SleepBox: A Tangible Tool Through Data-Enabled Design for Self-Tracking Sleep

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ABSTRACT

We spend about one-third of our lives asleep. With the development of IoT, nowadays numerous products sense and report sleep data, which increases awareness of sleep. However, most applications distracts users from focusing on daily activities that they have control over that improve sleep health. In this project, a data-enabled design methodology was conducted to answer the question: how to help people track sleep with both objective and subjective data? By probing and insight the real context, the concept of SleepBox, a tangible tool for self-tracking sleep was generated. A prototype was deployed at a participant's home in the informed step. The user experience was proved good and more opportunities are revealed.

CCS CONCEPTS

• **Computer systems organization → Embedded systems**; *Redundancy*; Robotics; • **Networks** → Network reliability.

KEYWORDS

tangible interface, sleep, IoT

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1 INTRODUCTION

Ever since three decades ago, Mark Weiser [21] envisioned a world of Ubiquitous Computing, researchers have been exploring and developing various technologies to expand the vision. Internet-of-Things (IoT) is one of the research topics. With the development of hardware and software, IoT technologies have been applied in various fields, the most typically transport and logistics, healthcare, smart environments, and personal and social applications [3].

Involved in healthcare and smart environments, sleep has also become an essential scenario for IoT in recent years. People spend about one-third of their lives asleep[3]. Sleep quality is one of the main factors to determine human health and well-being. With continuous monitoring, it can potentially decrease the risk of chronic diseases, mental problems, or accidents caused by sleep disorders[4]. IoT technologies empower the wireless communication of different devices for tracking sleep, as well as the communication between users and doctors or caregivers [4].

In recent years, there are many studies that develop smart sleep monitoring systems based on the concept of IoT [17] [9]. Also in the market, numerous products sense and report sleep data, which increases awareness of sleep and helps users address modifiable behaviors and their sleep hygiene [14]. Data acquisition and feedback is still a challenge. First of all, most research and products focus on the acquisition of objective data (such as sleep rhythm, breathing, and heartbeat) to analyze the relationship between sleep cycle time and sleep quality. However, such visual feedback of the sleep cycle brings a broken mindset to users [14], because users cannot directly control these aspects when asleep. As a result, users are distracted from focusing on daily activities that they have control over that improve sleep health. Other studies have focused on subjective data. For example, a sleep diary is a commonly used method of sleep status [6]. However, subjective data often requires analysis by sleep experts or doctors, and it is difficult for users to track sleep by themselves.

In this project, a data-enabled design methodology [18] was conducted to answer the question: how to help people track sleep with both objective and subjective data? In the contextual step, data and cultural probes were deployed in the participants' sleep environment. After data collecting, visualizing, and user interviews, design requirements were set for the design concept. Finally, SleepBox was designed for inputting daily parameters through a tangible interface. The tangible interface records subjective and objective data without the interruption of electronic screens, and it also assists in falling asleep with a light design. After using the box, the user can reach a digital visualization at any time to get data feedback. The prototype is tested in the field for 7days and the qualitative data was collected for more insights.

2 RELATED WORK

The clear definition of sleep health first appeared in 2014 by Daniel J. Buysse — "Sleep health is a multidimensional pattern of sleep-wakefulness, adapted to individual, social, and environmental demands, that promotes physical and mental well-being. Good sleep health is characterized by subjective satisfaction, appropriate timing, adequate duration, high efficiency, and sustained alertness during waking hours." [5] In the definition, there are five dimensions that are most relevant to the definition of sleep health:

- Duration: The total amount of sleep obtained per 24 hours
- Efficiency: The ease of falling asleep and returning to sleep
- Timing: The placement of sleep within the 24-hour day

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- Alertness: The ability to maintain attentive wakefulness
- Satisfaction: The subjective assessment of "good" or "poor" sleep.

These five dimensions are concluded as the SATED framework, and most dimensions can be measured across behavioral, physiological, and self-report levels of analysis. Different studies have developed technologies and methods for tracking sleep health.

2.1 Behavioral and Physiological Levels

On the behavior and physiological level, polysomnography (PSG), a combination of electroencephalography (EEG), electrooculography (EOG), and electromyography (EMG) data, is considered the gold standard to assess sleep [2]. However, complex, bulky, and on-body devices of PSG not only limit the system to labs, but also reduce time in bed, total sleep time, as well as sleep efficiency compared to the home-based scenario [13]. Therefore, a large number of products and researches tend to detect sleep health in the home environment.

Ballistocardiography (BCG) and Actigraphy are two common methods for monitoring sleep health in the home environment [17]. The former obtains sleep physiology data by measuring heart rate, heart rate variability and breathing rate [12], and requires contact with the human torso. The latter uses acceleration sensors to analyze body movement [15], often in the form of wearable devices such as bracelets. Both of these methods require contact monitoring during sleep, which will cause a bad user experience and even affect sleep. In recent years, popular smartphone applications that use built-in acceleration sensors or microphones for non-contact sleep monitoring provide a more user-friendly method, and visualization of the sleep cycle becomes common feedback. However, experiments have confirmed that whether it is a wristband device or a mobile phone application, the accuracy of monitoring the sleep cycle is very low (49.7 % consistency with PSG), while the classification of sleep and wake is more accurate (77.3 % consistency with PSG) [2] [10]. Therefore, these devices, in their current status, are suggested to be combined with subjective measurements such as sleep diaries [2].

2.2 Self-report Level

Sleep diaries are highly appreciated by clinicians in the use of assessment of sleep because they could provide a subjective overview of the individual's sleep and they are validated clinical tools. The traditional sleep diary contains 7 to 12 questions about bedtime routines and sleep behavior, in which users rate the scales on paper [1]. Nowadays, other factors such as the consumption of caffeinated drinks, exercising, taking medications or not, and mood throughout the day are also considered to be the potential cause of poor sleep quality and interrupted sleep. The sleep diary used in the National Sleep Foundation consists of two parts, the one filled in the morning and the one filled at the end of the day. Every morning, individuals track their nighttime sleep patterns, naps, feelings of sleepiness, while they input activities throughout the day, and bedtime routines at night.

Nowadays, more and more studies and products are starting to study digital sleep diaries [19] [11]. The digital sleep diaries have the advantages of continuous availability and clear content, and it can directly record the time the user fills in, thus overcoming some of the shortcomings of the paper-based diaries. The beautiful display and user guidance brought by the graphical interface also bring a better experience. In addition, applications such as Sleep Cycle [8] use data of daytime activities and subjective sleep assessment as labels that support supervised learning to help user self-tracking.

Although digital sleep logs have many advantages and are easier to integrate into IoT systems than paper diaries, it is not a wise practice to use electronic screens before going to bed. A study has shown that blue light inhibits the secretion of melatonin [22], making it more difficult to fall asleep. In addition, the use of mobile phones puts users in a state where information can be easily obtained, which may greatly extend the time of using mobile phones before going to bed, leading to later falling asleep and reducing sleep quality [7].

3 METHOD

The data-enabled design methodology was conducted to answer the question — how to help people self-track sleep with both objective and subjective data? The methodology has an emphasis on using data as creative input [18], which is developed for the IoT paradigm. The method consisted of two main parts: the Contextual Step and the Informed Step, and the entire design process completed the "8" model in these two steps, see 1.

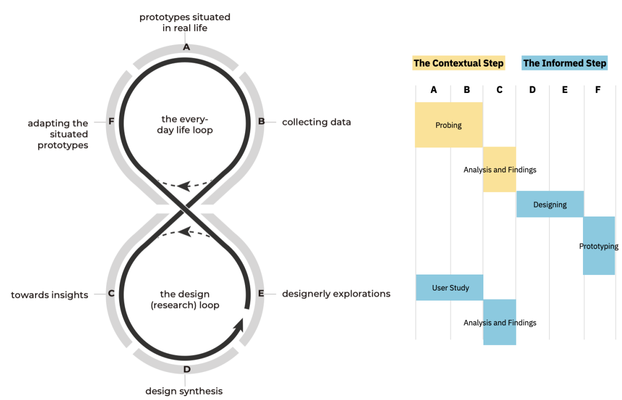

Figure 1: The data-enabled design process in this project

3.1 The Contextual Step

3.1.1 Probing. We use the data as materials to study the effects of sleep behavior, sleep environment, and related behaviors on sleep quality, see figure 2. These data were collected using a data probe and a sleep diary see figure 3. The data probe was placed on the bed, and the participants were asked to turn on the data probe and fill in the booklet before sleep, and turn off the data probe and fill in the booklet after waking up. The deployment of probes lasted for 7 days for 2 participants.

The data probe detected the objective sleep behavior and environmental data by several sensor modules, including movement (accelerometer MPU6050), noise volume (noise sensor), temperature and humidity (DHT11). The time data was also recorded when the participants turned on the probe before sleep, and turned off

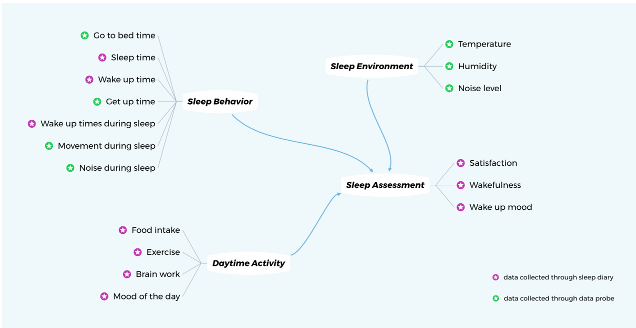

Figure 2: Data as materials in the contextual step

Figure 3: Data probe and sleep diary

the probe after getting up. All the data was collected through an ESP 32, and was uploaded to the ThingSpeak cloud platform.

A special booklet was prepared as a sleep diary, also a culture probe, aiming to collect the subjective behaviors information related to sleep during the day, and the self-assessment of sleep. Since the sleep and wake is hard to detect by the accelerometer MPU model, the participants were asked to report their impression on sleep duration and wake up times during sleep in the diary.

After analyzing the subjective and objective data together in a visualized way, we conduct semi-structured interviews with the participants for more insights. Participants' voices were recorded with their permission, and later the audio pieces were transcribed into text for analysis.

3.1.2 Findings. Different participants have very different subjective judgments of sleep quality. Among the three data after waking up: satisfaction, wakefulness, and waking mood as is shown in Figure 4, they are consistent in the situation of participant 1(p1), that is, high wakefulness, good mood, and high satisfaction. But Participant 2(p2) is not. Although he said that his evaluation of sleep quality is based on the level of wakefulness when he wakes up, this statement cannot be observed in the data visualization, and his mood when he wakes up is also very stable.

The influence of sleep behavior on sleep quality varies from person to person. The length of time in bed is calculated based on the time the user turns on and off the device. Due to technical problems, the data of the acceleration sensor is not completely obtained, so the length and efficiency of sleep are basically assessed

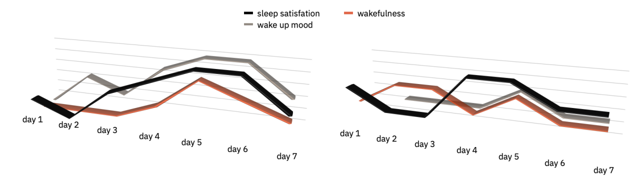

Figure 4: Data visualization of sleep assessment in the contextual step

by the participants. As is shown in Figure 5, the sleep satisfaction of p1 is very obviously related to the length of sleep, that is, basically the longer the sleep time, the higher the satisfaction with sleep. However, the sleep duration of p2 does not seem to be significantly related to sleep satisfaction, and the overall duration of the sleep does not change much.

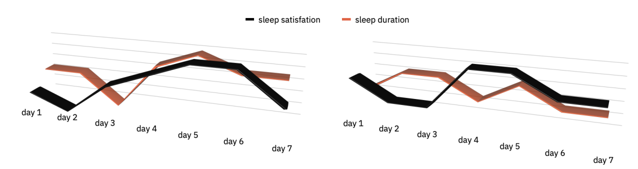

Figure 5: Data visualization of sleep satisfaction and sleep duration in the contextual step

Compared with the effect of sleep behavior on sleep quality, the satisfaction of p2 sleep seems to be more related to the daytime activities of the previous day. In the data visualization, see Figure 6, more brain activity and a small amount of exercise help him get a night of more satisfactory sleep. After viewing the visualization results, p2 analyzed by himself that "excessive exercise makes me unable to sleep due to excitement", which leads to lower sleep satisfaction. Although the correlation between p1's daytime activities and sleep satisfaction was not obvious, he believed that diet was the factor that had the greatest impact on sleep compared to other daytime activities.

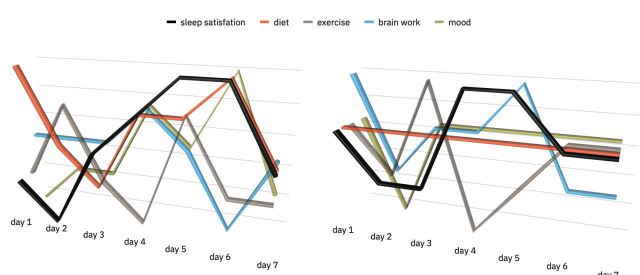

Figure 6: Data visualization of sleep satisfaction and daytime parameters in the contextual step

There was almost no obvious change in the environment of the two users during the 7 days of the experiment. The two participants said in the interview that the sleeping environment is similar every day, and they will create a habitual sleeping environment for themselves, such as opening a little curtain to ventilate and receive natural light (p1) or lowering the room temperature (p2). In addition, the rise or fall of temperature and humidity within half an hour of turning on the device, we guess it is the problem of the device itself, so consider canceling the monitoring of the sleeping environment in the next step.

In addition, the probes, as a preliminary prototype of a product, also had some impact on the sleep of the two participants. p1 indicates that the appearance of the probes makes him more aware of good work and rest. He thinks that the probes have a reminder function, and he hopes to get timely data feedback for self-tracking. p2 means that the process of using the probes gives him a sense of ritual before going to bed and can strengthen his sleep consciousness. Participants also said that filling in the sleep diary is cumbersome and easy to forget.

3.1.3 Summary. Three main insights can be summarized from the contextual steps: 1) behavior and daytime activities will affect sleep satisfaction, and the influence of different parameters varies from person to person. 2) Reflecting and recording before going to bed can provide users with a sense of ritual and enhance their awareness of paying attention to sleep. 3) Users expect simpler and smoother input data interaction, and more timely and personal data feedback.

3.2 The Informed Step

3.2.1 Design. Based on the results and insights of the contextual steps, we propose SleepBox, a system that helps users self-track their sleep. This system consists of a tangible interface and a graphical interface, see Figure 7.

In order to reduce the impact of blue light and excessive use of mobile phones on sleep, while avoiding the limitations of paper sleep diaries and cumbersome interaction procedures, we designed a tangible interface for users to reflect before bed and evaluate after bed. The user would get several recognizable tokens, each representing a different parameter, such as diet, mood, brain activity, caffeine intake, etc. Due to the differences in the living habits of each user, we also provide several blank tokens for users to label by themselves. Before going to bed, users select the three parameters they think are more important today, put the corresponding token on the slider's handle, and then score the three parameters in turn. The user presses the "Confirm" button as a signal for the end of the input, and the system uploads the token ID, score, and operation time to the cloud. Next, the orange light on the interface will gradually brighten and dim to guide the user to perform 4-7-8 breathing exercises to help fall asleep [20]. The acceleration sensor in the interface detects and uploads movement data in real-time during sleep. After waking up in the morning, the user scores the quality of sleep through the slider on the right. When the user presses the "confirm" button again, the system obtains the sleep quality score and the scoring time again.

The data of sleep behavior, daytime activity, and sleep quality assessment are collected through the tangible interface, and the information processed and visualized in the application. We have designed two pages, the first one focuses on sleep on a certain day, the second page is a statistical visualization to help users discover the relationship between the trends of different parameters. Users can access visual feedback at any time.

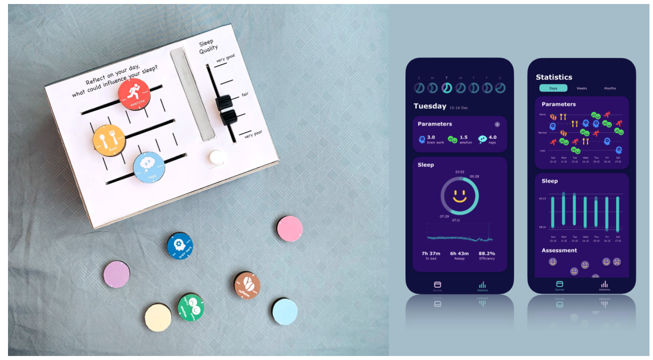

Figure 7: SleepBox system, includes a tangible interface (left) and graphic interfaces (right)

3.2.2 Prototyping. The ESP32 controlled data acquiring and transmitting via Wi-Fi in the tangible interface. It was developed using Arduino IDE. All scoring data was obtained using the slider rheostat and the analog-to-digital conversion(ADC) port in ESP32. We used radio frequency identification (RFID) sensors and customized three external antennas through vinyl cutting to identify three tokens simultaneously within a certain range of the slider rheostat. In the context step, the acceleration sensor MPU605 needs to use the I2C communication protocol, which was affected by the Wi-Fi transmission and causes no signal. So we chose the accelerometer model ADXL335 to transmit data through the ADC port.

The prototype of the entire system was built on the IoT platform ThingSpeak. The data of ESP32 was sent to the designated channel of the server using the HTTP protocol, and the API key guarantees the privacy of the data in this channel.

After downloading the raw data from the ThingSpeak platform, the researcher analyzed it. Among them, the time to fall asleep and the time to wake up were estimated by the change of the acceleration sensor data. The visual interface prototype was made by Adobe XD software and the graphical interface prototype can be accessed via the shared link.

3.2.3 User Study. One of the same participants in the contextual step was involved in the study in the informed step. The system prototype was deployed for 7 days, and the user was suggested to use the system every day. After the participant input data through the tangible interface after getting up, the shared link of the application prototype would be sent by email within 2 hours.

After collecting data for 7days, an interview was conducted. As user experience is an important aspect in the data-enabled design process, as well as to avoid the influence on user experience by this interview, the participants would firstly self-reflect on using the prototypes and fill in a user experience questionnaire(UEQ) [16]. After filling in the questionnaire, the results were discussed accordingly. The questionnaire consists of pairs of contrasting attributes that may apply to the product. A likert scale was used to represent gradations between the opposites of the attributes. During the interview, the most significant attributes were discussed, resulting in gaining insights in how the prototype is experienced.

Next to the questionnaires, the participant also looked back at the one-week data visualization together with the researcher, and discussed the data trend, relationship between data, and visualization way. The audio of the interview was recorded with permission and later transcribed into text for analysis.

3.2.4 Findings. The results of the UEQ show a good user experience for SleepBox. After the classification of the questions, the statistical results of UEQ are obtained. As shown in Table 1, the average scores of all six dimensions (score ranging from -3 to 3) are positive and no less than 1 point. Moreover, the user said that he used the physical interface correctly and checked the feedback of the graphical interface every day, and did not encounter any usability problems.

The tangible interface in the system provides a more attractive way to enter data than the popular graphical interface. First of all, the scores of the two attributes of perspicuity and efficiency in UEQ are no less than 2 points, which shows the tangible interaction is very simple, intuitive, and fast. Secondly, the attractiveness score reflects its interesting and pleasant features. The participant stated, "This device is very cute, so I was willing to use it." At the same time, he enjoyed the choice of different physical tokens and the personalized definition of the input data. He said, "If I use it for a long time, I think the blank token may not be enough for me to use." In addition, the physical interface supports users' longer-term use than mobile applications. Quietly existing in the scene associated with it, this tangible interface notifies the user in an unobtrusive way. "I don't think of opening an app for reflecting and inputting activities before going to bed. "as the user said," and I generally turn off notification permissions because I don't like being disturbed frequently."

4 DISCUSSION

The result of the user test shows a good user experience of the system, especially the advantages brought by the tangible interface. In this section, more topics will be discussed, where the limitation and future work are also included.

4.1 Potential for a healthier lifestyle

The system mainly realizes its value in increasing awareness of a healthy life. The participant's expectation of the system was to help him improve his sleep routines and get a healthy lifestyle. The participant said that the system did make some impact. First of all, the existence of a tangible interface can help users reflect before going to bed, thereby enhancing users' awareness to improve sleep through appropriate daytime activities. Secondly, daily visualization feedback allows users to understand some of their sleep behaviors, such as the time to go to bed and get up, which triggers awareness of behavior changes. The participants said, "Especially when I stayed up late last night, data visualization can strengthen my awareness to go to bed early today."

Enhancing awareness has the potential to trigger behavioral changes. However, the current study only obtained one week of data, and cannot support the proof of whether the user transitioned from the contemplation stage to the determination of even the action stage. Future research can continue to use the data-enabled design methodology to study the role of this system in behavior change.

Table 1: The UEQ resutls.

Dimension	score
Attractiveness	1.67
Perspicuity	2.50
Efficiency	2.00
Dependability	1.75
Simulation	1.25
Novelty	1.00

4.2 Optimizing User experience

Though the current system has a good user experience score, there are still some shortcomings. From the research perspective, only one participant was involved in the final user test, so there is a need to conduct the informed step with more participants.

From a designer's perspective, both the interfaces could be improved. For the physical interface, the current shape seems out of place in the sleeping environment. Sharp corners and edges can give people a sense of insecurity, so a softer prototype needs to be made. In addition, some data visualization methods of the graphical interface also need to be improved. For example, the user mentioned, "I directly ignored the statistics of daytime activities because it seems too complicated." Indeed, current visualizations concentrate a large amount of data on the same page, which makes it more difficult for users to understand. In the future, it is necessary to provide clearer and easier-to-understand visualizations to support users in self-tracking and exploration.

4.3 Embedding stable sensors and reliable algorithms

Although the current system can detect the user's actions during sleep through the acceleration sensor, this method is still not stable. In future prototypes, it may be possible to consider using the microphone embedded in the smartphone to obtain more accurate data more stably. The processing of these original data also requires reliable algorithms to accurately determine the specific dynamics of users.

Moreover, the relationship between sleep quality and various parameters is still in the stage of autonomous exploration by users. In the future when the prototypes are being deployed in the users' homes for a long time, the machine learning algorithms can be applied to generate the personalized data relationship and make predictions.

4.4 Design opportunities to assist in falling asleep

Staying in a sleep environment, adding functions to assist sleep can make this design development in the direction of commercialization. Although a light used to guide deep breathing training is now designed, this user study did not achieve the expected effect. The participant stated that he turned off the room lights and closed his eyes after pressing the confirmation button, and focused on the task of sleeping. Therefore, the light on the box used to guide the breathing exercise was not visible to him at all. It also reveals that similar to a paper sleep diary, the tangible interface can give users a sense of ritual before going to bed, thereby assisting sleep. In the future, there will be more opportunities, such as adding soothing music or smell to the device to assist Sleep.

5 CONCLUSION

This report described a data-enabled design process, which results in the concept of SleepBox, a physical tool for self-tracking sleep. Different from the other products, this tangible interface combines objective data of sleep behavior with subjective data of self-assessment of sleep and other activities. Graphic interfaces are designed to support data feedback. The final evaluation for 7day deployment shows good user experience and promising future opportunities.

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Appendix

Reflection

I am a master student from the department of Industrial Design, and this is my second year.

My learning goal for this year is to integrate and apply the professional knowledge I have learned before, thereby consolidating my professional skills and strengthening my identity as a designer. But this does not mean that I do not need to learn new methods and skills. On the contrary, I think that a designer needs to have the ability to learn with the times, especially to maintain curiosity and desire to explore new things. Therefore, I choose the data-enabled design method to guide my design process and pay more attention to the application of cutting-edge technology in the project.

Design and Research Process

In the last semester, I took the elective of Data-Enabled Design, where I learned this methodology that uses data as the design material. I think it is very interesting and fits the IoT design field. Looking back at the design process, as shown in the figure, I think I have a good command of this method. And I think this method is very suitable for studying some scenarios where user interviews cannot be conducted, such as sleep in this case, and exploring the living conditions of some special populations such as autistic patients.

Technology and Realization

My identity as a designer is to bridge users and technology. In the past year, I have focused on users and society, so this year I hoped to develop more on the expertise of technology and realization.

Based on my previous experience and interest of electronics, in this project I realized the functional probe and prototype with ESP32 and various sensors. To be honest it is not the first time I use ESP32 in a project, however, it is the first time for me to do all the work alone, including develop the ESP32, connect it to online server, and do the hardware connection. These tasks are more troublesome and take longer than I thought. In this process I learned a new IoT platform, ThingSpeak, to communicate with ESP32, and to deal with data. However, the data storage and signal interval were limited. It reminds me that with the everything in the life is becoming smarter, the data will be overloaded. So as designers need to be aware of how to save data storage space and data processing time when designing IoT.

Except for building the IoT system, I also learned about the differences between different models of accelerometers. This would help me to choose the suitable one in the future.

Moreover, in this semester I took the elective Designing User Interface with Emerging Technology to gain more information of cutting-edge technologies, and some hands-on experience as well. I also applied one of those technologies, NFC, in my project, and customized the antenna for the specific using case.

User and Society

Due to the pandemic, finding users for testing is much more difficult than ever before. Rather than following the path of user research that I am familiar with in a user-centered design process, this time I learned about how to involve users in a longer-term way, and use probes to get a more objective understanding of the context. By probing into the context of user, I enriched my professional skills of user research, and the knowledge of design ethnography.

Math, Data and Computing

Data is not only for validating, but also for exploring design space. Quantitative data and qualitative data need to be processed separately, for example applying statistical methods to quantitative data and content analysis to qualitative data, but they also need to be combined for observation, for example visualizing them together to gain interesting insights.

Moreover, took the elective Embodying behavior in the social context, where I learned the rational of supervised, unsupervised, and reinforcement learning, as well as the concept of explainable AI. I think these computing knowledge will inspire me in my future projects.

Conclusion

In this project, I developed my expertise and professional skills. I reached most of my goals set in my PDP and kept a logbook in a keynote file every week. Finally, I really appreciate the great support from my coach Dr. Rong-Hao Liang, and all the participants in the study.