a solution to the challenge of measuring and analysing the effects of light on human responses. The proposed system will enable researchers to measure the intensity of light at 450, 500, 550, 570 and 600 nm with 40 nm of full-width half-max detection. Therefore, once calibrated the device will measure the intensity of light at the wavelengths corresponding to the sensitivity peaks showcased by the different photoreceptors in the human body - 420, 480, 535, 550 and 565 nm - as well as at any other wavelength or wavelength range within the human visible spectrum.

The proposed product is comprised of three main elements: an electronic light sensor, a mobile application, and a secure database for scientific data storage. The electronic light sensor consists of a wearable device that research study subjects can comfortably carry with them for long periods of time while it measures the levels of light they are exposed to. The second component of the system is a mobile application, which retrieves the data from the sensor. It displays the data to the user and stores it locally for analysis. The final component of the system is a storage unit, which includes the functionality to both communicate with the mobile application and store the retrieved light data in a secure database accessible to researchers.

The use of this system will enable researchers at the Surrey Sleep Research Centre (SSRC) to correlate light intensity information with the any other biological and behavioural data they collect during the different studies. Since different wavelengths of light affect different photoreceptors within the human eye, which, in turn, play different roles on regulating processes within the body, it is vital to have detailed information on the levels of different coloured light the patients are exposed to. This will allow for a much more in-depth analysis than exclusively measuring the general light illuminance and will aid in researching the therapeutic applications of coloured light.

2.7 Light Sensor

Prior to commencing the development of the project, background research on the current available technologies was completed in order to determine both the feasibility of the product and the most appropriate technological options for its development.

There are chip-scale spectral sensing solutions available [3] that can be calibrated to measure the intensity of light at different wavelengths within the visible range. Additionally, there are chips and modules available to transmit data between electronic devices and mobile phones via standard Bluetooth protocol [51]. The idea for this project is to integrate one of these sensors and a Bluetooth module with a microcontroller, which will provide the necessary resources to collect the data from the sensor and send it to a mobile application. The device must be small and energy-efficient in order for study participants to be able to wear it comfortably. There are available resources for application development compatible with Bluetooth that feature in the Android Open Source Project [28]. To store the data, there are both free and paid storage options available, which include relational or Structured Query Language (SQL) and non-relational (NoSQL) databases. Data stored in relational databases must all adhere to the same structure, whereas non-relational databases are dynamic and can accommodate for unstructured data. Even though NoSQL databases are more flexible, SQL databases are widely used and currently have a larger number of resources available. Moreover, they provide a table-based structure which is suited for organising the data collected from the light sensor in this particular project. Therefore, relational databases were the approach chosen for this task.

The system built in this project is a wearable device and will be used to measure the intensity of light at the wavelengths that interact with the various human eye photoreceptor cells outlined in the previous section of this document. The data collected for each patient can then be analysed in conjunction with other data collected for each respective patient, such as sleep quality, heart rate, physical activity or general well-being. For this particular research work, the additional data was collected using a Xiaomi MiBand 3 device [65], however, alternative devices can also be used. This information will then be used for researching the relationship between light and the human body's responses for subjects who are healthy and for subjects who have different sleeping disorders.

3 Project Planning and Structure

3.1 Initial Planning

An iterative approach was chosen to develop the product in order to allow for flexibility and detection of potential errors from the early stages of the project. An initial Gantt chart was developed to divide the project into stages and organise the work considering external factors that can influence the project progress during the year, such as exam revision or coursework deadlines. Both the initial Gantt chart and a high-level Gantt chart for the second semester were included in Appendix A of this document. These efficiently distribute the workload according to exam periods.

3.2 Risk Assessment

The project carries several risks. These were analysed and prevented by considering their consequences and solutions in advance. The impact of the risks ranges from very severe to very mild. A breakdown of the most significant risks underlying the project together with their corresponding solutions can be found on Table 2.

Risk	**Impact Level**	**Consequences**	**Preventive Actions**
Hardware or PCB malfunctioning.	Very severe.	Wrong functioning of the sensor and consequent inability to collect data.	Enough time was left between stages to order new components if needed. Extreme care was taken when handling components.
Long lead time for hardware components.	Severe.	Inability to carry on with the project until the components arrive.	Hardware design was prioritised to order products early, using the time between deliveries to develop the software.
Malfunctioning of a module leading to malfunctioning of the whole system.	Severe.	Inability to save the data collected from the sensor smoothly and in one step.	The development and testing for each module was performed individually and using validated external tools to ensure robustness.
Reaching maximum memory storage for data.	Significant.	Inability to keep storing data.	A university server destined to storing large amounts of data was used and the possibility of vertically expanding the database was explored in order to ensure it would be possible to add more memory if needed.

Table 2: Risk assessment and solutions for the project.

3.3 Project Structure

The different stages of the project were structured following the Scrum methodology. Scrum is a framework which derives from the agile methodology and is commonly used to successfully develop complex products in the software development field [36]. However, several case studies have shown that the agile methodology increases productivity and deliverable quality in non-software projects as well [30]. The Scrum methodology consists of diving the project development into sprints or two-week long cycles. For this particular project, the cycles were one-week or two-week cycles depending on the complexity and time required to complete the tasks assigned to each sprint.

Each sprint meeting had three stages: the Sprint Review, the Sprint Retrospective and the Sprint Planning. During the Sprint Review, the work completed during the last cycle was reviewed. Both the complete and incomplete tasks were analysed, and solutions to any problems that may have arised were discussed. The Sprint Retrospective consisted of analysing the progress made during the sprint and determining whether the workload was adequate and how the next sprint can be improved. Finally, the Sprint Planning section of the meeting consisted of selecting and outlining the tasks to be completed during the next cycle.

3.4 Progress Tracking

The project work was tracked using the free online project management tool Trello [62]. Within the Trello environment, a board was created for the project. The board incorporated three sections: "Sprint Backlog", "In Progress" and "Completed". The tasks for each sprint were added after every meeting and moved between the sections as progress was made. An example of a sprint logged in the Trello environment can be found on Figure 1. Additionally, a laboratory book was used to develop the project sketches, log the meetings with the supervisor, and annotate the experiments and the test results as well as any problems or setbacks encountered throughout the development of the product.

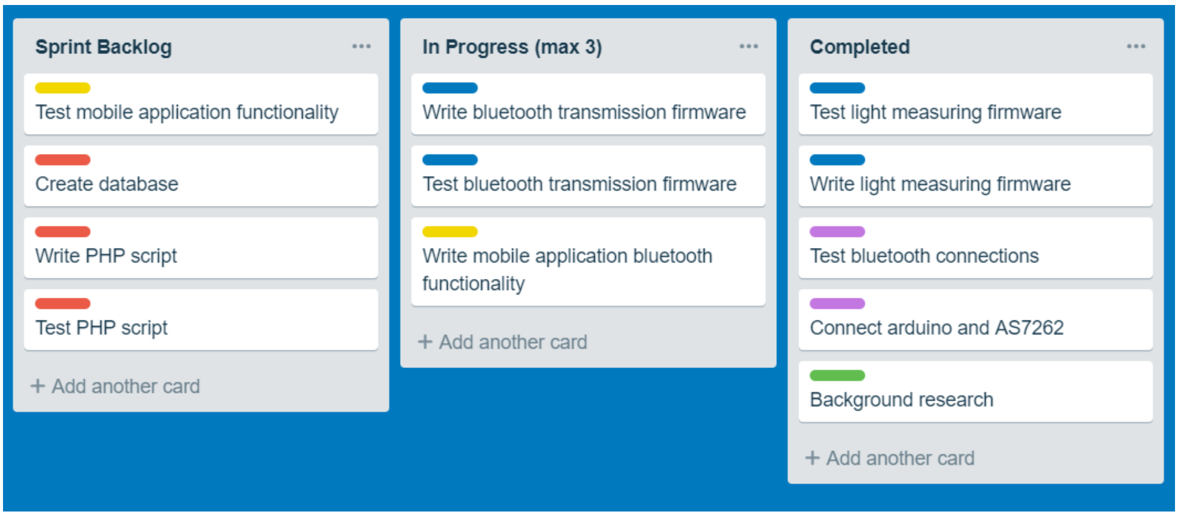

Figure 1: Example of a sprint logged in Trello.

4 First Prototype: Technical Aspects and Testing

Once the research was successfully completed, a prototype for the product was designed and developed. The prototype was divided into four sections: hardware, firmware, application and data storage. The individual parts of the prototype were tested separately as well as in combination with each other. Figure 2 shows a simplified diagram of the project components.

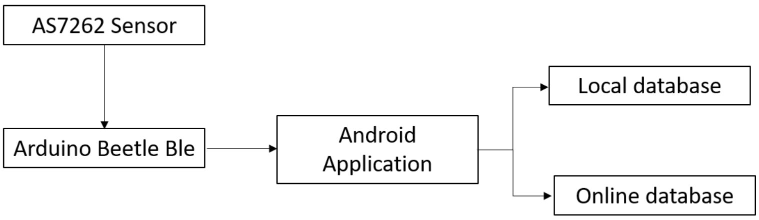

Figure 2: High level diagram of the Bluetooth light sensor system.

4.1 Hardware Development

The initial hardware prototype was developed using the Arduino Beetle BLE from DFRobot [11] and the AS7262 Sensor from AMS [2] in the AS7262 Breakout Board from Adafruit Industries [34].

The Arduino Beetle BLE was chosen due to several factors. To begin with, it incorporates Bluetooth Low Energy technology through the chip CC2540 from Texas Instruments [35], which allows for the retrieved sensor data to be sent to a mobile application via Bluetooth communication. The Bluetooth Low Energy approach was chosen to minimise the device's power consumption [8]. This makes the product both more user friendly by reducing the number of charges required, and environmentally friendly by reducing the battery usage. Finally, its 28.8mm X 33.1mm size and 10g weight makes it appropriate for a user to wear comfortably during the studies.

The AS7262 Sensor Breakout Board measures both the ambient temperature and the light intensity at six channels which cover the human visible spectrum of light. The channels correspond to 450 nm, 500 nm, 550 nm, 570 nm, 600 nm and 650 nm, each represented by a Gaussian curve with 40 nm Full Width at Half Maximum (FWHM), as shown on Figure 3. These channels correspond to the colours Violet, Blue, Green, Yellow, Orange and Red, respectively and can be calibrated using diffused light. The temperature is measured in degrees Celsius and the light intensity values are measured in $\frac{Counts}{\frac{\mu W}{cm^2}}$. The sensor can provide both raw and calibrated light intensity values [20]. Both the Arduino Beetle BLE and the AS7262 incorporate the Inter-integrated Circuit (I^2C) Protocol, which constituted a simple and efficient option for serial communication between devices [63].

For this prototype the Serial Clock (SCL) and Serial Data (SDA) connections were used to enable I^2C communication between the devices. The components were connected using a breadboard, and the connections were tested using both a Digital Multi-meter and the built-in LEDs to ensure the correct voltage was supplied to the components.

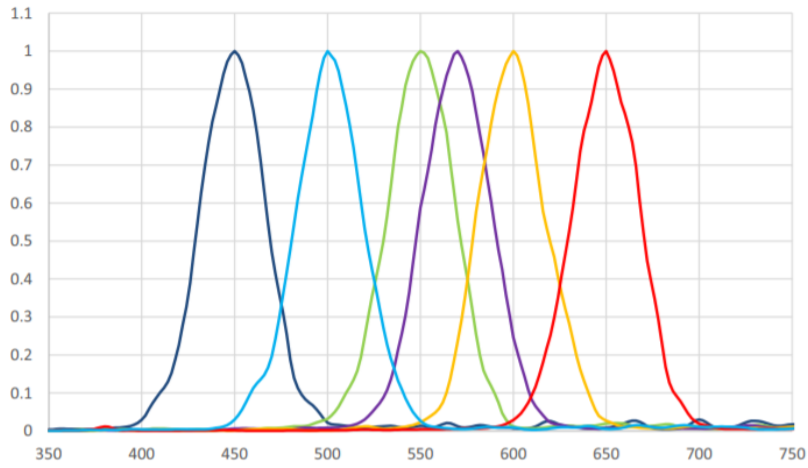

Figure 3: Gaussian curves representing colour channels measured by AS7272. Source: [20].

The device has three main elements that consume power: the microprocessor ATMega328P in the Arduino, the Bluetooth Chip CC2540 and the AS7262 sensor. The theoretical current consumption of the ATMega328P is 15 mA. The Bluetooth chip consumes 20 mA when sending and 18 mA when receiving according to its specifications. An oscilloscope was used to measure the time the Bluetooth takes to send a block of data. The Bluetooth was measured to take around 3 ms to send a piece of data, therefore the values for the Bluetooth chip current consumption need to be scaled by 0.003. The sensor consumes 5 mA. Additionally, the two LEDs on the board were estimated to consume around 1 mA each. Therefore, the total current consumption of the device when transmitting data every 5 seconds is given by $I_s = 5 + 15 + \frac{20*0.003}{12} \approx 20$ mA, which multiplied by 1.2 to accommodate for errors and hardware variations gives a total theoretical consumption of the device of approximately 26 mA $\pm$ 10% error. The experimental current consumption of the device was measured to be 28 mA, which is within the theoretical error margin.

A rechargeable Lithium Polymer battery of 3.7V and 1800 mAh was chosen for the product in order to limit both the waste and the energy used, since recharging the battery requires less energy than making a new one [10]. The Adafruit Micro Lipo was chosen as the charger in order to be able to comfortably recharge the battery through a USB connection [33]. Since Lithium Polymer batteries should not be discharged further than 80% of their capacity, the total power provided by the battery is equal to $I_b = 1800 * 0.8 = 1440$ mAh. Thus, the device is expected to function for $T = \frac{1440}{28} \approx 51$ hours after the battery is recharged. A Micro Lipo - USB LiIon/LiPoly charger was used to recharge the battery [33]. The first prototype hardware can be observed in Figure 4.

The prototype was cased by using transparent heat shrink tube with an attached metal butterfly pin back, with the section of the casing corresponding to the temperature sensor and the AS7262 chip being removed to allow for the light to reach it directly. This approach was chosen for its affordability, light weight, and easy manipulation. It allows the user to pin it to their clothes either on either their chest or their arm. Pictures of the first prototype of the device with casing and being worn by a user can be found on Figures 5 and 6, respectively.

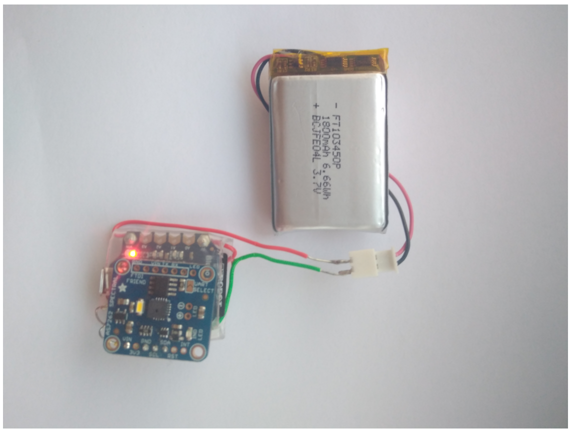

Figure 4: First hardware prototype of the sensor.

Figure 5: First hardware prototype of the sensor with casing.

Figure 6: Image showing a user wearing the first prototype of the device.

4.2 Firmware Development

The Arduino Integrated Development Environment (IDE) was used to develop the prototype firmware [4]. The data from the sensor was extracted by combining several functions from the Arduino library for the Adafruit AS7262 Sensor Breakout Board. The firmware code can be found on Appendix B of this document. It initially tests that a correct connection has been established between the Arduino and the sensor. This is followed by an extraction of the ambient temperature values, as well as the intensity of the light at at the six different channels. The data is then formatted and sent to the mobile application using the BLE functionality in the Arduino.

The correct performance of the code to read the sensor was tested by printing the results at each stage and checking them through the serial monitor available in the Arduino IDE. The correct functioning of the Bluetooth connection from the Arduino was tested by using the open source BlunoBasicDemo application installed in an android device. This application was developed by DFRobot and enables the user to check the connection and correct transmission of data between a mobile device and an Arduino Beetle BLE [54].

4.3 Application Development

Android Studio, which is the official IDE for Android app development [29], was chosen for the development of the mobile application. It was selected as the development environment due to its high number of available frameworks, debugging options and resources. Version control was performed by using the open-source version control system Git [27]. The mobile application incorporates more than 10 classes, therefore and due to length constraints for this document, its complete source code can be downloaded from the GitLab repository [21].

The open source BLE Generic Attribute Profile (LeGatt) template was used as a starting point to develop the application [57]. The application was divided into modules for scanning for the particular Bluetooth device, receiving data from it, time stamping the values and displaying them, and storing the data. This modular approach was chosen in order to simplify the error debugging process and to avoid the whole application's malfunctioning should there be an error in any of the parts.

First, the application functionality to connect to the Arduino and receive its data was implemented. This was tested by displaying the received data on the application screen and comparing the results to the results displayed in the Arduino IDE Serial Monitor. The data was then time stamped and displayed in the correct format. The third step was to implement the data storage options. For this, an innovative approach was incorporated into the project. The data was not only stored in an server database, but it was also stored in a local database. Even though it was not listed on the requirements, this approach was chosen to prevent the loss of data in the situation where the network connection of the mobile device is lost. Since the product is a wearable, there is a high chance of the users walking through an area with poor network connection. The application stored the data in a local database and when there is a network connection available, it sends the data to the server database, hence synchronising both databases to contain the same information.

Additionally, the User Interface (UI) was made intuitive and user-friendly by displaying the data which has successfully synchronised with the server database in yellow and the data which is not synchronised yet in red. The application was configured to run in the background by modifying the Bluetooth LeGatt template and by using android services together with activities, hence allowing for the data to be logged continuously even if the application is accidentally closed. Figure 7 shows an example of the data stored in the local database and displayed through the application.

Figure 7: Data stored in the local database displayed through the application.

4.4 Data Storage

The advantages and disadvantages of relational databases and non-relational databases were thoroughly analysed. The data received from the sensor has a fixed structure, which consists of a timestamp followed by the light intensity value, and can easily be accommodated to the tables in relational databases. Moreover, relational databases are more established and standarised than non-relational databases, with a larger number of testing tools and resources being available for the former ones. These features not only make migration of data an easy process, but it also ensures patient data is handled securely. These advantages were considered to outweigh the flexibility that non-relational databases offer and therefore a relational database approach was chosen for this project.

The computer language Structure Query Language (SQL) is widely used for relational databases and was chosen to implement the data storage options in this project. The open source Android library SQLite was used to implement the local storage functionality. From the mobile application, a local database is created. It contains a table with seven columns corresponding to: Timestamp, Violet, Blue, Green, Yellow, Orange and Red, where each column contains the intensity of the light in the range measured by the channel in the sensor corresponding to that colour. Once the database is created, the stored data remains in the database even if the application is closed and re-opened.

The creation and correct storage of the information in the SQLite local database was tested by trying different data combinations and checking their correct storage in the memory by accessing the phone's storage on the computer. By default, the data will be stored in the phone's internal memory. An in-depth analysis of the amount of data compared to the phone's memory was performed to ensure data will not be lost due to lack of space. Each data unit i.e one timestamp value and six light intensity values was found to fill approximately 38 bytes.

Most of the widely used phones nowadays have 32GB of memory. This allows the application to store around 842,105,263 bytes. However, SQLite incorporates the functionality to store the data in a specified folder, so external memory cards can be used if required. Should the local database run out of space, the data will keep storing in the server database. The SQLite database will be cleared when the user returns for a check-up, therefore making the space available for the data recorded during the next few days.

A MySQL server was established on the computer using XAMPP [22]. XAMPP is an open source web server solution that incorporates interpreters for scripts written in the Personal Home Page (PHP) language. MySQL is an open source Relational Database Management System (RDBMS) that incorporates SQL [43]. Through the set-up server, MySQL databases can be created and accessed. A database was created for the sensor, which incorporates a table with seven columns to store the timestamp, violet, blue, green, yellow, orange and red light intensity values, respectively. A PHP script was written to implement the connection between the mobile application and the database, which can be found on Appendix C of this document. The script receives the data from the mobile application via POST requests and uploads it to the database, notifying the application of any errors in the process. To ensure the correct functioning of the script, the system was tested using Postman, which is a free HTTP client for testing web services [50].

Once the local storage and server storage functionality were tested separately, a function in the application was written to integrate them by using online resources [41]. The correct functioning of the back-end of the software was tested by sending data to the local and server databases directly from the application. Once the correct functioning of this part was ensured, the full device prototype was put together. For each data transmission, the data from the sensor is successfully read by the Arduino, which sends the data to the mobile application. The mobile application connects to the device, timestamps and correctly formats the data, storing it in the local database and sending it to the PHP script when there is a networking connection available. The PHP script stored the data in the MySQL database, sending a confirmation to the mobile application once the process is complete. Figure 8 shows an example of the data stored in the server database.

Timestamp	Violet	Blue	Green	Yellow	Orange	Red
Mon Nov 29 19:25:43 GMT +00:00 2018	91	51	133	165	306	194
Mon Nov 29 19:25:48 GMT +00:00 2018	89	51	131	162	304	193
Mon Nov 29 19:25:53 GMT +00:00 2018	94	51	132	164	305	195
Mon Nov 29 19:25:58 GMT +00:00 2018	65	51	131	162	300	193
Mon Nov 29 19:26:03 GMT +00:00 2018	19	17	41	63	115	61
Mon Nov 29 19:26:08 GMT +00:00 2018	28	9	51	56	205	103
Mon Nov 29 19:26:13 GMT +00:00 2018	64	50	130	160	298	187

Figure 8: Example view of data stored in the server database.

5 Device Calibration

In order to analyse the performance of the sensor at different wavelengths within the human visible range, data was collected using the device for the range 350-750 nm in 5 nm intervals. The data collection process was carried out at the Advanced Technology Institute [45] by using a standarised light source. The source consists of a Bentham PVE300 incident photon to current conversion efficiency system, which includes two lamps: a 75W Xe lamp used for the wavelength range of 300 - 600 nm and a 100W Quartz halogen lamp used in the 600 - 1800 nm range. The Bentham PVE300 system was calibrated for the 300 - 1100 nm wavelength range using a crystalline silicon reference cell.

For each 5 nm interval in the 350-750 nm range, several measurements were taken with the sensor and averaged to provide an accurate light intensity value in order to reduce the error. The absolute light intensity values recorded by the sensor can be found on Figure 9. The characteristics for each channel were then normalised by using the algorithm present in the reshape function developed by MathWorks [49]. The normalisation results can be found on Figure 10. It can be seen from Figure 9 that the intensity range for the different channels is represented by a Gaussian curve, which matches the theoretical prediction extracted from the device data sheet and presented in section 4.1 of this document.

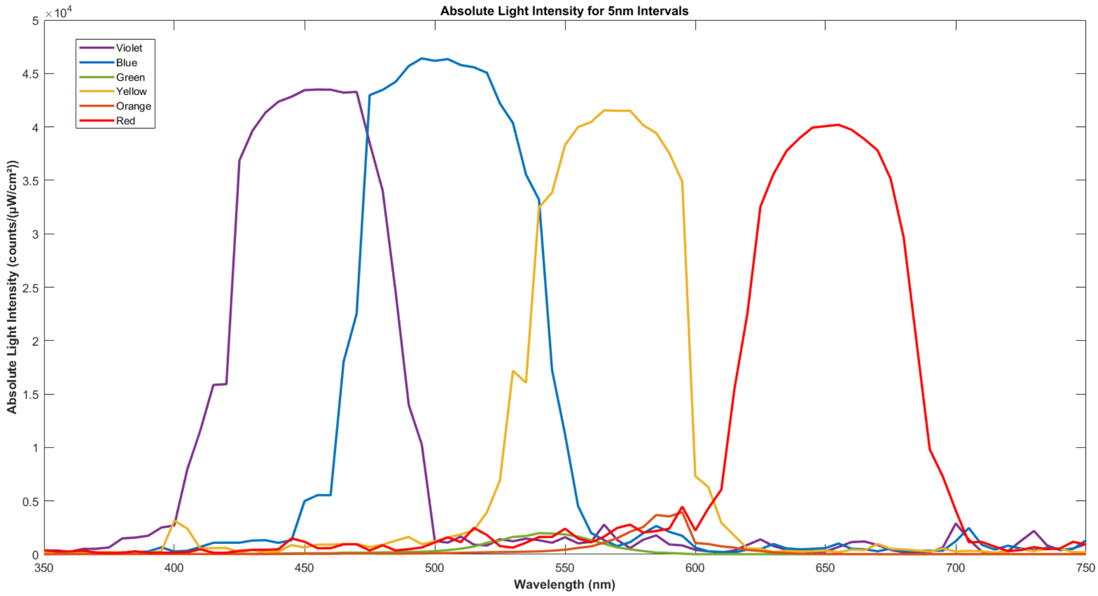

Figure 9: Absolute Light Intensity values recorded by the sensor for the visible spectrum.

Since the light sensor measures the intensity of light across different channels in $\frac{Counts}{\frac{\mu W}{cm^2}}$, this indicates the number of charges (counts) extracted per μW of incident light at the given wavelength. To analyse the relationship between the counts measured by the sensor and the intensity of the incident light measured in $\frac{\mu W}{cm^2}$, the absolute values recorded by the sensor for each wavelength were mapped to the calibration values obtained for the Bentham PVE300 system itself from Figure 11. The table containing the numerical values from which the graph was extracted can be found on [21].

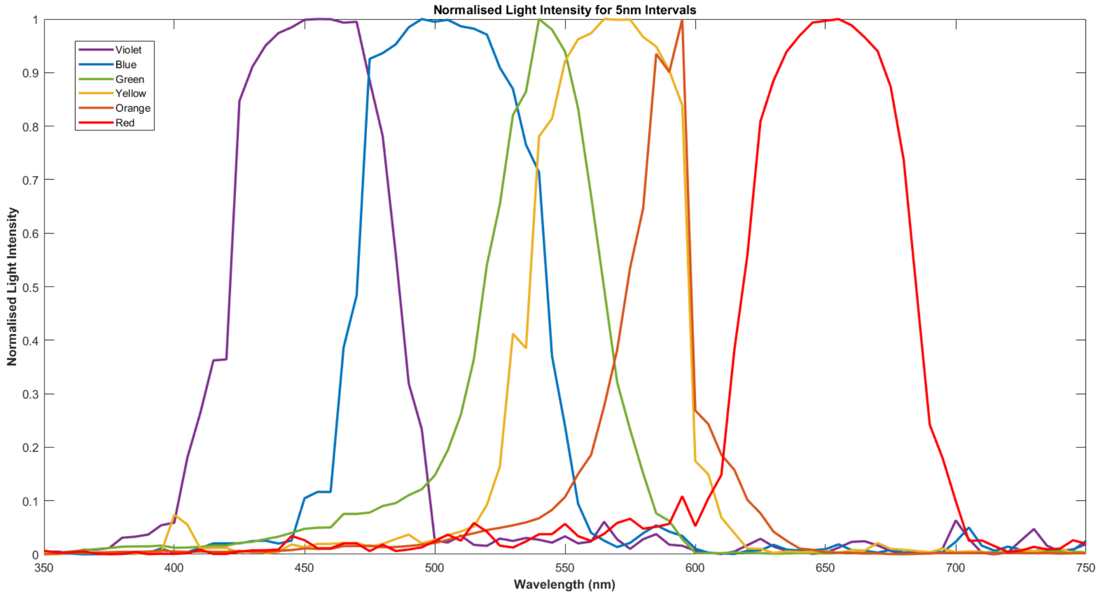

Figure 10: Normalised Light Intensity values recorded by the sensor for the visible spectrum.

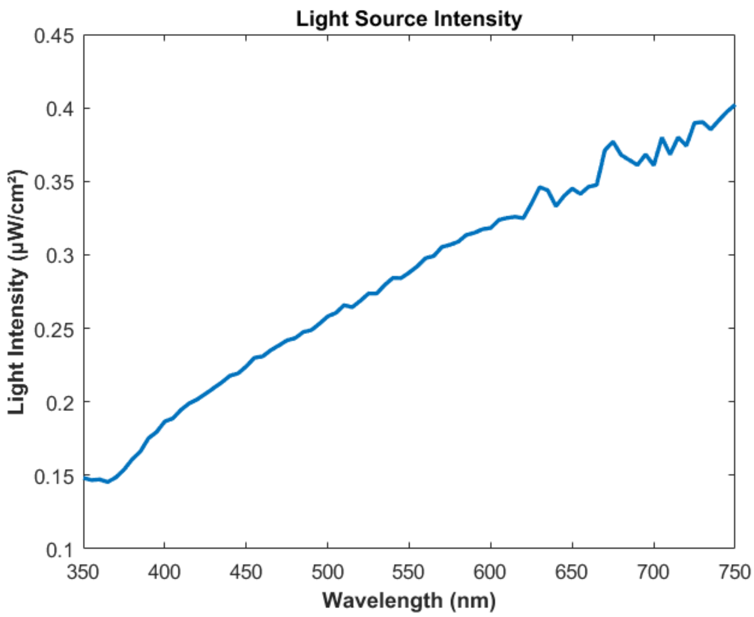

Figure 11: Reference intensity values for the visible spectrum obtained from the Bentham PVE300 system.

To perform this mapping, for each wavelength, the light sensor registered a value for each channel. The values for the channels whose Gaussian curve includes that specific wavelength were found to be significant, as opposed to the values recorded by the channels that do not include that wavelength which were negligible, as previously shown on Figure 9. The value registered by the sensor in each channel and for the given wavelength is considered as the maximum possible value measured by the sensor that corresponds to the light source intensity extracted from Figure 11. This assumption can be made because for the gathering of this maximum intensity value the sensor was exposed to a pure source that uniquely emitted at that wavelength. Moreover, the sensor was located at the same distance from the light source as the crystalline silicon reference cell used to calibrate the Bentham PVE300 system. Thus, for a new measurement, in order to find the intensity of the light at a particular wavelength from the values output by the sensor, the channel or Gaussian curve whose maximum sensitivity or peak is closest to the wavelength is selected. The maximum value and its corresponding mapping obtained for that specific wavelength during calibration are extracted from Figures 9 and 11, respectively. The intensity for the new measurement can then be calculated as follows:

$$\text{Intensity} = \frac{\text{Sensor Measurement} * \text{Corresponding Calibration Source Value}}{\text{Calibration Sensor Value}}.$$

The correct units of the equation above were checked as follows: $\frac{\mu W}{cm^2} = \frac{\frac{Counts}{\frac{\mu W}{cm^2}} * \frac{\mu W}{cm^2}}{\frac{Counts}{\frac{\mu W}{cm^2}}}$, which results in the identity 1=1 and is therefore consistent.

The mapping from the absolute values recorded for each of the 5 nm intervals to their corresponding normalised values offers researchers a standarised way of measuring the intensity of light at any particular wavelength. This includes the five wavelengths - 420, 480, 535, 550 and 565 nm - highlighted in section 2.4 of this document due to their relation to the spectral sensitivity of the human eye.

Additionally, from Figure 9 it can be observed that the Gaussian curves corresponding to the green and orange channels have a significantly lower peak than those representing the violet, blue, red and yellow channels. Therefore, for the data collected during the analysis performed in subsequent section 6 of this document, the green and orange channels are expected to report lower light intensity values than the other channels.

In order to further calibrate the device, data was collected at the Surrey Sleep Research Centre (SSRC) [59] by using a high intensity light source. The light intensity values for different scenarios including outdoors, indoors, as well as exposure to a light source both directly and through sunglasses were recorded with the sensor. The simulated scenarios, as well as plots of the sensor data can be found on Figure 12.

Time	Activity	Light Level
12:22:00	Outdoors	Very High
12:22:51	Indoors - Beside window	High
12:23:28	Indoors - Not beside window	Normal
12:24:00	Indoors	Normal
12:26:00	Indoors - Facing lamp without glasses	Extremely High
12:28:00	Indoors - Facing lamp with glasses	High
12:29:00	Indoors - Facing lamp without glasses	Extremely High
12:29:55	Indoors - Lamp disconnected	Normal

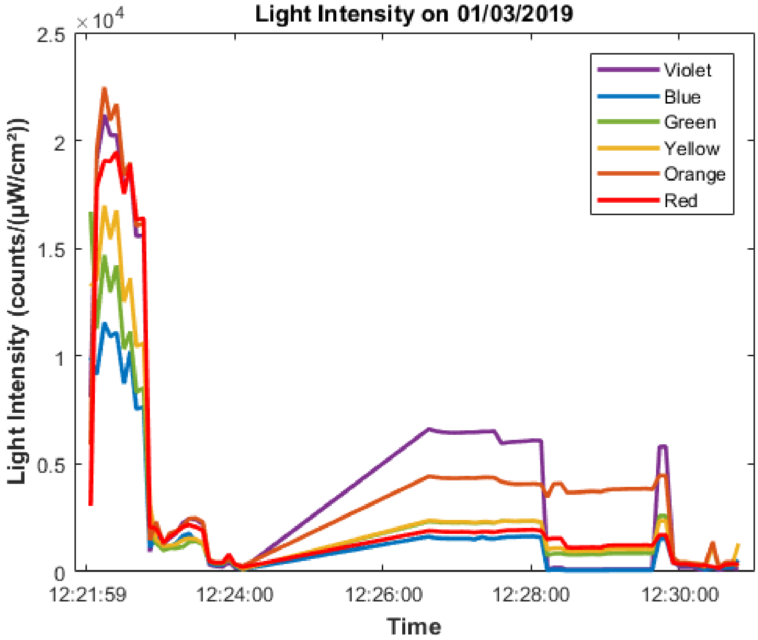

Figure 12: Light intensity values recorded by the sensor during calibration at SSRC.

From Figure 12 it can be seen that the light intensity values are highest when the sensor was exposed to the outdoor environment. These values decrease when the user returns indoors and the sensor is therefore exposed to lower light levels. When the sensor was placed facing the light source, a spike in the light intensity can be observed from the graph, with the values remaining at a constant high level during the entire time the sensor was exposed to the source. At 12:28, when the sensor was placed behind the sunglasses to simulated a dim environment, the light intensity recorded drops as expected, rising again once the glasses have been removed from the sensor's field of view. Thus, it was concluded that the light sensor's measurements successfully reflect the changes in the environment efficiently and in real-time, demonstrating a successful performance of the device during the preliminary data collection.

6 Second Prototype: Product Optimisation

A second and final iteration was made on the product in order to optimise it. The motivation behind the optimisation was to reduce the device's size, reduce its power consumption, remove unnecessary components to customise the device for this particular project, and increase user-friendliness. The optimisation included changes to both the hardware, by designing and building a custom Printed Circuit Board (PCB), the firmware to program the new chosen Bluetooth module, and the software to ensure the correct communication between the application and the sensor. Additionally, changes were implemented to the database in order to store the data in a secure server managed by the University of Surrey, thus allowing the SSRC researchers to easily access it and analyse it together with additional data collected during the studies, such as heart rate, sleep status and physical activity of the subjects.

6.1 Hardware

6.1.1 Design

The microcontroller and Bluetooth section of the device were re-designed into a custom Printed Circuit Board (PCB) in order to allow for lower power consumption and a smaller device. The new design features the minimal circuit required to work with the ATMega328 and the HM-11 Bluetooth Low Energy (BLE) module to efficiently manage the communications. It includes a 3.3V voltage regulator to provide the appropriate power input to both the microncontroller and the module. It also includes a JST connector for the battery, and the necessary breakout pins to flash the ATMEGA328 with the Arduino bootloader as well as program it and to connect it to the AS7262 Breakout Board. The routing of the board was performed manually, with a 10 mils track thickness for the power tracks and an 8 mils thickness for regular tracks. The design was completed using EAGLE software [6]. The following list enumerates the components used in the custom PCB:

- Microcontroller ATMEGA328 [17]
- Voltage Regulator MIC5225-3.3 [19]
- Bluetooth Module HM-11 [58]
- 16 MHz Ceramic Resonator [55]
- 10 K Resistors [14]
- 0.1 μF Capacitors [13]
- 10 μF Capacitor [15]
- 500 mAh LiPo Battery [16]
- JST PH Vertical Connector

Additional information about these components can be found on their linked references. Furthermore, Figures 13, 14 and 15 show the schematics for the circuit, the PCB top layout, and the PCB bottom layout, respectively. Further information on these as well as the original Eagle files for the PCB can be found on the repository [21].

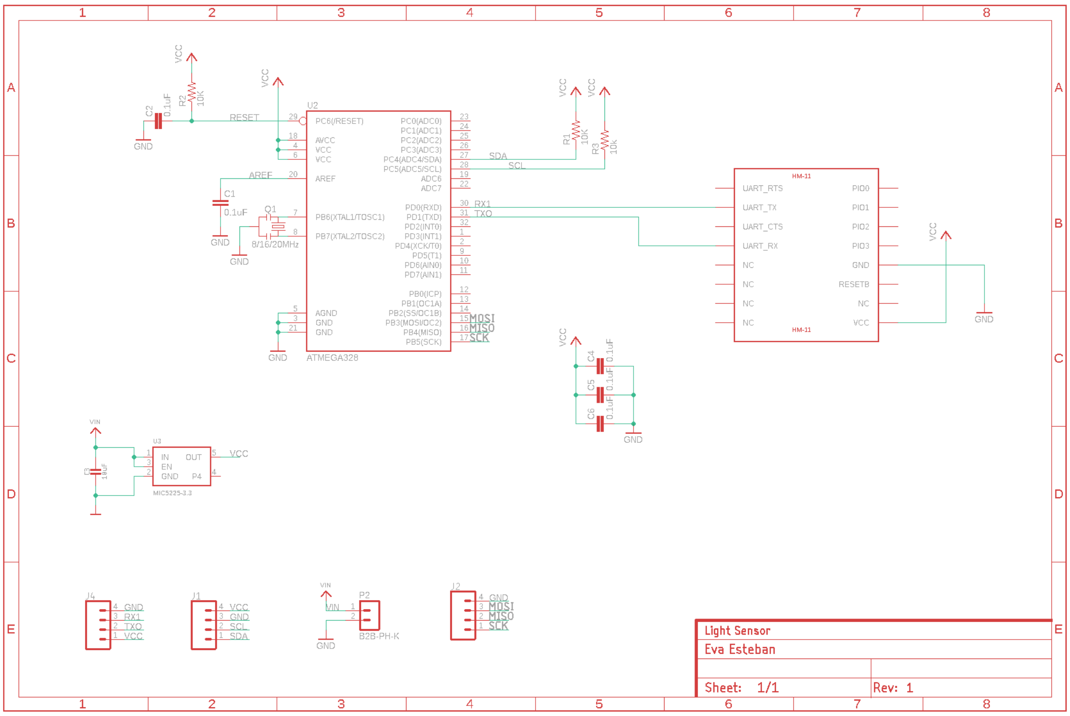

Figure 13: Improved circuit design schematic.

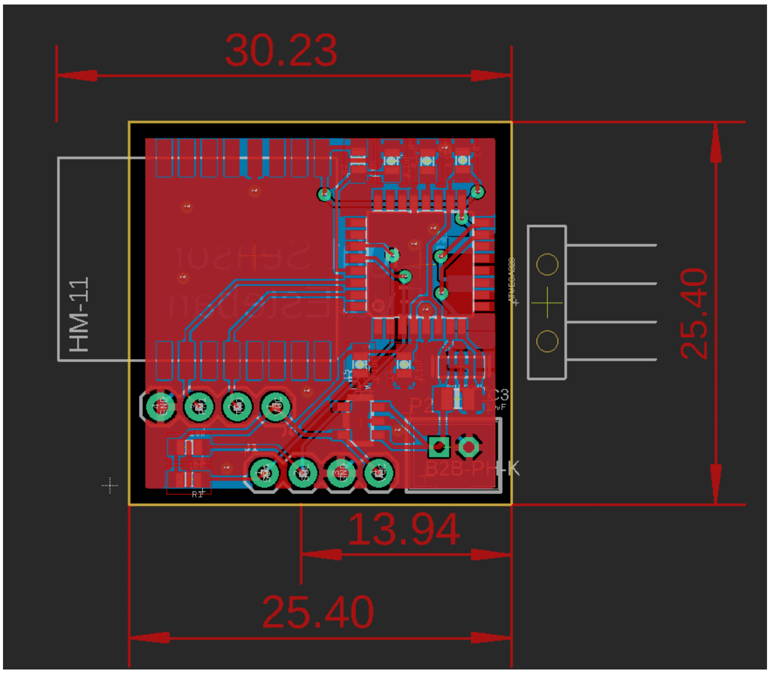

Figure 14: Improved circuit PCB top layout.

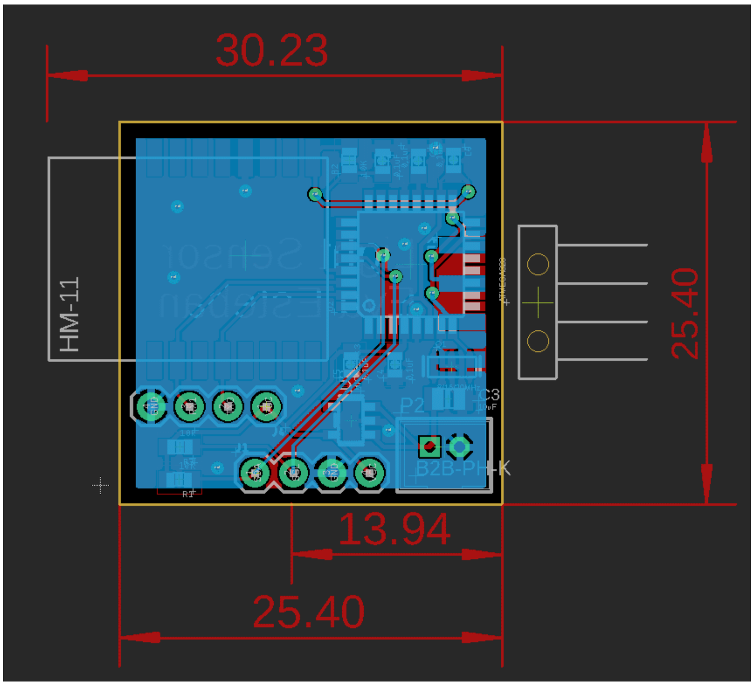

Figure 15: Improved circuit PCB bottom layout.

6.1.2 Integration, Power Consumption and Testing

The majority of the PCB components were soldered onto the board using leaded solder wire, flux, and a soldering iron. For the smaller components such as the ceramic resonator soldering paste was used in combination with flux to reduce the probability of short circuiting the pads. Once soldered, the board was tested for continuity by using a Digital Multi-Metre. This procedure consisted of comparing the voltage of different pads and component legs on the board that should have the same voltage. The PCB was then connected to the AS7262 Breakout Board and tested in the same way.

The PCB includes three main components: the microprocessor ATMega328P, the Bluetooth module HM-11 and the AS7262 sensor. The theoretical current consumptions for the microprocessor and the sensor are 15 mA and 5 mA, respectively. The Bluetooth module HM-11 consumes approximately 18.2 mA when receiving and 20 mA when transmitting, and was programmed to transmit data once every 15 seconds. Analogous to the power calculation performed for the first prototype, the total current consumption of the device is given by $I_s = 5 + 15 + \frac{20*0.003}{4} \approx 20$ mA. This value was multiplied by a factor of 1.2 to accommodate for any errors and hardware variations, giving a total theoretical consumption of the device of approximately 24 mA $\pm$ 10% error. The experimental current consumption of the device was measured to be 21 mA. Hence, by removing the unnecessary components from the first prototype, such as the LEDs, on the PCB design, as well as increasing the time between Bluetooth transmissions, the power consumption was successfully reduced by 5 mA per minute. Further work in reducinge power consumption involves incorporating additional memory to the device in order to pre-process the data, hence enabling the activation the device's sleep mode during the times when light measurement data is not being sent to the mobile application.

A rechargeable Lithium Polymer battery of 3.7V and 150 mAh was chosen for the final prototype, effectively reducing the size of the wearable. The total power provided by the battery is equal to $I_b = 150 * 0.8 = 120$ mAh. Thus, the device is expected to function for $T = \frac{120}{21} \approx 6$ hours after the battery is recharged. The standard JST PH connector on the device allows the users to connect either the battery from the first prototype or any other standarised Lithium Polymer battery of 3.7V should a longer operating time be required. The LiPo charger used to recharge the battery for this prototype was the same as the one used for the first prototype. The final device hardware can be observed in Figure 16.

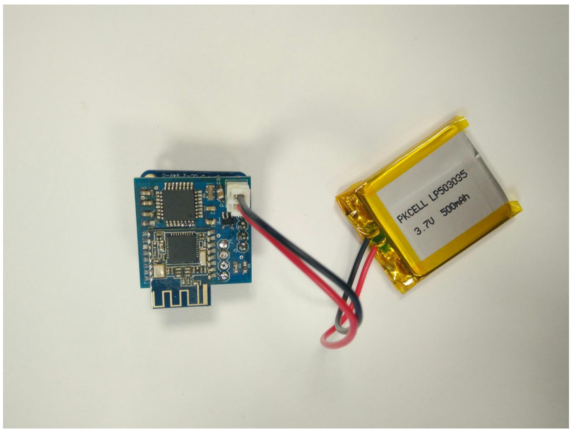

Figure 16: Final hardware prototype of the sensor.

This final prototype of the device was cased by using transparent heat shrink tube with an attached metal butterfly pin back, analogous to the first prototype. The section of the heat shrink corresponding to the AS7262 chip aperture and temperature sensor was removed in order to allow for the light to reach it directly. A picture of the final cased light sensing device can be found on Figure 17. Additionally, a picture of a user wearing the final device can be observed in Figure 18.

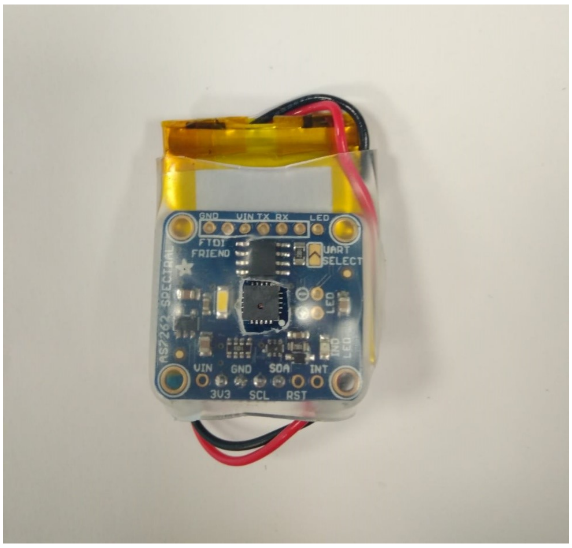

Figure 17: Final hardware prototype of the sensor with casing.

Figure 18: Image showing a user wearing the final prototype of the device with casing.

6.2 Firmware

Since the UART connection from the ATMega328P is serially connected to the HM-11 module, an Arduino Uno [?] was used to program the microcontroller through the Serial Peripheral Interface (SPI) by using the 'Arduino as ISP' option provided by the software.

The firmware code written to the device can be found on the Appendix B of this document. It measures the intensity of light for the six channels covered by the sensor, as well as the ambient temperature, every 15 seconds. No significant benefit was observed during the data collection process when measuring the light levels every 5 seconds with the first prototype, therefore, the time was extended to 15 seconds. This, in turn, further reduced the power consumption of the device. Nevertheless, the flexibility of the sensor allows for the time between samples to be changed by programming the device via the Arduino IDE should a different interval length be required.

6.3 Software

The option for the user to rate their level of tiredness after each night's sleep was incorporated into the application. This data is timestamped and stored both in the local and in the server databases in order to analyse it together with the light intensity and temperature values from the sensor, as well as the heart rate and steps values obtained from the MiBand. A view of the application's User Interface (UI) with the new added feature can be found on Figure 19. The source code for this new and improved version of the mobile application can be downloaded from the GitLab repository [21] in the same way as the source code for the first prototype of the application.

6.4 Data Storage

A new MySQL database together with the corresponding PHP scripts for data storage was implemented in a server provided by the University of Surrey. The server's operating system is Ubuntu, thus the database set-up and managing is performed using Linux commands. The server operates continuously, allowing for the data to be readily available to the Surrey

Sleep Research Centre (SSRC) at any time, as well as stored in a secure location, as opposed to storing the data in the server in the personal computer. The server's IP address is 131.227.92.228 and port 1880 was configured for the communication with the database. Figure 20 shows an example of data displayed in the server database.

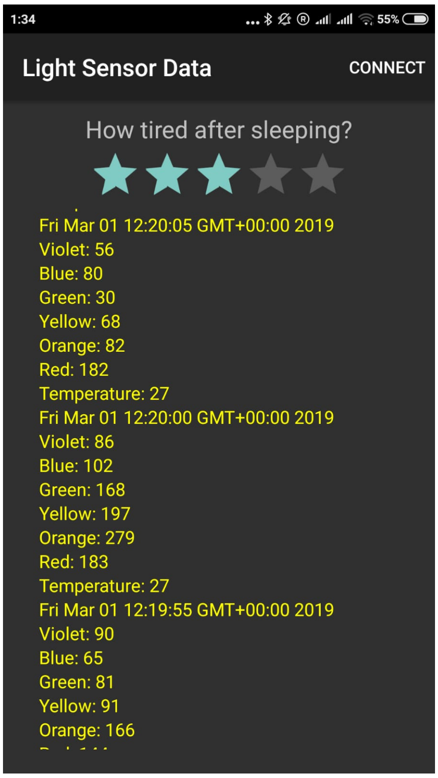

Figure 19: Example view of the mobile application incorporating user sleep rating.

Timestamp	Violet	Blue	Green	Yellow	Orange	Red	Temperature	Tiredness
Wed Apr 10 11:05:10 GMT+01:00 2019	7881	2599	7517	5028	6592	2422	30	3.0
Wed Apr 10 11:05:15 GMT+01:00 2019	6515	2644	7727	5484	6098	2378	30	3.0
Wed Apr 10 11:05:21 GMT+01:00 2019	8195	3976	7796	6476	7748	3399	30	3.0
Wed Apr 10 11:05:26 GMT+01:00 2019	11391	7138	9144	7270	8107	3226	30	3.0
Wed Apr 10 11:05:31 GMT+01:00 2019	2068	2022	3046	2659	2349	1554	29	3.0
Wed Apr 10 11:05:37 GMT+01:00 2019	17793	19706	20592	23837	14118	9061	29	3.0
Wed Apr 10 11:05:42 GMT+01:00 2019	22436	18764	21767	25018	17444	14829	29	3.0
Wed Apr 10 11:05:47 GMT+01:00 2019	18900	21118	19232	22916	14506	9936	29	3.0
Wed Apr 10 11:05:53 GMT+01:00 2019	18952	20504	19177	22907	14456	9938	28	3.0
Wed Apr 10 11:05:58 GMT+01:00 2019	18316	19047	19718	22785	14268	9693	28	3.0
Wed Apr 10 11:06:03 GMT+01:00 2019	1136	1217	1047	1039	658	538	28	3.0
Wed Apr 10 11:06:19 GMT+01:00 2019	1421	2140	1863	2454	1782	1617	27	3.0
Wed Apr 10 11:06:25 GMT+01:00 2019	1561	2374	2143	2824	2049	1860	27	3.0
Wed Apr 10 11:06:30 GMT+01:00 2019	1565	2381	2156	2838	2062	1870	27	3.0
Wed Apr 10 11:06:36 GMT+01:00 2019	1541	2341	2103	2760	2000	1814	27	3.0
Wed Apr 10 19:22:08 GMT+01:00 2019	51201	38465	8404	27853	47802	51201	27	3.0
Wed Apr 10 19:22:23 GMT+01:00 2019	51201	38303	8369	27612	47582	51201	27	3.0
Wed Apr 10 19:22:38 GMT+01:00 2019	51201	35268	8008	24428	44220	51201	27	3.0
Wed Apr 10 19:22:53 GMT+01:00 2019	51200	35340	7987	24433	44143	51201	27	3.0
Wed Apr 10 19:23:07 GMT+01:00 2019	51200	36512	8029	25565	45433	51201	27	3.0
Wed Apr 10 19:23:23 GMT+01:00 2019	49670	33781	7809	23594	41308	51201	27	3.0
Wed Apr 10 19:23:37 GMT+01:00 2019	49320	33741	7784	23460	41002	51201	27	3.0
Wed Apr 10 19:23:52 GMT+01:00 2019	50157	34414	7778	23639	41239	51201	27	3.0
Wed Apr 10 19:24:08 GMT+01:00 2019	50268	34681	7769	23744	41369	51201	27	3.0
Wed Apr 10 19:24:23 GMT+01:00 2019	49736	34095	7738	23479	41017	51201	27	3.0
Wed Apr 10 19:24:37 GMT+01:00 2019	47698	33359	7667	22657	39309	51201	27	3.0
Wed Apr 10 19:25:07 GMT+01:00 2019	33852	20008	7483	17892	30257	51201	27	3.0
Wed Apr 10 19:25:22 GMT+01:00 2019	31712	17776	7448	17219	28703	51201	27	3.0
Wed Apr 10 19:25:37 GMT+01:00 2019	31186	17544	7436	17145	28442	51201	27	3.0
Wed Apr 10 19:25:52 GMT+01:00 2019	28591	16524	7409	16969	27165	51201	27	3.0

Figure 20: Example view of data stored in the University server database.

7 Data Collection and Analysis

7.1 Methodology

Data was collected for analysis by a user wearing the device for time periods of approximately one hour on different days while performing various activities and getting exposed to environments such as outdoors, indoors, darkness and coloured lighting. The files for the data collected can be found on the GitLab repository [21]. The data collection process consisted of two phases: gathering of light intensity data independently, and gathering of light intensity data together with temperature, steps and heart rate data. The first five instances of data collection presented in this report were gathered using the first prototype measuring the values every 5 seconds while the final prototype was being designed and developed, while the last instance of data collection was performed with the final prototype gathering data every 15 seconds. The light intensity and the temperature data were collected using the sensor itself, and both the steps and heart rate measurements were obtained from the Xiaomi MiBand 3 [65]. This additional data was collected in order to analyse the correlation of the light levels detected with the activity performed by the user at the time of the measurement. The data was stored in the secure database presented in the previous sections of this report, and analysed by using Matlab software [42] in order to optimise the process of extracting the parameters to plot.

7.2 Data Collected and Analysis for Different Scenarios

Initially, in order to test the data collection capabilities of the device, data was collected for approximately an hour on the 12th of December 2018. Both the activities of the user and the light levels to which the sensor was exposed were recorded during the data collection experiment. These levels range from Darkness to Extremely High and their corresponding intensities can be found on Figure 21.

In further analysing the data, a peak in the light intensity can be observed at 16:44. This spike corresponds to the exposure of the user to the outdoor light levels, which are expected to be significantly higher than the indoor levels. Between 16:44 and 17:13, the light intensity values show a decreasing trend. This correlates well with the decrease in light levels experienced as the evening progresses, a process that occurs around 16:00 and 18:00 during the winter months in the United Kingdom, where the data was collected. A considerable increase in the light intensity values can be observed at 17:13, which corresponds to the moment when the sensor was positioned to face the sky. Additionally, during the period of darkness in which the sensor was situated under a blanket, the light levels recorded are negligible. Finally, a smaller spike occurred at 17:34, which is the time when the user stood beside a lamp.

Regarding the lower intensity values recorded for the green and orange channels compared to the other channels, this matches the lower maximum values presented for these channels in section 5 of this document. Thus, it can be concluded that the light levels recorded by the sensor on the 27th December 2018 provide an accurate representation of the light levels present in the activities performed by the user during the collection period.

Time	Activity	Light Level
16:39	Indoors	Low
16:44	Outdoors	Very High
17:13	Outdoors - Facing the sky	Extremely High
17:20	Indoors	Normal
17:26	Indoors - Under blanket	Darkness
17:34	Indoors - Beside lamp	High

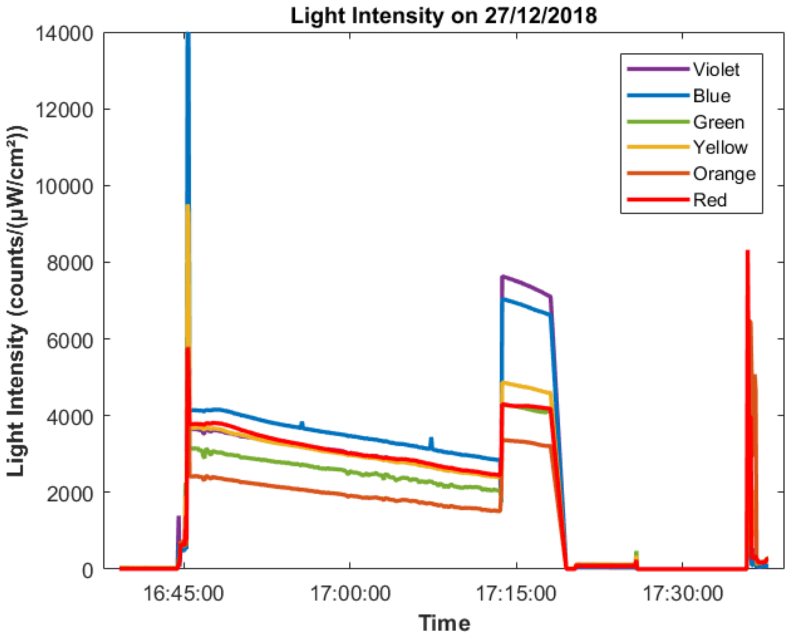

Figure 21: User activities and light intensity levels recorded during data collection with the first prototype sensor on 27/12/2018.

On the 24th January 2019, a different user was requested to wear the sensor and additional data was collected for approximately an hour. The activities performed by the user together with the light levels recorded can be found on Figure 22.

As shown on Figure 22, small spikes on the light intensity values can be observed when the user transitions from standing or sitting in a regular area inside the home to standing or sitting beside a window or a light source such as a lamp. This can be observed at 15:51 and 16:25. Moreover, a large spike in all the light channels can be observed when the sensor is oriented to face a light source at 16:33. On the other hand, when facing a red and orange object such as the user's clothes, the orange values recorded by the sensor increase significantly compared to both the previous orange values and the other channels. Furthermore, when the sensor is placed under a blanket at 16:20, the intensity values recorded are negligible, which correlates well with the lack of light the sensor is exposed to in that scenario. Finally, an increase of the light intensity recorded by all the channels can be observed between 16:04 and 16:10, when the user steps outdoors. Since this time period corresponds to the evening time during the winter months in the United Kingdom and the outdoor light decreases in intensity between 16:00 and 17:00 during this season, the slow progressive decrease in light intensity shown on the graph as time advances is expected.

Time	Activity	Light Level
15:44	Indoors	Normal
15:51	Indoors - Beside window	High
15:53	Indoors - Not Beside window	Normal
15:56	Outdoors	Very High
16:04	Outdoors - Beside Building	Very High
16:10	Indoors	Normal
16:20	Indoors - Under blanket	Darkness
16:22	Indoors	Low
16:25	Indoors - Beside lamp	High
16:29	Indoors - Facing lamp	High
16:31	Indoors - Facing light red/ orange clothes	Normal
16:33	Indoors - Facing lamp	High
16:36	Indoors	Normal

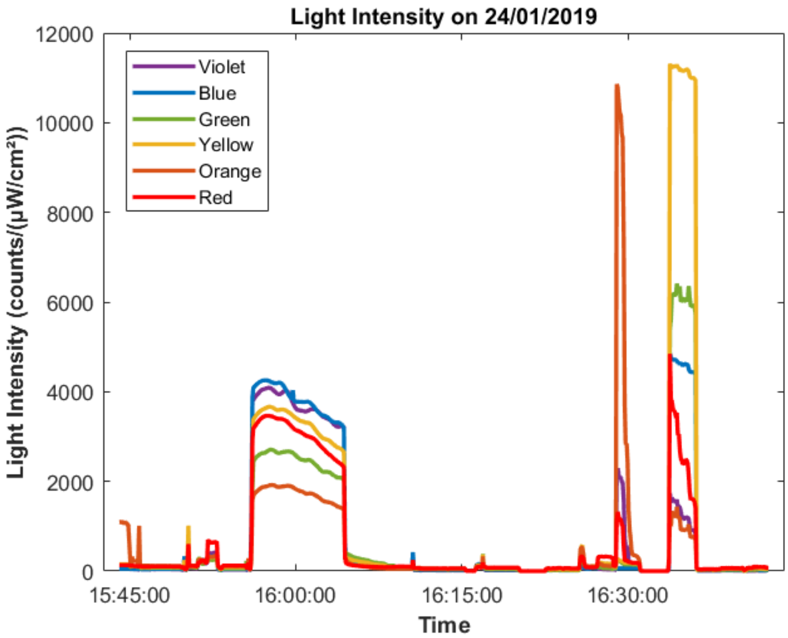

Figure 22: User activities and light levels recorded during data collection with the first prototype sensor on 24/01/2019.

On the 25th January 2019, additional data was collected for the same user with both the light sensor and the MiBand 3. The results can be found together with the user activities on Figure 23. From Figure 23 it can be noted that the intensity of the light presents a maximum between 12:32 and 13:42, which corresponds to the time interval when the user is outdoors. Moreover, smaller spikes can be observed in the light values measured at 12:02 and at 12:23. These correctly match the times at which the sensor was located beside a window.

Time	Activity	Light Level
12:02	Indoors - Beside window	High
12:19	Indoors - Moved to room with less light	Normal
12:23	Indoors - Beside window	High
12:32	Outdoors	Very High
13:42	Indoors	Normal

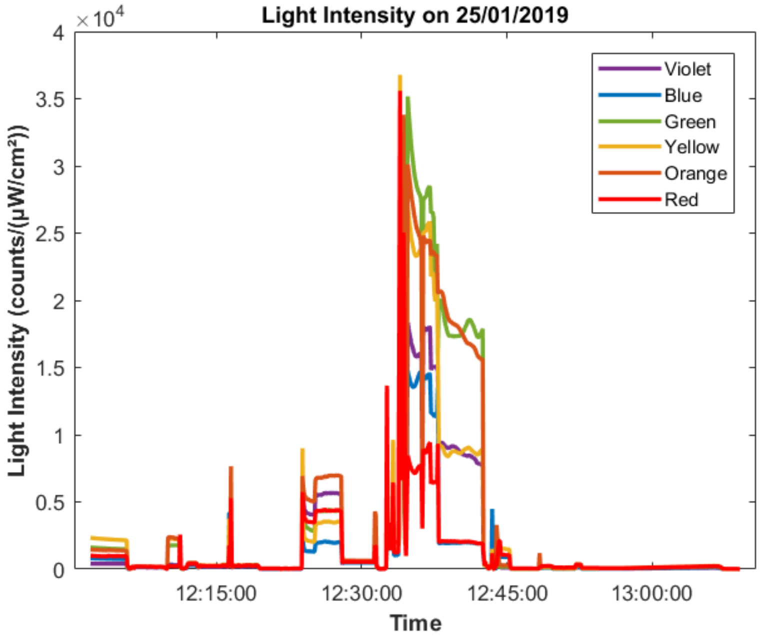

Figure 23: User activities and light levels recorded during data collection with the first prototype sensor on 25/01/2019.

On the 26th January 2019, approximately an hour of data was collected. This data includes not only the light intensity values but also the ambient temperature as well as the number of steps and heart rate of the user. The activities performed by the user during the data collection period together with the values recorded by both the sensor and the MiBand 3 can be found on Figures 24 through 27.

The intensity of light recorded by the sensor increases and decreases accordingly in a different proportion for each of the channels. A large spike in light intensity can be observed for all the channels at 9:01, which corresponds to the time when the user went outdoors. While the blue and red channels increase around 5,000 counts, the orange and green increase approximately 1,500 counts. This correlates well with the maximum values registered for each of the corresponding Gaussian distributions presented in section 5 of this document. The violet and yellow channels are situated in between these two maximum and minimum limits. Moreover, between 9:10 and 9:13 a small spike on the light intensity can be observed, which corresponds to the time when the user was sitting beside a window. The greatest spike in intensity can be observed from 9:25 until the end of the data collection period. This increase in the light values correctly matches the time when the user went outdoors again. A larger spike than the one observed at 9:01 is expected, since the weather outdoors was less cloudy and progressed further into the day.

Time	Activity	Light Level
8:44	Indoors	Normal
8:46	Indoors - Opened curtains	High
8:53	Under blanket	Darkness
8:57	Out of blanket	Normal
8:59	Sitting beside window	High
9:01	Outdoors - Cloudy	Very High
9:10	Indoors - Beside window	High
9:13	Indoors - Not beside window	Normal
9:23	Indoors - Light on	High
9:25	Outdoors - Less cloudy	Very High

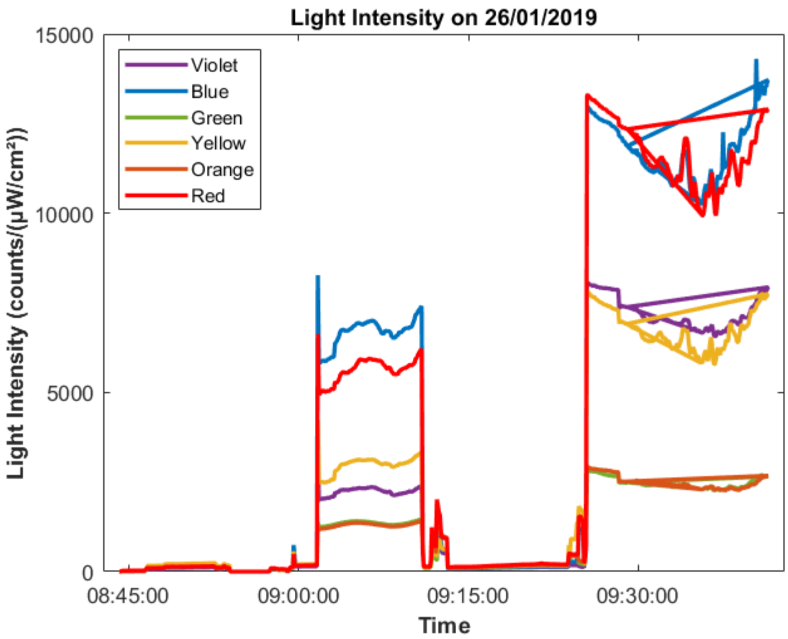

Figure 24: User activities and light intensity levels recorded during data collection with the first prototype sensor on 26/01/2019.

Additionally, the temperature values recorded by the sensor were analysed in order to ensure a correct functioning of the sensor's temperature measurement feature. The temperatures registered by the sensor on the 26th January 2019 can be found on Figure 25. Overall, the temperature varies between 13 and 30 degrees Celsius (°C) with gradual transitions between stages. The maximum temperature registered corresponds to the time period when the user covered herself up with a thermal blanket, thus the spike in temperature is expected due to the close contact of the sensor with the user's body as well as the warm blanket. The minimum temperature observed in the graph was registered during the two time periods when the user was outdoors. This drop in temperature to 13 °C is well correlated with the temperature of the 26th January 2019, which was registered to be around 11 °C [64].

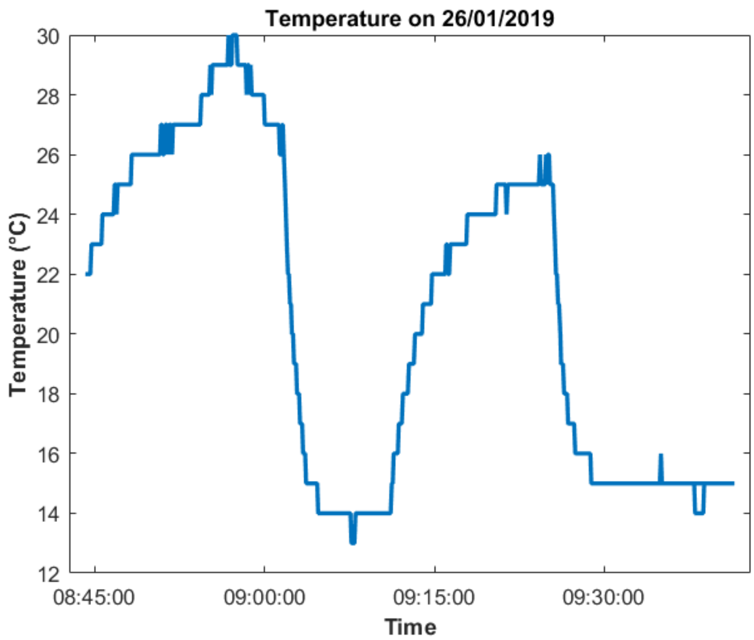

Figure 25: Temperature values recorded during the data collection with the first prototype sensor on 26/01/2019.

Finally, Figures 26 and 27 show the user heart rate data and the total number of steps taken by the user, respectively. It can be seen that the heart rate recorded increases in intensity when user activity, such as going outdoors, is registered. Moreover, the largest increase in the number of steps performed by the user occurs between 9:23 and 9:35, which corresponds to the period when the user changes location from indoors to outdoors. Thus, the light intensity levels recorded by the sensor correlate well with both the activities performed during the collection of data, as well as with the step and heart rate values recorded by the MiBand 3.

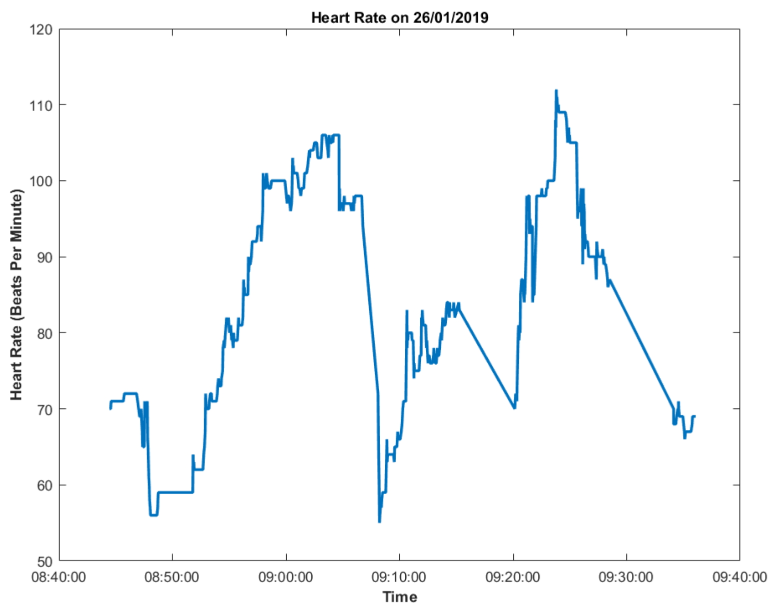

Figure 26: User heart rate data recorded during the data collection with the first prototype sensor on 26/01/2019.

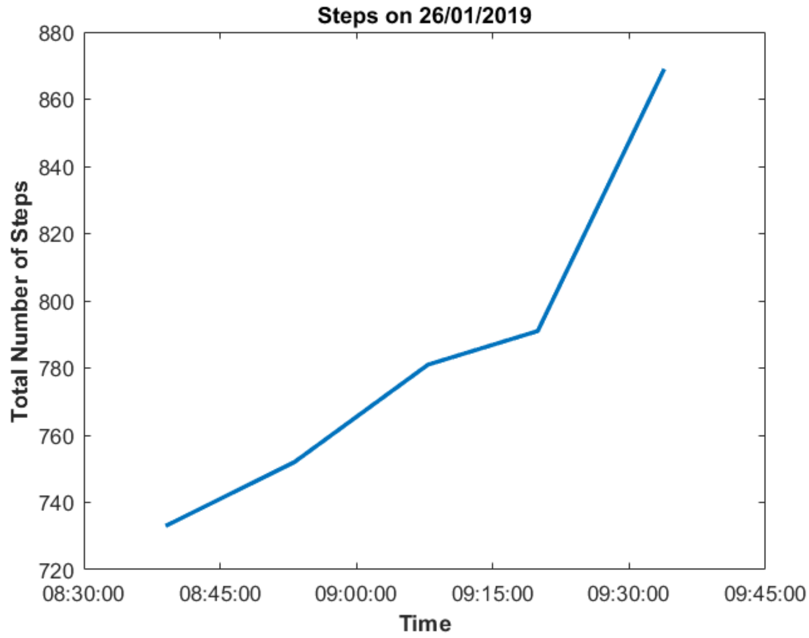

Figure 27: User step data recorded during the data collection with the first prototype sensor on 26/01/2019.

On the 20th March 2019 both the sensor and the MiBand 3 device were used to collect data on light intensity, temperature, user heart rate and user steps for approximately an hour. The activities performed by the user during the data collection session and the corresponding light intensity values measured by the sensor are presented on Figure 28.

From Figure 28, it can be observed that the light intensity registered by the sensor increases when the user goes outdoors at 14:27 and at 14:55. A significantly higher spike is observed when the sensor is directly oriented towards an active lamp at 14:22. This behaviour is expected due to the fact that in the outdoors environment the sensor was exposed to shadows from clouds and other artifacts and therefore the intensity registered by it should be lower than when it was directly exposed to a strong light source such as the lamp. furthermore, negligible light intensity values can be observed between 14:16 and 14:18, and between 14:45 and 14:52, when the sensor was placed under a blanket, which matches the expectations. The temperature recorded during this time period is presented on Figure 29. The temperature varies between a maximum value of 30 °C and a minimum of 17 °C. The high temperature periods correspond to the moments when the sensor is placed under the blanket, while the low temperature measurements are linked to the time when the sensor is outside. This behaviour is expected analogous to the scenario presented in the data analysis for the 26/01/2019.

The heart rate for the user as well as the total number of steps taken at the given time intervals were also measured, with the results being presented on Figures 30 and 31 below. The increases shown on both the heart rate and the steps graphs can be matched to the time period when the user either went outdoors or changed position i.e moving from inside the blanket to outside the blanket. On the other hand, the decreases in heart rate and constant value for the total number of steps correspond to the times when the user was indoors and exposed to normal levels of light.

Time	Activity	Light Level
14:10	Indoors - Beside window	High
14:12	Indoors - Not beside window	Normal
14:16	Under blanket	Darkness
14:18	Out of blanket	Normal
14:22	Indoors - Facing lamp	High
14:25	Indoors - Not facing lamp	Normal
14:27	Outdoors - Walking	Extremely High
14:42	Indoors	Normal
14:45	Under blanket	Darkness
14:52	Out of blanket	Normal
14:55	Outdoors	Extremely High

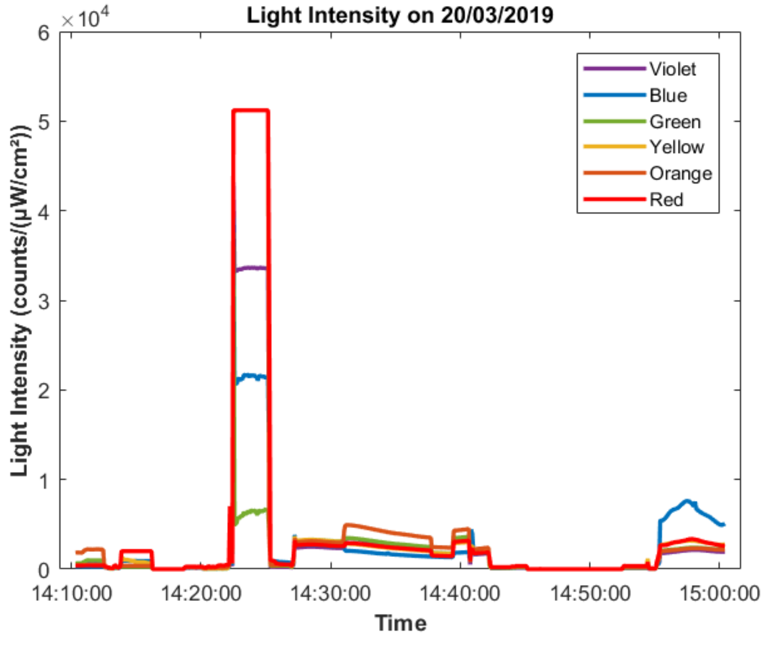

Figure 28: User activities and light intensity levels recorded during data collection with the first prototype sensor on 20/03/2019.

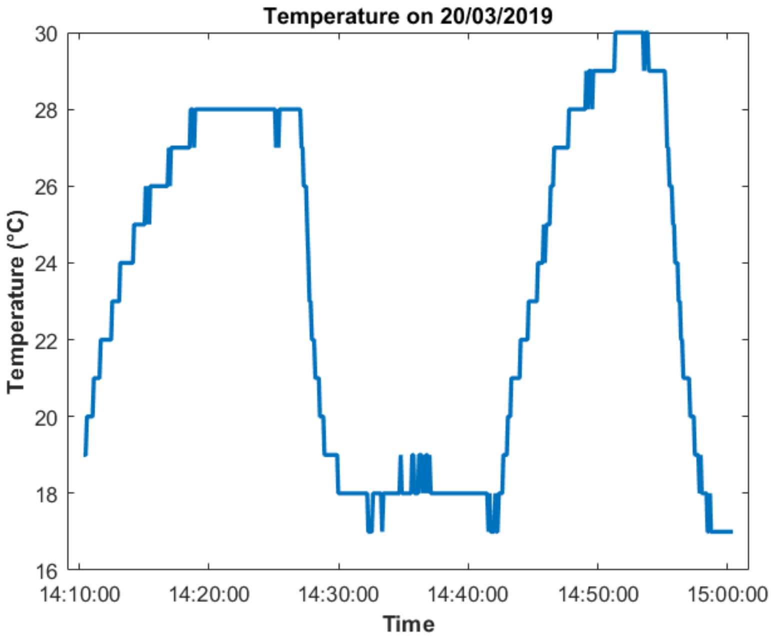

Figure 29: Temperature values recorded during the data collection with the first prototype sensor on 20/03/2019.

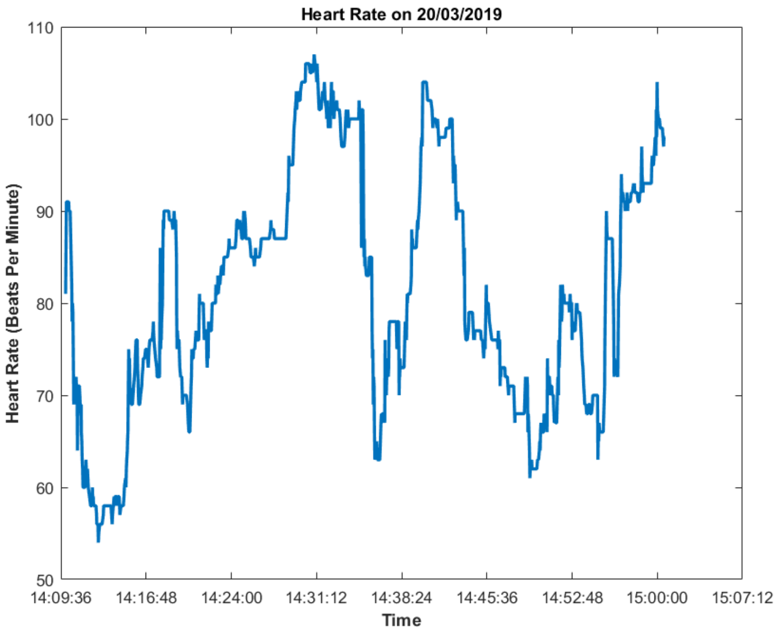

Figure 30: User heart rate data recorded during the data collection with the first prototype sensor on 20/03/2019.

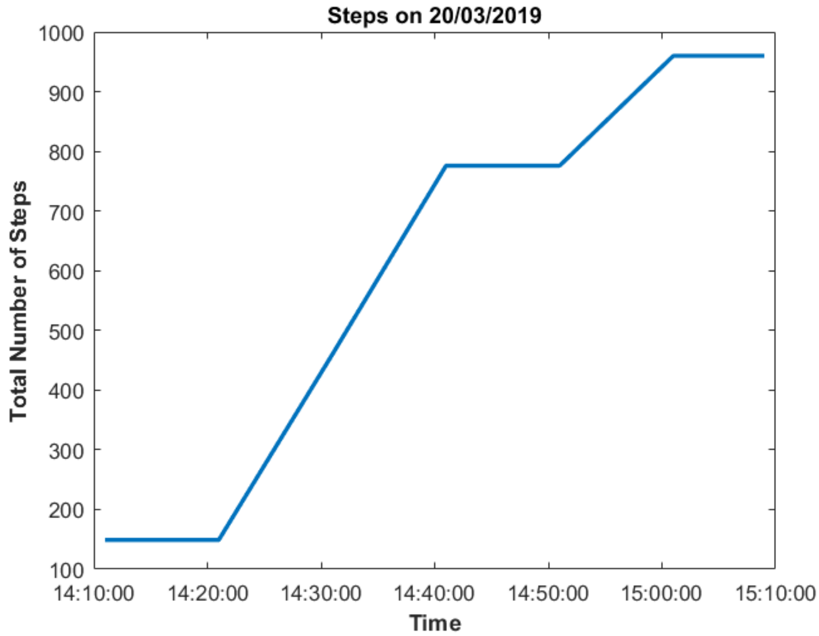

Figure 31: User step data recorded during the data collection with first prototype sensor on 20/03/2019.

In order to test the correct functioning of the custom PCB, a final set of recordings were collected on the 10th April 2019 with both the final prototype of the sensor and the MiBand 3. The plots obtained were compared to the curves and trends followed by the data collected with the first prototype presented above. Figures 32 through 35 present the activities performed by the user as well as graphs of the light intensity, temperature, heart rate and steps, respectively.

From Figure 32 it can be observed that the intensity registered for the light reaches its maximum value when the sensor was exposed to the outdoors environment at 19:05, and to the direct illumination by a lamp at 19:22. The minimum value is reached when the sensor is placed under a blanket at 19:14, as expected. The transition between different stages for the data collected with the final prototype sensor shows greater stepping than in the data collected by the first prototype sensor. This is due to the fact that the latter collects the data every 15 seconds, while the former records the light values every 5 seconds. Nevertheless, these steps were not found to alter the data analysis process in any way.

Time	Activity	Light Level
19:03	Indoors	Normal
19:05	Outdoors	Very High
19:10	Indoors	Normal
19:14	Under blanket	Darkness
19:22	Indoors - Facing lamp	High
19:26	Indoors - Not facing lamp	Normal

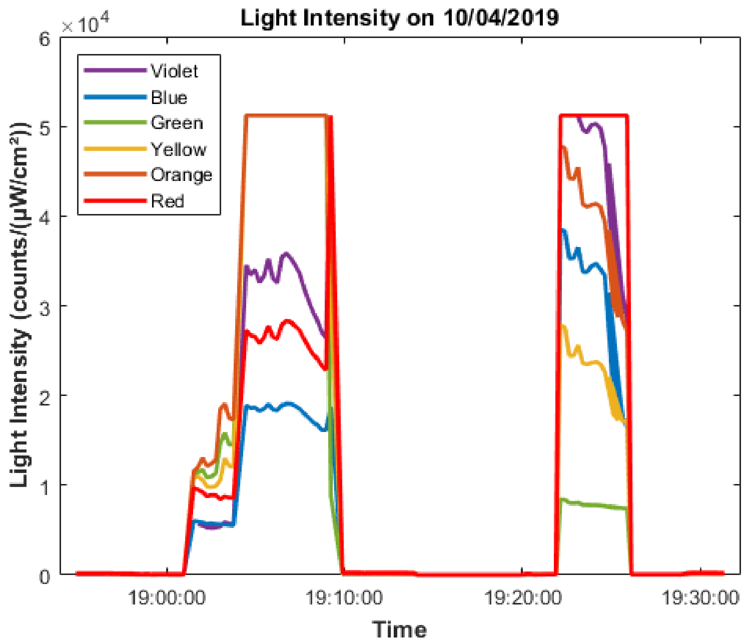

Figure 32: User activities and light intensity levels recorded during data collection with the final prototype sensor on 10/04/2019.

Additionally, the temperature values recorded by the sensor can be found on Figure 33. The maximum temperature of 32 °C at 19:20 and the minimum temperature value of 15 °C at 19:10 correspond to the times when the sensor was placed under a blanket and taken outdoors, respectively. The transition between stages is gradual as expected, following the same trend as the other instances of data collected with the first prototype.

Regarding the heart rate and steps data collected with the MiBand 3, which can be found on Figures 34 and 35, it can be observed that both the heart rate and the number of steps increase when the user walks outdoors or changes indoor position, such as when placing the sensor under a lamp, and remain stable for the periods of time when the user is still.

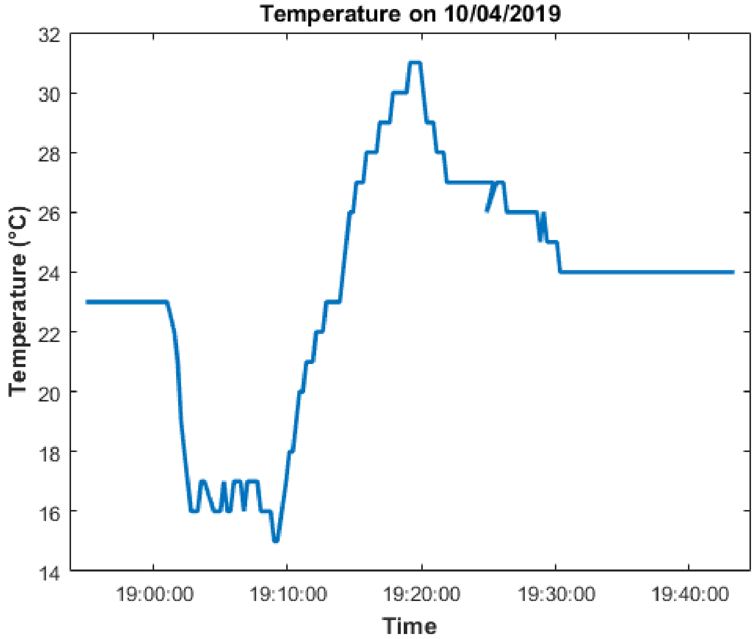

Figure 33: Temperature values recorded during the data collection with the first prototype sensor on 10/04/2019.

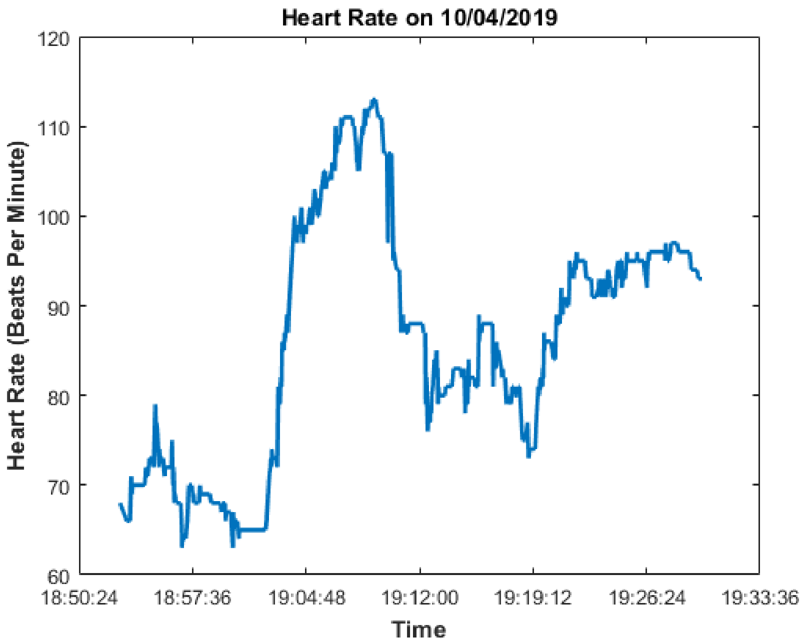

Figure 34: User heart rate data recorded during the data collection with the final prototype sensor on 10/04/2019.

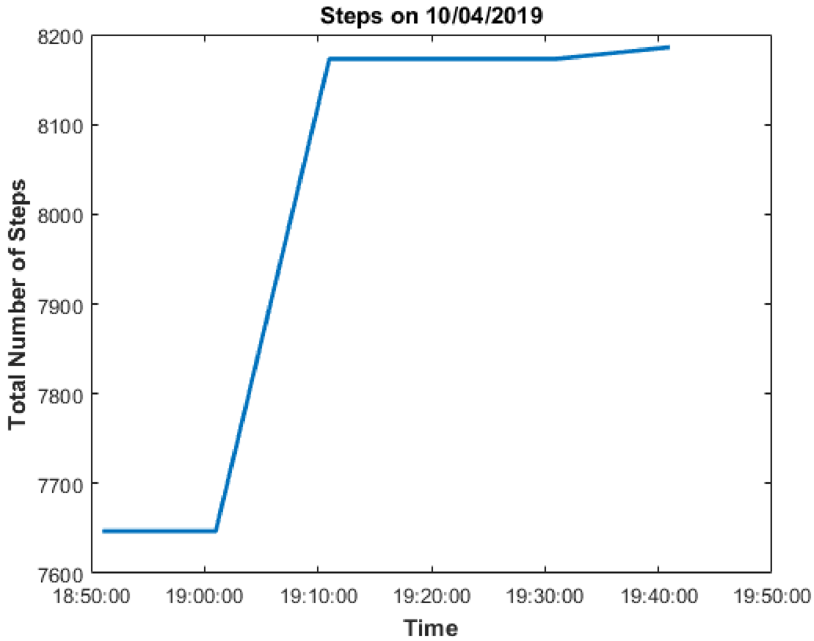

Figure 35: User step data recorded during the data collection with the final prototype sensor on 10/04/2019.

7.3 Evaluation and Value

From the above-mentioned analysis performed on the data collected on different dates, time periods and scenarios, it can be concluded that the light intensity values recorded by the different channels of the light sensing device correlate well with the ground truth light values for the scenarios tested. This data also correlates well with the temperature values recorded by the sensor, as well as the heart rate and number of steps measurements provided by the MiBand 3. Generally, for periods of activity such as going outdoors the light intensity, heart rate and number of steps parameters were found to increase, while the temperature value decreased. This is contrary to the periods of low activity when the user remained indoors and for which the light intensity and heart rate tend to decrease, the total number of steps remained approximately constant, and the temperature value decreased. Data collected for additional users and scenarios not present in this document due to length constraints can be found on the GitLab repository [21].

The value of this analysis for researchers resides on the ability to fuse both the temperature and light intensity data recorded by the sensor with any other relevant data by storing it in the database and analysing it with a processing tool such as Matlab, analogous to the procedure previously described. In this way, the influence of light on patients' wellbeing can be analysed together with external parameters in a standarised way. To examine a particular wavelength, researchers can consult section 5 of this document and map their recorded values to the correct channel and normalised intensity for comparison. This satisfies the need to develop a standarised approach to spectral sensing and light intensity measuring presented in section 2 of this document as the motivation for this project.

8 Total Cost

The costs for the full project can be found on Table 3. Even though the initial allowance for the project was £100, discussions were held with the project supervisor and this quantity was incremented. This is due to the device's robustness, quality and specifications considered a priority over the device's cost. The majority of the hardware components were obtained from the suppliers DigiKey [18] and RS Components UK [56] in order to obtain the discount for educational institutions that they provide to the University of Surrey. Moreover, even though building an initial prototype required an investment, this iterative approach was chosen in order to be able to collect real data and test the functionality of the product as soon as possible, while the final product was being optimised.

Component	**Cost (£)**
Arduino Beetle Ble - DFRobot	≈ 15
2 AS7262 Breakout Boards - Adafruit	≈ 32
3.7V 1800mAh Lithium Rechargeable Battery - RS Pro	≈ 9
1 Micro Lipo USB LiIon/LiPoly charger - Adafruit	≈ 6
Prototype casing	≈ 0.05
Final casing	≈ 0.05
Custom PCB	≈ 15
Custom PCB components	≈ 35
3.7V 500mAh Lithium Rechargeable Battery - DigiKey	≈ 10
Total	$122.1 \approx 122$

Table 3: Individual and total costs for the project's hardware components.

The final cost of the project was £122, which is successfully lower than the initial prediction of £158 with an error margin of $\pm 25\%$ stated in the Midterm Report. The majority of the financial investment of this project lies in the hardware components and in their correct functioning since the software tools and storage space used are freely available. For situations such as ordering Printed Circuit Boards (PCB), ten instances of the PCB were ordered in total to avoid the risk of ordering a single PCB and it being damaged, as this would delay the progress of the project by a significant amount of time.

9 Challenges and Lessons Learnt

During the course of the project, several unexpected problems aroused, which influenced both the timeline of the development of the product and the final design of the device. These challenges were successfully addressed, and valuable lessons were gained from them.

9.1 Main Challenges

To begin with, as mentioned above, the hardware design chosen for the first prototype consisting of the Bluno Beetle from DFRobot and the AS7262 SparkFun Development Board incorporates low-power mode in hardware, but fails to provide the option to use this functionality freely. Even though the device Bluno Beetle is advertised as a low-power device, the current firmware version mounted on the Bluno Beetle does not allow the user to set the device in sleep mode at certain times, as the firmware version to allow for this is currently being developed by the team of DFRobot [12]. Since investigating the sleep mode of the device when not transmitting over Bluetooth was one of the ideas to incorporate low-power into the project, a custom Printed Circuit Board (PCB) was developed. In this board, the ATMega328 device was flashed with the bootloader for an Arduino Uno [5], which does incorporate the possibility of launching low-power and sleep modes if needed, hence reducing the overall power consumption of the device and the number of times the user will need to recharge it, which, in turn, increases the overall convenience of wearing the sensor for the study participants.

A second challenge faced during the development of the product was the large delivery time of the custom PCB. The board was ordered from JLCPCB [38], which is China's largest PCB prototype manufacturer. The Express Delivery option was chosen, which on average provides a 7 to 10 working days delivery. However, the board took approximately a month and a half to arrive. This was due to celebrations such as the Chinese New Year which was celebrated on the 5th of February for 2019. Even though the additional delay in January due to Christmas was taken into account, the board had been expected to arrive at the beginning of February since the Chinese New Year celebration was not considered. To compensate for this, data was collected with the first prototype while the custom PCB was being shipped. Nevertheless, the delivery time caused a significant delay in the development of the project, as the new prototype could not be tested until March even though the tests had initially been planned for February.

Additionally, even though the PCB design completed with Eagle software included the right footprint for the ceramic resonator, which consists of three pads (input, ground, output), when exporting the Gerber files to send to the PCB manufacturer, an error caused these to incorporate five pads for the resonator. As a result, the three pads of the resonator were being short circuited when the component was soldered onto the board. In order to solve this problem, the two extra pads were scrapped off manually and with care from the board which, consequently, eliminated the short circuit and lead to a successful functioning of the PCB.

9.2 Key Knowledge Acquired

Throughout the project and as a result of applying independent learning to solve the numerous challenges presented above, a large number of hardware, firmware, software, networking and data storage concepts were successfully learnt, together with an extensive background on the influence of coloured light on human health.

To begin with, through researching reliable websites as well as reading highly-regarded books and papers on the topic, knowledge was gained on the strong influence of certain light wavelengths, such as those corresponding to the blue band in the visible spectrum (450 to 495 nm), on human general health which, in turn, determines our quality of sleep. A background analysis on the current methods employed by researchers to measure the intensity of certain light wavelengths was performed in order to design and build a pioneering device for performing this task. Further information on the literature review can be found on section 2 of this document.

Regarding the hardware section of the project, the differences between Universal Asynchronous Receiver/Transmitter (UART), serial protocol I^2C and Serial Peripheral Interface (SPI) as communication interfaces between electronic devices was successfully understood. By developing custom firmware for the project, the ability to read and write data from an electronic device by using Arduino technology was acquired. The Bluetooth communication protocol was understood, as well as how to send data from the device to a mobile phone by using a microcontroller and a Bluetooth Low Energy Integrated Chip (IC).

By optimising the first hardware prototype, knowledge on Printed Circuit Board (PCB) design using Eagle software was acquired, resulting in the successful re-design of the device with reduced size and power consumption. The ability to solder using both standard manual soldering for the largest parts of the design, as well as solder paste and flux for the smallest components, was acquired. Both continuity checks and power measurement checks were performed on the prototypes of the sensor to ensure their correct functioning.

By developing an Android application, Java was learnt as a programming language together with how to operate the Android Studio IDE. The Bluetooth communication protocol was understood in order to interface with an electronic device through the application. Additionally, knowledge on HTTP POST request method and its implications for network security was acquired by programming the application to send data to the database via the network.

As regards networking and data storage, PHP script development skills were acquired by writing a script to correctly store the incoming data from the mobile application in the University of Surrey server. For this part of the project, a MySQL database was set up and used, therefore increasing the knowledge on MySQL syntax and storage principles and structure.

Throughout the whole project, an extensive understanding was acquired on how to debug and test the integration between components. As previously mentioned in this document, the Scrum methodology was employed to structure the project, which facilitated the setting of specific sprints for debugging the product and ensuring a correct and timely communication between the different components developed.

10 Extensions and Future Work

10.1 Use in Scientific Studies

This project was intended to design a system consisting of a lapel worn light sensor as front end, and a mobile application together with a secure database as back end. The work completed includes the selection of the right components and systems, their development, evaluation and calibration, and the integration and testing of the full set up, which successfully provides a proof of concept for the light sensing product.

The PCB schematics, mobile application and database developed are currently being used as part of a follow-up acceleration project in which the device will be further minimised, with low-power mode being incorporated into the product. This pre-commercial version of the project will be completed in June 2019 and will constitute the basis of a medium scale digital-health project including approximately 30 participants that will be pursued at the Surrey Sleep Research Centre (SSRC). Innovative features which are being explored for this commercial product include the use of energy harvesting for IoT devices.

10.2 Energy Harvesting for IoT Devices

A widely researched topic which is nowadays experiencing significant breakthroughs is the concept of energy harvesting for Internet of Things (IoT) devices. IoT devices are devices that have the ability to exchange data by wirelessly connecting to networks. Following this definition, the light sensor system developed in this project can be considered an IoT device.

Nowadays, most IoT devices are powered by batteries. However, the power provided by batteries, especially by the small batteries usually incorporated into wearable devices, is limited. An efficient and environmentally friendly alternative to increase the power delivered to the devices and, in turn, increase the products' lifetime is the new concept of energy harvesting. Energy harvesting is the process of taking energy from environmental sources such as light or wind, or other sources such as body movement, storing it, and converting it into electrical energy that can power devices, particularly wearable.

There are two main types of systems for energy harvesting. While in "Harvest and Use" systems the energy harvested is directly used, in "Harvest-Store-Use" systems the energy is stored to be used when required in the future. The former systems rely on the harvested energy and will remain inactive when this energy is not sufficient to power it. The latter systems store the energy in a secondary storage and use it once the battery energy has been consumed by the device [44].

Mechanical energy is one of the main sources implemented into energy harvesting systems. The mechanical energy of an object is the energy produced by that object's position (potential energy) or motion (kinetic energy). One of the sources of kinetic energy commonly exploited for energy harvesting purposes is human movement, which can be present in actions such as walking or moving the limbs. By using different energy harvesting principles the energy created by human movement can be converted into usable electrical energy. The main energy harvesting principles for kinetic energy can be classified into triboelectric, piezoelectric, and electrostatic energy harvesting. Previous studies have shown that piezoelectric or electrostatic materials can produce between 2V and 10V of output voltage [44].

In addition, solar energy constitutes another one of the main sources implemented into power harvesting applications. This option has been shown to generate between 3 and 4.5 V, which is suited to most wearable devices power requirements [39].

Commercially available devices which use mechanical energy harvesting to function are currently available. An example of this is the Seiko Kinetic Watch by Hayakawa of the Seiko Epson Corporation [31]. This watch constitutes a compact wearable device that successfully uses kinetic energy to power itself.

10.3 Energy Harvesting for the Light Sensor

Solar or kinetic energy harvesting are proposed as a alternatives to increase the lifetime of the light sensor presented in this project. The approach chosen for the solar energy harvesting will resemble the above-mentioned products that have been developed and be an appropriate choice due to the sensor's purpose which is to be exposed to light. The approach using mechanical energy, and more specifically, kinetic energy harvesting will be based on piezoelectric or electrostatic materials, and match the previously mentioned products. Since it has been shown that more kinetic energy can be generated from limb movement compared to general movement, larger amounts of kinetic energy will be produced by the device when it is worn by the user on their limbs rather than on their chest. A combination of both techniques can also be considered.

Future work should focus on investigating the latest materials available to implement energy harvesting. This would not only expand the lifetime of the product, but also reduce its size and weight, since a smaller and therefore lower capacity battery could be incorporated into the project.

11 Conclusion

A fully-functional prototype was designed, developed and tested for the light sensing system, successfully meeting the goal set for this project. The current system accurately measures the intensity of light at different wavelengths throughout the visible spectrum, as well as the ambient temperature and the user's rating of their tiredness level. It has been successfully calibrated to measure the intensity at specific wavelengths, including the five specific wavelengths presented in the literature review section of this document that researchers require to analyse the influence of light on human health.

The light and temperature data recorded by the sensor together with the user tiredness rating is time stamped and transmitted via Bluetooth to a mobile device through the developed Android mobile application. It is then stored both locally and in a secure server at the University of Surrey by using PHP scripting and MySQL technologies. The mobile application allows both the user and medical professionals to access the data in real time, and indicates whether the light values need to be synchronised with the server.

Multiple data collection sessions were run during the course of the project. For these, the light intensity and temperature data recorded by the sensor was stored and analysed together with the heart rate and physical activity data gathered from the MiBand 3 device. It was concluded that the light intensity and temperature values reported by the sensor correlate well not only with the Gaussian distribution that represents each colour theoretically, but also with the activities performed by the user and the data extracted with the MiBand 3 device.

The light sensor, mobile application and database developed work together to provide researchers with the ability to measure the intensity of light at different wavelengths within the visible spectrum and examine it together with any other data in a similar way to the analysis for light intensity, heart rate and steps data performed in this document. Therefore, researchers both at the Surrey Sleep Research Centre (SSRC) and at other research centres around the world will have access to a standarised tool and a step-by-step method to collect and share light intensity data. This satisfies the need in the scientific community to measure the intensity of light in a standarised way which provides a more in-depth analysis than the current lux metres being used by the community.

Future work to improve the sensor includes incorporating energy harvesting from the user's own kinetic energy into the sensor in order to reduce its battery requirements and consequently the size of the device, which will, in turn, increase the sensor's efficiency, practicality and user-friendliness. The proof of concept provided by this work constitutes the basis for the development of the pre-commercial version of the product which will be used in a number of clinical studies at the Surrey Sleep Research Centre (SSRC) during the next few years.

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Appendix A: Gantt charts

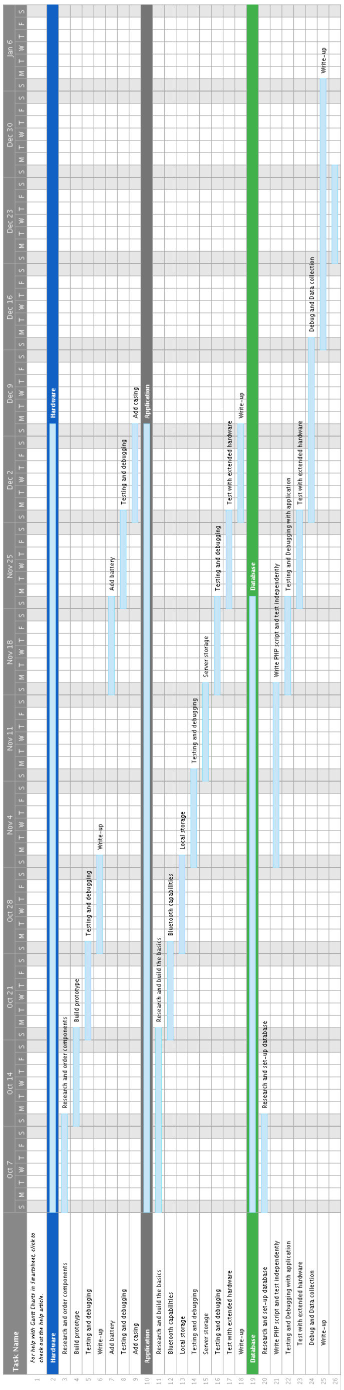

Figure 36: Project Gantt chart for semester 1.

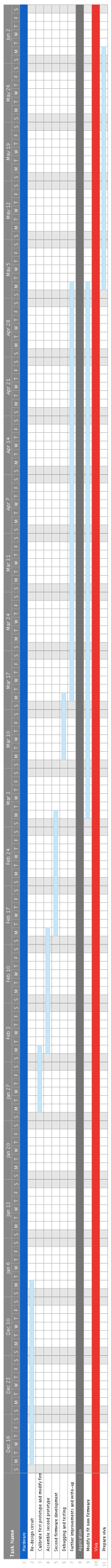

Figure 37: Project Gantt chart for semester 2.

Appendix B: First and Final Prototypes Firmware Code

```
#include <Wire.h>
#include "Adafruit_AS726x.h"

  // Sensor object
  Adafruit_AS726x ams;

  // Buffer to hold colour and temperature values
  sensorValues[AS726x_NUM_CHANNELS];

void setup() {

  // Set baud rate to 115200 to communicate with the mobile application
  Serial.begin(115200);

  // Configure serial connection
  while (!Serial) {
    Serial.print("not serial");
  }

  // Connect to the sensor
  if (!ams.begin()) {
    Serial.println("Error");
    while (1);
  }

  // Set sensor pin LED_BUILTIN as output
  pinMode(LED_BUILTIN, OUTPUT);
}

void loop() {

  // Get the number of milliseconds since the program was initialised
  long initTS = millis();

  // Read temperature
  uint8_t temp = ams.readTemperature();

  // Start measuring
  ams.startMeasurement();

  // Wait for data
  bool rdy = false;
  while (!rdy) {
    delay(5);
    rdy = ams.dataReady();
  }

  // Read colour and temperature values
  ams.readRawValues(sensorValues);

  // Create a string with the colour values in the right format
  String colourValues = String(sensorValues[AS726x_VIOLET]) + String(',') +
      String(sensorValues[AS726x_BLUE]) + String(',') + String(sensorValues[
      AS726x_GREEN]) + String(',') + String(sensorValues[AS726x_YELLOW]) +
      String(',') + String(sensorValues[AS726x_ORANGE]) + String(',') + String(
      sensorValues[AS726x_RED]) + String(',') + String(temp) + String('-');

```

```
  // Send values via Bluetooth
  Serial.print(colourValues);

  // Wait 5 seconds
  delay(5000);
  }
}
```

Code 1: Arduino code for the first prototype of the sensor.

```
#include <Wire.h>
#include "Adafruit_AS726x.h"

#define LOOP_PERIOD 15000 //Loop period in milliseconds

  // Sensor object
  Adafruit_AS726x ams;

  // Buffer to hold colour and temperature values
  sensorValues[AS726x_NUM_CHANNELS];

void setup() {

  // Set baud rate to 115200 to communicate with the mobile application
  Serial.begin(115200);

  // Configure serial connection
  while (!Serial) {
    Serial.print("not serial");
  }

  // Connect to the sensor
  if (!ams.begin()) {
    Serial.println("Error");
    while (1);
  }

  // Set sensor pin LED_BUILTIN as output
  pinMode(LED_BUILTIN, OUTPUT);
}

void loop() {

  // Get the number of milliseconds since the program was initialised
  long initTS = millis();

  // Read temperature
  uint8_t temp = ams.readTemperature();

  // Start measuring
  ams.startMeasurement();

  // Wait for data
  bool rdy = false;
  while (!rdy) {
    delay(5);
    rdy = ams.dataReady();
  }
```

```
  // Read colour and temperature values
  ams.readRawValues(sensorValues);

  // Create a string with the colour values in the right format
  String colourValues = String(sensorValues[AS726x_VIOLET]) + String(',') +
      String(sensorValues[AS726x_BLUE]) + String(',') + String(sensorValues[
      AS726x_GREEN]) + String(',') + String(sensorValues[AS726x_YELLOW]) +
      String(',') + String(sensorValues[AS726x_ORANGE]) + String(',') + String(
      sensorValues[AS726x_RED]) + String(',') + String(temp) + String('-');

  // Send values via Bluetooth
  Serial.print(colourValues);

  // Wait loop period
  while (millis() < initTS + LOOP_PERIOD) {
  }
}
```

Code 2: Arduino code for the final prototype of the sensor.

Appendix C: PHP Script

```php
<?php
$username = "sensorUser";
$password = "sensorPassword";
$server = "localhost";
$database = "dbSensor";
$table = "sensorcolours";

$conState = mysqli_connect($server,$username,$password,$database);

if($conState)
{
    if(isset($_POST['timestamp'], $_POST['violet'], $_POST['blue'] , $_POST['green'] , $_POST['yellow'] , $_POST['orange'] , $_POST['red'], $_POST['tempe'], $_POST['score'])){
      $Timestamp=$_POST['timestamp'];
      $Violet=$_POST['violet'];
      $Blue=$_POST['blue'];
      $Green=$_POST['green'];
      $Yellow=$_POST['yellow'];
      $Orange=$_POST['orange'];
      $Red=$_POST['red'];
      $Tempe=$_POST['tempe'];
      $Score=$_POST['score'];
      $query = "INSERT INTO $table(Timestamp, Violet, Blue, Green,Yellow, Orange,Red, Temperature, Tiredness)VALUES('".$Timestamp."', '".$Violet."','".$Blue."','".$Green."','".$Yellow."','".$Orange."','".$Red."','".$Tempe."','".$Score."');";
      $result = mysqli_query($conState,$query);
    if($result){
      echo "OK";
    } else{
      echo "ERROR";
    }
}
}

mysqli_close($conState);

?>
```

Code 3: PHP script to send data from the mobile application to the online database.