Dyson School of Design Engineering

MEng Design Engineering

DE4 – SENSING & IOT COURSEWORK

Joseph Shepherd – CID: 01217499

Presentation URL:

https://drive.google.com/open?id=1i43Ws51qGaPHdJHzmDacVL71lJy6Truh

Code & Data:

https://github.com/Jshepherd97/SIOT-SLEEP

1. Introduction and objectives

An ever-growing number of scientific sleep studies publishing easily accessible information has meant that people are becoming aware of the importance of sleep on both long- and short-term wellbeing and health. Therefore, in the age of 'the quantified-self' we are seeing more and more people motivated to track and improve their sleeping habits. A trend which has been facilitated by advancements in the embedded sensor technology of commercially available devices such as smartphones and smartwatches which have made accurate sleep tracking available to the masses (Kolla et al., 2016) In a recent CNET survey 30% of people were already tracking their sleep and another 30% were planning on starting soon (Turrentine, 2019).

A vast number of these scientific papers and studies focus on the effects of indoor environmental conditions (temperature, light, noise, humidity etc.) on the duration and quality of ones sleep (Falbe et al., 2015; Kay et al., 2012; Kim et al., 2010). In response, we have observed the rise of a new market of 'sleep tech'; 'smart' products such as lights, alarms, eye-masks and even beds which aim to favourably alter or block these environmental conditions with the hope of improving the quality of sleep. It is within this niche that this project also operates; trying to leverage data and technology to favourably alter the sleeping environment of a smart home. The aim of this project was to track indoor environmental quality (IEQ) and sleep activity over a week long period, to investigate the relationship between the data sources and to develop an IOT solution that prompts a change in the bedroom environment to favourably affect the sleep of the user. The IOT prototype presented focuses solely on the temperature of the bedroom and trying to alter it for ideal falling asleep conditions.

The objectives of this project were to:

1- Create an IOT sensing unit that measures indoor environmental quality in my bedroom
2- Collect and store this data using robust network communications
3- Collect sleep activity data using a smartphone and smartwatch
4- Analyse the time series data sets for cross and auto correlation
5- Communicate important information using an online GUI that live streams data in a useful and easy to understand way
6- Prototype an IOT solution that create actuations to change the bedroom environment

2. Data Sources and sensing set-up

IEQ Data (Temperature, Humidity, pressure, Light, Gases)

The IEQ data points were collected using hardware setup in the bedroom environment, specifically a Pimoroni 'Enviro+' sensor board attached to a Raspberry Pi 3B+ computer. This all-in-one environmental monitoring board houses a BME280 sensor recording temperature, pressure and humidity in the bedroom environment, a LTR-559 light and proximity sensor recording Lux level in the room and a MICS6814 analog gas sensor recording the changing levels of 3 types of gases – reducing, oxidising and NH_3 in the indoor environment, making for a total of 7 IEQ data points being captured. Physical set-up and connection of the hardware was very straightforward: The Enviro+ is a fully assembled pHAT-format board which connects to the Pi via the 40 GPIO pin header, making for a very compact and robust piece of hardware. Software set-up was relatively simple but there was some time-consuming sensor calibration which had to be done; due to the proximity of the sensor board to the Pi, heat radiated from the Pi's CPU affected the temperature reading from the board. This had to be compensated for by recording the Pi's CPU temperature, applying a factor to this value and using this to decrease the sensors temperature reading. Using a second digital temperature sensor for comparison (shown in Figure 1a) this reduction factor was tweaked until both sensors gave the same reading for a prolonged period of time. The hardware set-up was placed in a fixed position in the bedroom, next to the bed and near to a large window (Figure 1b). The Raspberry

Pi stayed plugged in and connected to Wi-Fi for the duration of the project collecting and publishing data during both day and night.

Figure 1 - IEQ Data Collection Setup: Up-close of hardware and secondary temperature sensor (Left) General area (Right)

Sleep Data (Actigraphy, Heart rate)

Sleep activity was recorded by two means: Actigraphy (measurement of movement) and Heart rate. Actigraphy data was captured using a smartphone through the 'Sleep as Android' app – by placing the smartphone on the mattress during sleep this app uses the smartphone's embedded accelerometer to detect the user's movements in bed and graphs this data to show activity throughout the night. Heart rate was captured using a smartwatch with an optical heart rate sensor through the 'Heart trace 2' wear OS app. This set-up is shown in Figure 2.

Figure 2 - Sleep data Collection Setup

3. Data collection and storage process

Data collection

The 'Enviro+' board has a bespoke python library with easy-to-use functions that make pulling data from its sensors very simple. A custom algorithm was written in python which utilised this library to simultaneously collect data from all sensors once a minute. For increased accuracy and to remove the effects of instantaneous noise. four readings were taken for each sensor over a twenty second period and the average of these was the given value for that minute. During the two week period that room conditions were recorded, data collection was only interrupted twice – the first of these was due to the Pi temporary losing internet connection and not being able to push the CSV file to Github – an unforeseen error which was consequently handled by embedding the push function in a try and except loop – and the second was due to building works in the home which required the power to be temporary turned off.

The tracking of sleep data was started manually each night when getting into bed and stopped in the morning upon waking. Unfortunately, due to the use of third-party applications and hardware to collect the sleep data, collection was restricted to the software's own sampling rates and collection parameters. The heart trace app attempted to take a heart rate reading every five minutes and the sleep as android app continuously measured accelerometer data recording an average actigraphy value every five minutes, This sleep data was collected for a total of eight nights in the two week period.

Data storage

All data collected on the Raspberry Pi was instantly written to a CSV file and stored locally, this file was then pushed to Github every hour using the PyGithub python module. Simultaneously, this data was also uploaded to a Thingspeak channel using the Thingspeak RESTFUL API, communicating over HTTP using a unique API read key to publish the live data to the channel. This allowed the data to be viewed and visualised in real-time from anywhere and became a useful touchpoint to quickly check the room conditions during the project. Due to the use of third-party software the Sleep data could not be automatically uploaded to Github , ThingSpeak or cloud storage and was instead manually exported from the apps as CSV files which were then uploaded to Github.

4. Basic characteristics of the end-to-end system

The overall system is shown in figure 3. Hardware continuously collects IEQ data in the bedroom environment and publishes this to the ThingSpeak Channel. On the ThingSpeak platform the 'Time Control' app is used to perform scheduled analysis of the data at certain time intervals, which dictates the push notifications sent to the user via the IFTTT platform. The data published to the ThingSpeak channel is simultaneously displayed on the web-app site which acts as the user's main touchpoint and their dashboard for the mysleepclimate system.

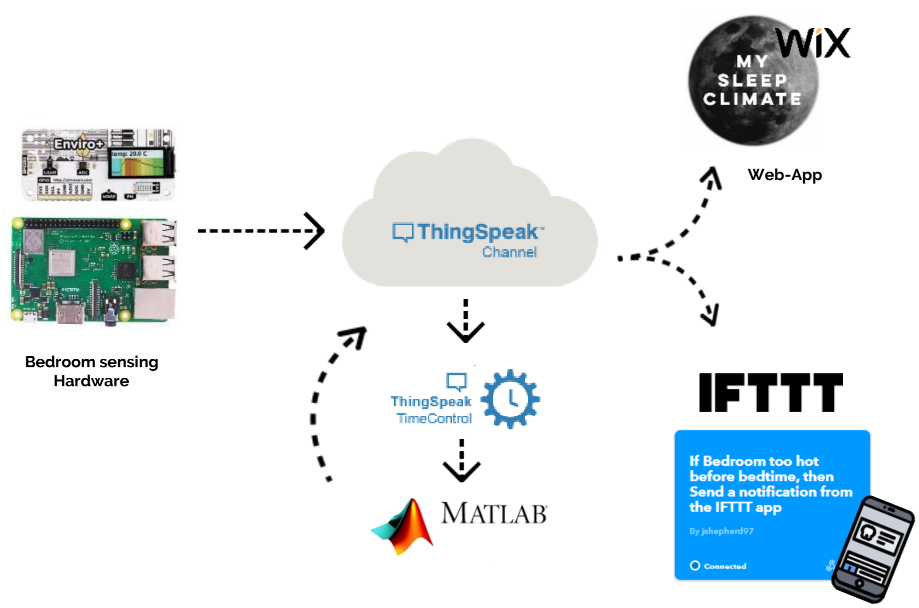

Figure 3 - The Mysleepclimate end to end system

5. User interaction and the Front-End Platform

Data analysis (shown in section 6) showed that temperature has a strong correlation with sleep activity, a finding that is backed by much scientific sleep research (Okamoto-Mizuno and Mizuno, 2012). Consequently, the IOT system developed is primarily focused on sensing the bedroom temperature and prompting actuation to favourably affect it.

Push notifications

The user has two main points of interaction with this system, the first of which is the push notifications sent to their phone through the IFTTT platform. Thirty minutes before the user's scheduled bedtime they are sent a push notification directly to their smartphone which tells them the current temperature of their bedroom, whether it is too hot or too cold and what suggested actions they could take to change it before bed, the notification can be clicked to open the web-app, showing the most up to date temperature reading and more suggested actions. An example notification is shown in figure 4. At the set time the ThingSpeak 'Time Control' app triggers a MatLab analysis file to run which checks the temperature reading and based on the value triggers one of multiple 'webhooks' which in turn notify the IFTTT platform to send the relevant push notification to the user. Five minutes before bed a second push notification is sent to the user which links to the mysleepclimate web-app prompting them to check the temperature one last time as well as the nights weather forecast, suggesting relevant actions to alter the temperature or prepare for the night ahead (Figure 5).

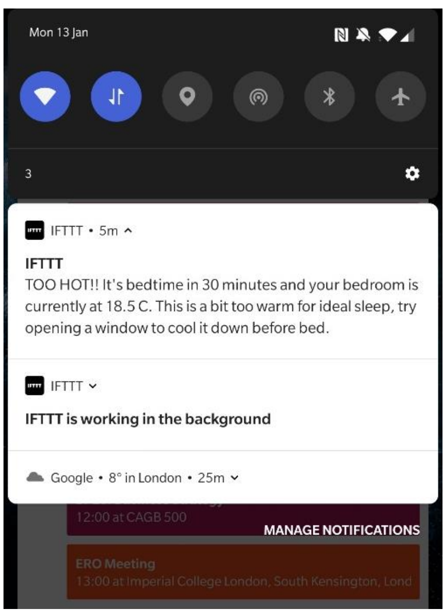

Figure 4 – 'Too Hot' push notification

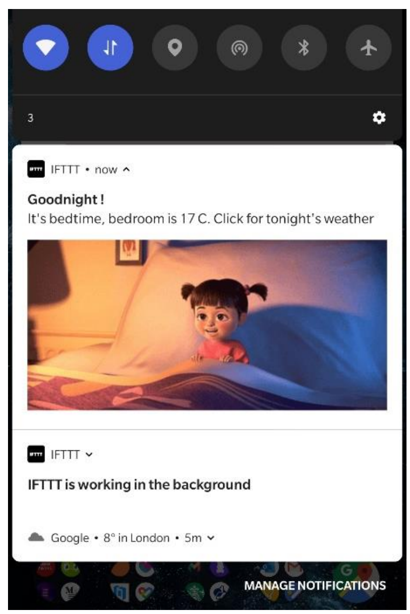

Figure 5 - Goodnight sleep notification

Web app

The main touchpoint of the mysleepclimate system is the web-app which can be accessed at www.mysleepclimate.com. This is a Wix hosted website that acts as a GUI for the bedroom data and is the user's personal system dashboard. It displays the live IEQ data from the ThingSpeak platform, giving the user a snapshot of the bedroom environment and providing both immediate and long-term suggested actions that they can take to favourably change the temperature of their room for a better night's sleep. The current temperature is displayed in an easy-to-understand way; using a coloured temperature gauge and an indicator light which glows green when temperature is in the ideal range (Figure 6). If temperature is not in the ideal range the user can click 'Too Hot' or 'Too Cold' and be presented with actionable suggestions to counteract this (Figure 8). The site also displays the weather forecast for the night which might be of interest to the user (Figure 7) and again couples this with a few actions they might want to take based on the forecast (Figure 8). Lastly, historical data – the last few hours of IEQ points are displayed on the site, allowing the user to check on the state of the room and view changes in temperature over time (Figure 9).

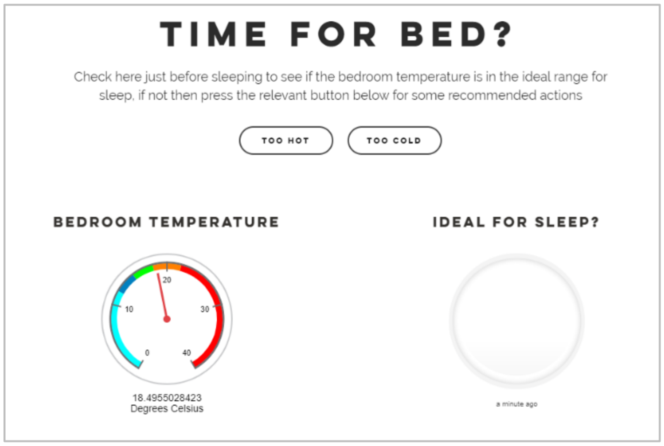

Figure 6 - Current bedroom temperature displayed on Web-App

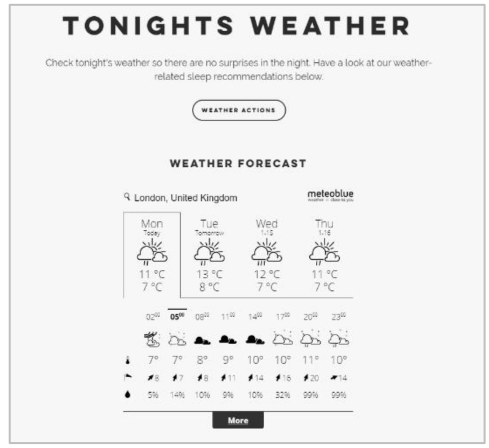

Figure 7 - Web-app Weather interface

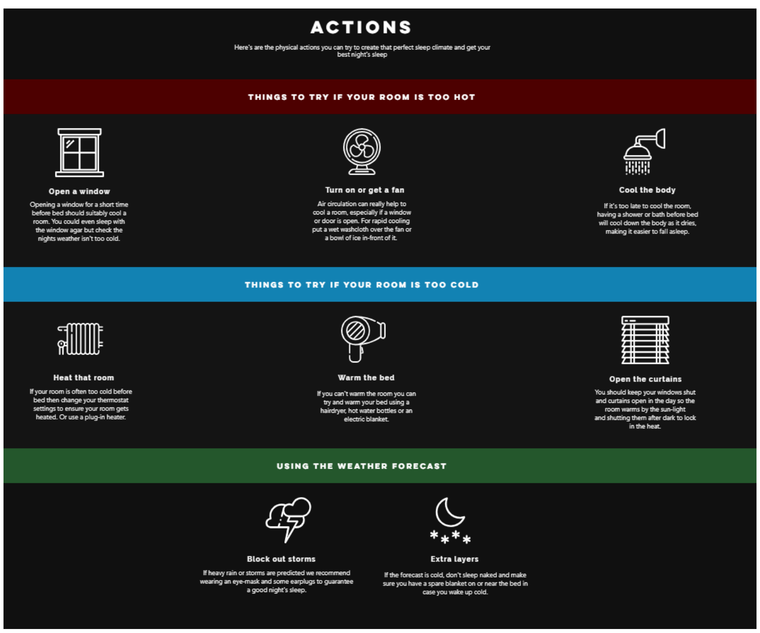

Figure 8 - Suggested actions section of the Web-app

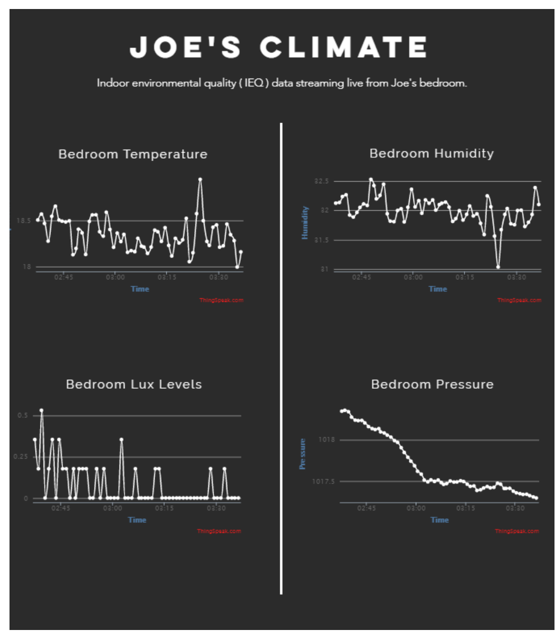

Figure 9 - Historical IEQ Data

6. Data visualisation, analytics and insights

Pre-Processing

As previously mentioned, the IEQ data had a few missing data points due to a temporary error state and an unexpected power outage, before data analysis could take place these gaps in the data had to be filled; this was done through linear interpolation in MatLab. Similarly, before the sleep activity data could be correctly graphed and analysed it also had to go through some manual data processing. The lack of control over data recording within the apps meant that the CSV files were written in slightly different formats and recorded at slightly different times. Additionally, the heart trace app often failed to take a reading causing the period between data points to fluctuate massively and the sleep as android app regularly changed from recording a value every 5 minutes to one every 6. Therefore, when combining these data sets the sleep data was resampled minutely using linear interpolation, synchronising the three data sets with a common time vector.

Visualising data

Analysis of the temperature and sleep activity data collected over eight nights was performed using MATLAB and the normalised data sets for 6 of the 8 nights are plotted against each other in Figure 10. The yellow line is the temperature value which always shows a gradual decrease throughout the night and the blue and red lines are the actigraphy and heart rate data respectively. These two datasets visually show a positive correlation, which is expected as they are both measures of sleep activity.

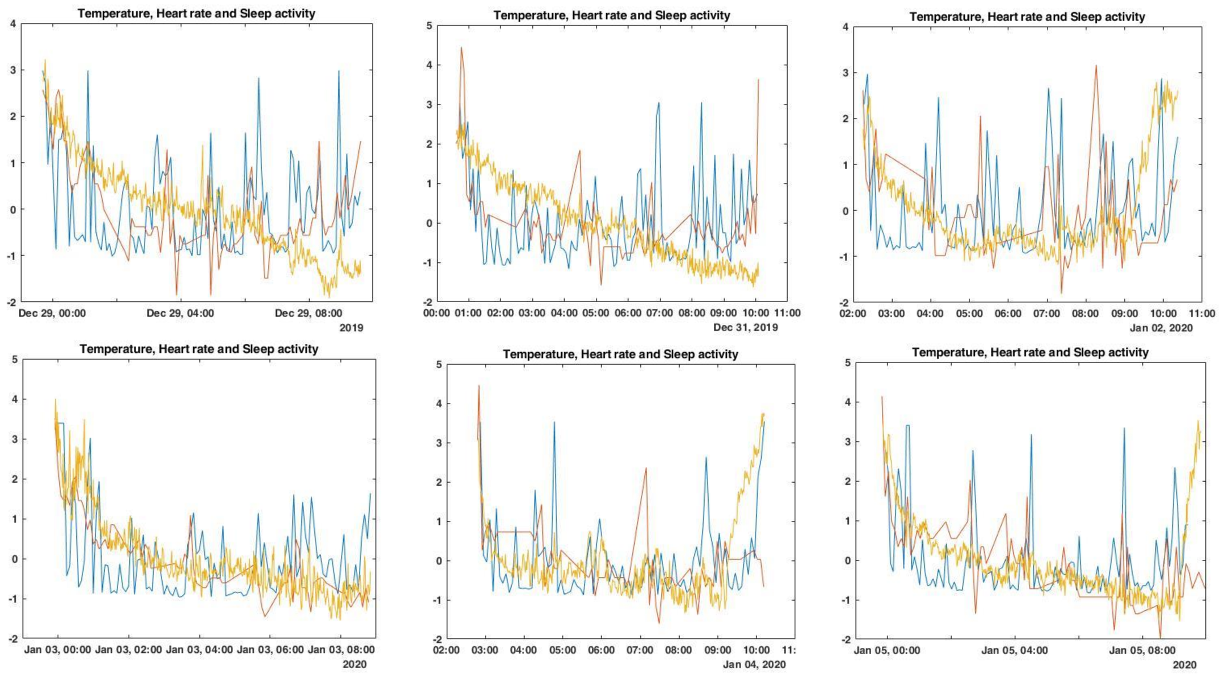

Figure 10 - Normalised Temperature, Heart Rate and Sleep Activity for 8 nights

Auto-correlation

The temperature of the room over a two-week period is shown in Figure 11. This data has been resampled using hourly means to smooth the data and remove noise, it looks to show temperature periodicity on a daily or bi-daily basis. To investigate this periodicity, the time series temperature data was tested for auto-correlation, and it was found that the bedroom temperature had a seasonality of 0.5 days as shown in Figure 12. This was predictable as temperature expectedly oscillates over a day; peaking during the day and dropping during the night.

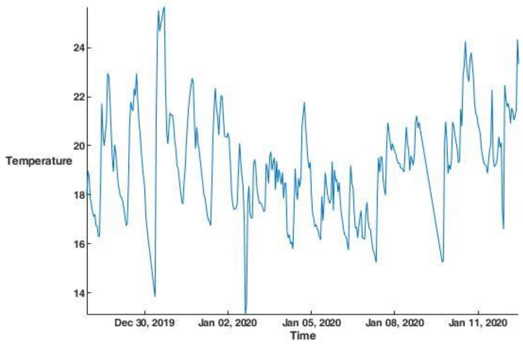

Figure 11 - Mean Hourly Bedroom Temperature

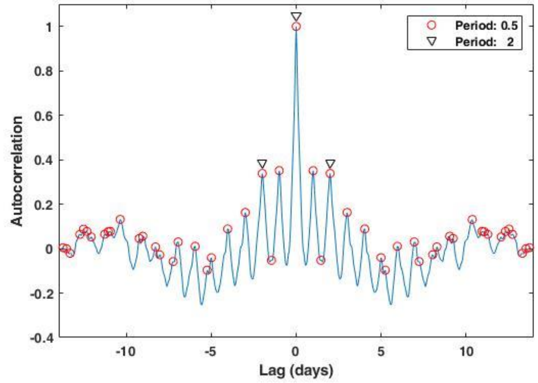

Figure 12 - Temperature Autocorrelation and periodicity

<u>Cross -correlation and analysis</u>

Cross-correlation was tested for all combinations of the three main time series datasets (Temperature, Heart rate and Actigraphy). Because of the non-continuous nature of sleep data capture (e.g. only recorded during the night) cross-correlation was computed for one night's worth of data at a time, with these being compared to spot trends, for each combination three cross-correlation plots are shown. The relationship between temperature and heart rate consistently showed the strongest and most significant correlation with a peak correlation coefficient of 0.84 (Figure 13). Interestingly, this peak always occurs at a lag time of 0, meaning that changes in temperature and heart rate occur simultaneously, without delay between them.

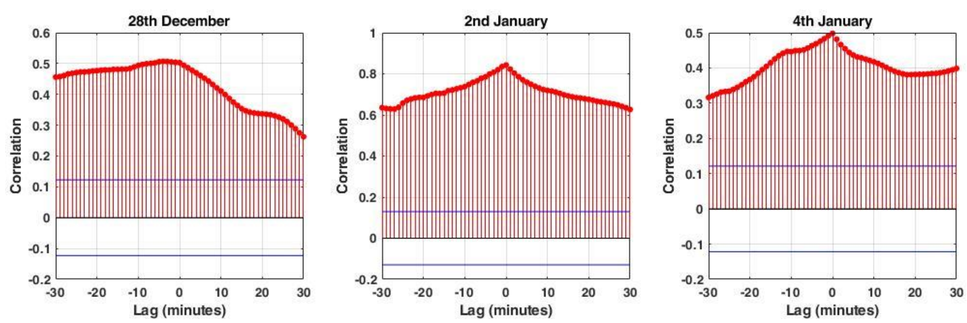

Figure 13 - Correlograms for Temperature and heart rate

Temperature and Actigraphy also showed significant but slightly weaker correlation, with peak coefficient usually around 0.3-0.4 (Figure 14). Similarly, peaks occurred at 0 lag time, but the correlation-lag pattern is was not symmetrical, with higher correlation coefficients on the side of negative lag. This could represent a possible delayed relationship between the user moving in bed and the bedroom temperature increasing, however, this seems unlikely and is only weakly eluded to.

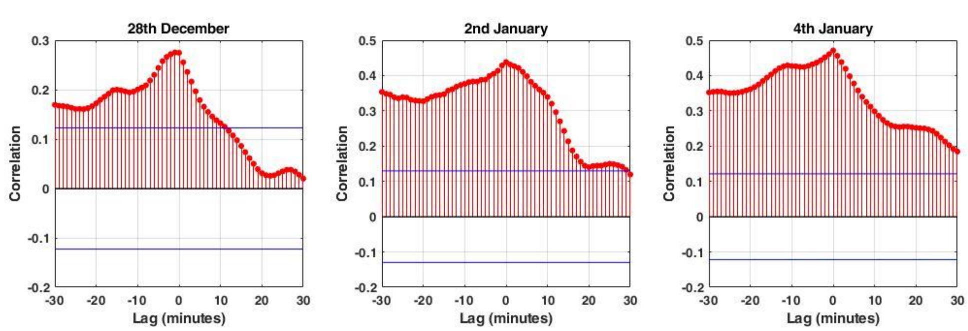

Figure 14 - Correlograms for Temperature and actigraphy

Cross correlation between actigraphy and heart rate continuously shows a peak correlation coefficient of 0.4 (Figure 15), although this is still a significant value it is surprising that these two measured of activity were not more strongly correlated. Again, the peaks occurs at a lag time of 0 meaning that increases in movement and heart rate happen concurrently, which makes sense as moving the body intrinsically raises BPM., The observed tendency for higher coefficients on the side of positive lag may represent how heart rate stays high for a short while after movement.

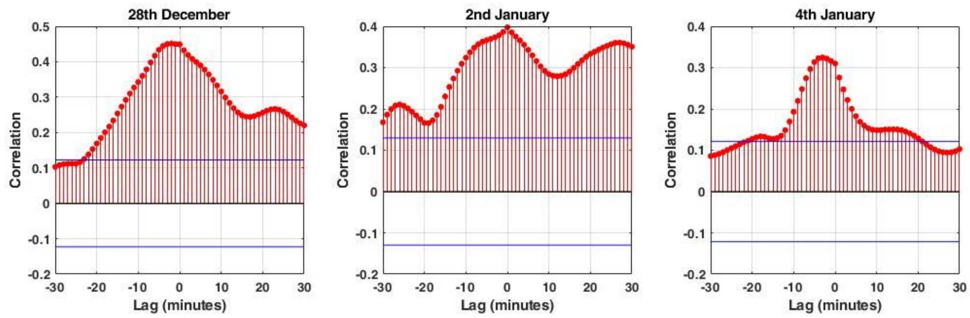

Figure 15 - Correlograms for actigraphy and heart rate

7. Discussion

The aim of this project was to capture data on indoor environmental quality and sleep activity, to cross-analyse the data and to use the findings to develop a user-friendly IOT system that would help users get a better night's sleep. I believe that in its current state this solution serves as a good pretotype for a personal sleep climate system and offers some novel functionality that even in its rudimentary state might be of interest to users.

This current system focuses exclusively on temperature as data analysis and scientific research suggested it was the most important of the IEQ measures and it is one of the easiest to affect. The bedroom's temperature is of specific importance in three different scenarios: the first is the temperature of the bedroom when falling asleep, the second is the temperature during the night and the third is the temperature when waking up. This current prototype focuses solely on the first scenario, trying to ensure the bedroom's temperature is close to ideal (15-18 degrees) at bedtime. This scenario was chosen because it seemed the most actionable within the scope of the project, as changing the temperature before sleep could be achieved with a low-tech solution by utilising a 'human in the loop'. Through prompted action (push notifications) bedroom temperature is favourably altered without the need for additional 'smart' tech such as a smart thermostat and the system can consequently be easily replicated in any home. For the current system the only tech needed is an internet connected temperature sensor – something that can be created for around £15 using a Pi zero W and a cheap sensor, whereas temperature actuation during the night-time can only be achieved through the use of an internet connected thermostat or a heater/fan connected to a smart plug; expensive technology which wasn't available in the test home and was out of budget for the project. Of course, this means that the current system requires physical effort and input from the user and is less 'smart' and seamless. However, the current system framework could easily integrate these devices through its existing connection with the IFTTT platform, becoming a fully autonomous controller of sleep climate for users in a 'smarter' home.

Data analysis in this project showed a strong causal relationship between temperature and heart rate. With scientific research suggesting that a decrease in heart rate is necessary to fall asleep, this project was developed on the premise that by lowering the bedroom temperature before bed, the user's heart rate would similarly decrease, and they would fall asleep with greater ease. Through day-to-day use of the system it has been proven that by following the actions suggested at the notified time, the bedroom's temperature can be lowered to a favourable value in time for bed. However, it has not been tested whether the user finds it easier to fall asleep or favours the conditions for doing so, to validate this system this would need to be evaluated moving forward.

8. Future work and development

In its current form the system serves as a smart bedroom thermometer, which notifies users before bed if their bedroom is too hot or too cold and suggests simple actions, they can take to change this in time for sleep. In this prototype state the system offers simple but useful functionality and a novel interaction which could be made more emotive by playful branding and rich notifications from a mysleepclimate phone app. As aforementioned the only hardware required for this system is an internet connected temperature sensor, something which could be cheaply built into a consumer product and might have a business case when packaged with the system. This product could be made even more attractive and feature packed by adding a colour changing light to the device – acting as a 'calm technology' indicator for the bedroom temperature.

However, what is more exciting is the possibility to grow the system through further integrations with IOT products and services, The current system is designed to be low-tech and requires a 'human in the loop' completing suggested actions that in turn favourably affect the temperature of the bedroom. Further development of this system requires the automation of these tasks allowing mysleepclimate to regulate bedroom temperature autonomously, making for a truly smart system that doesn't need user input. As formerly eluded to, this type of autonomy would be possible through smart thermostat integration, allowing the system to seamlessly actuate the heating or cooling of the room in response to the temperature value at a given time. Fortunately, this integration is surprisingly easy given the current framework of the system. At the moment when the bedroom temperature is too hot or too cold before bed a custom webhook triggers the IFTTT platform to send a push notification to the user, in the IFTTT (if this then that) context the webhook which signifies 'too hot' or 'too cold' is the 'this' action and the push notification is the 'that' action. Given this set-up, to automate the heating of the room all that needs to be changed is the 'that' action triggered by the IFTTT platform. Figure 16 shows one option for a 'that' command using a 'netatmo' smart thermometer, with this action I could trigger the thermostat to start heating or cooling the bedroom to a certain temperature, in response to my 'this' command. This automation would mean the system could automatically actuate the bedroom temperature before sleep, prevent it getting too high or too low during the night and increase the temperature before waking up, making it easy to get out of bed in the morning.

Furthermore, in an ideal system, sleep data (actigraphy and HR) would be streamed to the web-app the same as the IEQ data, showing the user their last night's sleep activity and comparing it with their bedroom conditions for more detailed and useful data feedback. However, the use of third-party sensing apps without API's made this impossible and moving forward DIY sleep tracking hardware or more simply a mysleepclimate sleep tracking app which similarly uses the phones accelerometer would have to be developed to introduce this functionality.

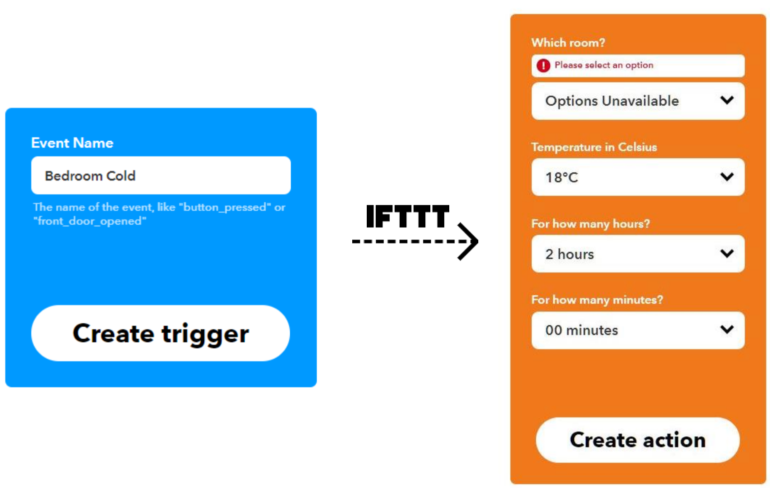

Figure 16 – IFTTT action triggering 'Netatmo' smart thermostat with existing webhook

9. References

Falbe, J., Davison, K.K., Franckle, R.L., Ganter, C., Gortmaker, S.L., Smith, L., Land, T., Taveras, E.M., 2015. Sleep Duration, Restfulness, and Screens in the Sleep Environment. Pediatrics 135, e367–e375. https://doi.org/10.1542/peds.2014-2306

Kay, M., Choe, E.K., Shepherd, J., Greenstein, B., Watson, N., Consolvo, S., Kientz, J.A., 2012. Lullaby: a capture & access system for understanding the sleep environment, in: In UbiComp.

Kim, M., Chun, C., Han, J., 2010. A Study on Bedroom Environment and Sleep Quality in Korea. Indoor Built Environ. 19, 123–128. https://doi.org/10.1177/1420326X09358031

Kolla, B.P., Mansukhani, S., Mansukhani, M.P., 2016. Consumer sleep tracking devices: a review of mechanisms, validity and utility. Expert Rev. Med. Devices 13, 497–506. https://doi.org/10.1586/17434440.2016.1171708

Okamoto-Mizuno, K., Mizuno, K., 2012. Effects of thermal environment on sleep and circadian rhythm. J. Physiol. Anthropol. 31, 14. https://doi.org/10.1186/1880-6805-31-14

Turrentine, L., 2019. Not tracking sleep? It's official: You're missing out [WWW Document]. CNET. URL https://www.cnet.com/news/sleep-tracking-study-shows-health-improvements-and-more/ (accessed 1.10.20).