Low-power Smart Earring for Longitudinal Earlobe Temperature Sensing

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Abstract

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Body temperature is an important vital sign which can provide valuable insights into a person's health condition, including the presence of fever. Moreover, it is known to be correlated with activities such as eating, exercise, and mental states. However, continuous temperature monitoring poses a significant challenge. This thesis presents Thermal Earring, a first-of-its-kind smart earring that enables a reliable non-invasive wearable solution for continuous temperature monitoring. The Thermal Earring takes advantage of the unique position of earrings in proximity to the head, a region with tight coupling to the body unlike watches and other wearables which are more loosely worn on extremities. We develop a hardware prototype in the form factor of real earrings measuring 11.3 mm, weighing 335 mg, and consuming only 14.4 uW which enables a battery life of 28 days in real-world tests. We demonstrate this form factor is small and light

enough to integrate into real jewelry with fashionable designs. Additionally, we develop a dual sensor design to differentiate human body temperature change from environmental changes. We explore the use of this novel sensing platform and find it measures temperatures that are stable within $\pm 0.32^{\circ}C$ during periods of rest. Using these promising results, we investigate its capability of detecting fever by gathering data from 5 febrile patients and 20 healthy participants. Further, we perform the first-ever investigation of the relationship between earlobe temperature and a variety of daily activities, demonstrating earlobe temperature changes related to eating and exercise. We also find the surprising result that acute stressors such as public speaking, exams, and paper deadlines cause measurable changes in earlobe temperature. We perform multi-day in-the-wild experiments and confirm the temperature changes caused by these daily activities in natural daily scenarios. This initial exploration seeks to provide a foundation for future fever monitoring, activity detection, and stress assessment.

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Chapter 1. INTRODUCTION

Wearable devices with sensors have gained significant popularity in recent years and are becoming a ubiquitous part of daily life. A survey in 2022 estimated that almost 40% of US households own wearable devices such as smartwatches [39]. Wearables which are often in contact with a user's body throughout the day offer unique opportunities for interaction, health sensing, and activity tracking. As a result, companies and researchers have explored using a variety of accessories for sensing such as smart rings [3, 32], smart glasses [46], fitness earbuds [13, 35], and smart clothing [41, 45]. We observe however that an entire class of common accessories worn by millions of people every day has been largely ignored: jewelry. For example, in the United States alone, about 76% of women have ear pierced, which is nearly twice the current adoption rate of wearable devices like smartwatches and there is a growing trend of men embracing earrings, indicating its widespread acceptance as a fashionable choice [10].

Earrings, in particular, present a unique opportunity for continuous physiological signal monitoring. Unlike headphones and earbuds, earrings are typically worn continuously throughout the day and could be used as an unobtrusive continuous sensing platform. Moreover, earrings have the further advantage of being tightly coupled to a user's body in contrast to watches and necklaces which can easily move or shift against the skin. In addition to these form factor considerations, the proximity of earrings to the head provides key sensing advantages. Emotions such as embarrassment or other stressors can cause a person's face and ears to "turn red," inducing substantial blood flow to the head and ears. One result of these changes in blood flow is a change in temperature. Body temperature is a crucial vital sign that can indicate a person's health conditions but challenging to sense continuously. Elevated core body temperature of 38°C (100.4°F) or higher, also known as a fever, is the primary predictive symptom for many viral infections including influenza and COVID-19 primary [6, 19, 20]. Traditionally, the temperature is measured with a thermometer orally, axillary, in-ear, or by skin. However, using a thermometer can only provide sporadic measurements that might miss important temperature data points. For example, a fever can be intermittent, leading to fluctuations in temperature over the course of a viral infection. Similarly, the ability to measure fine-grained temperature changes could yield new insights into the wearer's daily activities or novel health signals.

This thesis presents Thermal Earring, a small, light, and low-power smart earring that enables a reliable non-invasive wearable solution for continuous earlobe temperature sensing. We develop a hardware prototype in the form factor of real drop earrings measuring 11.3 mm, weighing 335 mg, and with a battery life of one month. We explore the use of this novel sensing platform and find it measures temperatures are stable within $\pm 0.32°C$ during periods of rest. Using these promising results, we investigate real-world use cases by gathering data from 5 febrile patients and 20 healthy participants, which helps develop algorithms for fever detection. Further, we investigate the relationship between earlobe temperature and a variety of daily activities such as eating and exercise, as well as, temperature changes correlated to stressful events such as public speaking and exams.

1.1 SMART EARRING SENSING PLATFORM

Smart jewelry is an emerging class of wearable devices that seeks to combine fashion and function by integrating sensing technologies into jewelry accessories. Previous work exploring smart jewelry items include smart necklaces which have been used for silent speech recognition [49] and medication adherence detection [28], bracelets for user interaction [16, 44], health monitoring and intervention [1, 15], and rings for interaction [3] and health monitoring [32]. Prior works also have explored earrings for photoplethysmography (PPG) sensing [26], and wellness tracking with heart rate [36].

By integrating various sensors and communication technologies, smart jewelry enables a variety of applications for health sensing, user interaction, and information sharing. However, developing a functional and fashionable smart jewelry sensing platform requires addressing multiple technical challenges. The system must be small and lightweight for comfortable use. These constraints on size and weight also introduce fundamental constraints on the power consumption of the system due to the limited energy density of batteries. For example, in addition to highly limited capacity, small batteries have severely limited current output making it challenging to run devices like radios to offload the sensing data.

Thermal Earring is a first-of-its-kind wireless smart earring that investigates temperature measurement. To design a system within the above strict form factor constraints, we leverage the highly integrated nRF52 Bluetooth SoC which is available in a highly miniaturized 3x3mm package and a 1 mm2 temperature sensor (TI HDC2010). We observe however that the battery and microcontroller consume much of the size and weight of our device which may exceed the space available on a user's earlobe. Meanwhile, the larger components, such as the microcontroller and battery, are placed in the dangling part of the earring, ensuring a compact and comfortable design that maintains the shape of a common earring. Further, we optimize the circuit and power consumption of the chip to operate on a miniaturized battery that only supports continuous discharge currents of 0.25 mA with our Bluetooth chip that requires 5 mA during transmission and demonstrate it runs continuously for almost one month.

1.2 CONTINUOUS BODY TEMPERATURE MONITORING

Body temperature as an important vital sign can provide valuable insights into a person's health condition. Although invasive techniques such as arterial catheters [23] or e-pills [29] provide the most accurate measurement of core body temperature by entering the body through arteries or intestines, they are not suitable for everyday use. Non-invasive thermometers, such as oral, tympanic thermistors, and infrared temporal thermometers, are more commonly used but require specialized devices that may only be used a few times a year [34] and typically require the users to actively initiate the measurements.

Past work has attempted to develop more accessible and ubiquitous methods of temperature sensing by incorporating temperature sensors into wearable devices [5, 11, 22, 24], utilizing thermal cameras [30, 47], or leveraging existing temperature sensors on smartphones [7]. Wrist-mounted temperature sensors have been extensively explored for core-body temperature sensing, for example, Apple Watch and Fitbit, however, they have struggled to provide accurate measurements due to noisy temperature signals from the wrist. As a result, these devices only provide one average temperature reading per day, primarily from data during sleep. Similarly, Oura Ring offers skin temperature monitoring on the finger, which is also from the body extremities, making the temperature data noisy due to distance from the core body and more susceptible to motion artifacts. Infrared thermopile sensors mounted on headphones have been used to monitor tympanic temperature directly and longitudinally [5], but require the user to wear their headphones to make measurements which may not be suitable in many environments. Another approach for temperature sensing is using thermal cameras on facial video [30, 47]. However, these sensors are expensive and not suitable for personalized health sensing applications. In addition to dedicated hardware, researchers have developed software models map smartphone temperature to core-body temperature when the phone is in contact with the user's head [7]. However, this method requires a dedicated interaction to make spot-estimates rather than passively sensing temperature longitudinally.

Thermal Earring takes advantage of the unique position of earrings on the head and tight coupling to the earlobe to provide a reliable and stable measure of body temperature. We find in initial trials across six users in the wild that earlobe temperature reading remains stable during their rest time with a maximum standard deviation of 0.32°C (0.58°F) compared to a smartwatch (EmbracePlus) that varies by over 0.72°C (1.3°F). We note that this is promising for future applications such as ovulation tracking which requires 0.28°C to 0.56°C accuracy [40].

Accurately measuring the earlobe skin temperature requires also isolating the effect of ambient temperature changes, which is one of the fundamental challenges of measuring body temperature using noninvasive wearable devices. One way to measure these effects would be to add a second temperature sensor isolated from the body dedicated to measuring ambient temperature. This is however not possible on a watch form factor where much of the surface area is coupled to the skin or within 1cm. We observe however that common earring designs include a point that is attached to the earlobe as well as a dangling decorative portion that does not make contact with the body. Leveraging this observation, we propose a novel dual temperature sensors system that incorporates an additional temperature sensor in the dangling part of the earring to capture the ambient temperature. This unique design enhances the reliability and accuracy of temperature measurements from non-invasive wearable devices, surpassing the temperature accuracy achieved by existing wearable devices.

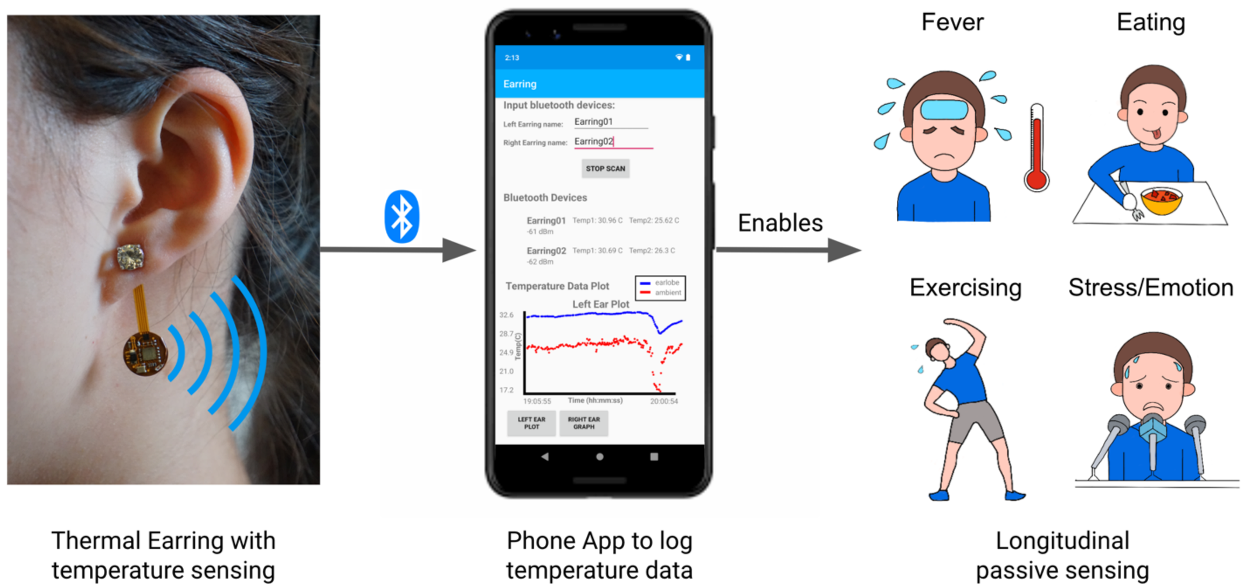


Figure 1.1. Overview of the Thermal Earring

Chapter 2. THEORY OF OPERATION

As the temperature reading from the earlobe is different from core body temperature and is the first time to be investigated comprehensively. This section is to give background on earlobe skin temperature and presents the theory of body temperature changes.

2.1 BODY TEMPERATURE

Core body temperature refers to the internal temperature of the body, specifically in the deep tissues and organs. It is regulated by the body's thermoregulatory system, which helps maintains a relatively stable core temperature despite external temperature changes. The average core body temperature for a healthy adult is around 37°C (98.6°F).

Skin temperature differs from core body temperature in several ways. While the body regulates core temperature to maintain a certain number, skin temperature varies as a function of core body temperature, environmental temperatures, and physiological changes. Skin temperature tends to be lower than core temperature and can fluctuate over time and across different regions of the body. The skin plays a vital role in thermoregulation through various mechanisms such as insulation, blood flow control (vasodilation and vasoconstriction), and sweating [48]. Vasodilation increases blood flow to the skin surface, facilitating heat dissipation. Conversely, vasoconstriction reduces blood flow to conserve heat within the core. Sweating enables heat to evaporate from the skin's surface, thereby facilitating a decrease in skin temperature. Overall, the skin responds to internal and external temperature changes to keep the core body temperature stable.

Moreover, recent research indicates that changes in skin temperature can serve as an indicator of stress. For instance, increased skin temperature in facial and forehead regions has been observed during periods of stress, while decreases have been reported in finger and nose skin temperature [18]. As a result, monitoring changes in skin temperature has the potential to provide valuable insight into an individual's physiological and emotional state.

2.2 EARLOBE TEMPERATURE

The human ear is one of the acral regions that help regulate body temperature. The earlobe, in particular, has a large blood supply that aids in maintaining temperature balance by controlling blood vessels. As shown in Figure 2.1(a), the posterior auricular artery supplies blood to the back of the ear, while the superficial temporal artery supplies blood to the front of the ear, face, and certain areas of the head. These two branches, stemming from the external carotid artery in the neck, contribute to the regulation of ear temperature. Figure 2.1(b) which is a thermal image of human facial region taken by a thermal camera, which shows the heat distribution around the ear, head, and neck. Naturally, the forehead, chin, and neck have higher skin temperature compared to the nose, cheek, and ear. Also, there’s heat radiation around the skin surface. Given its proximity to the head and blood vessel supply, the earlobe serves as a promising location for temperature monitoring.

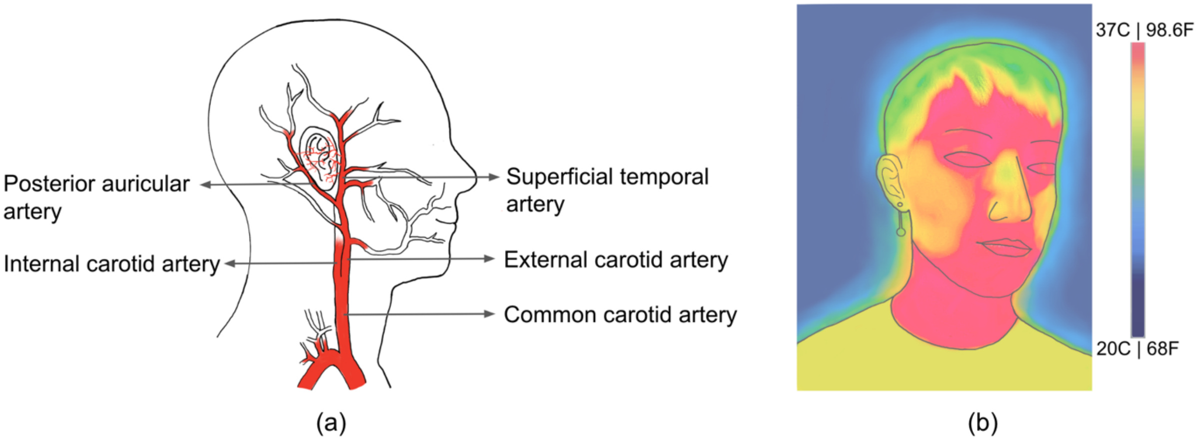


Figure 2.1. Background on earlobe skin temperature.
(a) The Blood vessels around the ear. (b) The heat distribution around the ear, head, neck

In addition, the earlobe's proximity to the brain presents the possibility of capturing changes related to stress and emotions. Notably, changes in emotional states such as embarrassment, anxiety, and anger can cause the ears and face to turn red, which is a natural physiological response governed by the autonomic nervous system. This response is because of dilated blood vessels and increased blood flow from the superficial temporal artery, triggered by the release of adrenaline, leading to a rise in temperature in ear and face [21]. Consequently, the earlobe temperature has the potential to serve as a valuable biomarker for tracking changes in emotional and physiological states.

2.3 DANGLING TEMPERATURE

To distinguish changes in the earring temperature signal due to body temperature from changes due to environmental temperature, we add a second temperature sensor to the Thermal Earring. This sensor is strategically placed on the dangling section of the earring, to maximize isolation from the body. The dangling temperature sensor is designed to detect the ambient air temperature around the ear, rather than the body itself. In practice, the dangling temperature sensor still couples to the heat from the body because the ambient air around the ear is affected by the radiated heat from the neck and head, as illustrated in Figure 2.1(b). As a result, the dangling temperature is typically higher than the ambient environment temperature due to the radiant heat emitted from the neck. However, the dangling temperature sensor still provides valuable variations for detecting changes in environment temperature, which we will evaluate and discuss further in the later section.

2.4 USER DEPENDENCE

While the body is very good at maintaining a nominal core-body temperature of 37°C (98.6°F), both body temperature and skin temperature vary from user to user. Numerous factors, including but not limited to age, gender, body weight, and metabolic rate, can all affect body temperature over time [37]. The skin temperature is affected by subcutaneous fat which insulates heat [8]. For example, the skin's insulator properties of the female body are better than the male body because of a greater subcutaneous fat content [27, 48]. As a result, women tend to have slightly higher skin temperatures than men [43] which is reflected in our experiments.

Chapter 3. SYSTEM DESIGN AND EVALUATION

When designing a smart earring, it is crucial to consider various constraints, including size, weight, and power consumption. The size of the smart earring should be small enough to ensure a comfortable fit on the earlobe, while the weight should be kept light enough to prevent any discomfort or strain. Additionally, ensuring long battery life is essential for a practical user experience to avoid the need for frequent recharging or battery replacement. However, the limited battery capacity due to the size and weight limitations requires thoughtful co-design for low-power and small system.

Drawing inspiration from the common drop earring shape, the Thermal Earring adopts a similar design. We strategically position the small temperature-sensing unit directly on the user's earlobe. Meanwhile, the larger components such as the microcontroller and battery are discreetly placed in the dangling part of the earring. This design ensures a compact and comfortable overall structure that retains the appearance of a typical dangling earring. In this section, we introduce the key components of the Thermal Earring system, including the temperature-sensing unit, wireless communication, and battery. We also evaluate the system's performance.

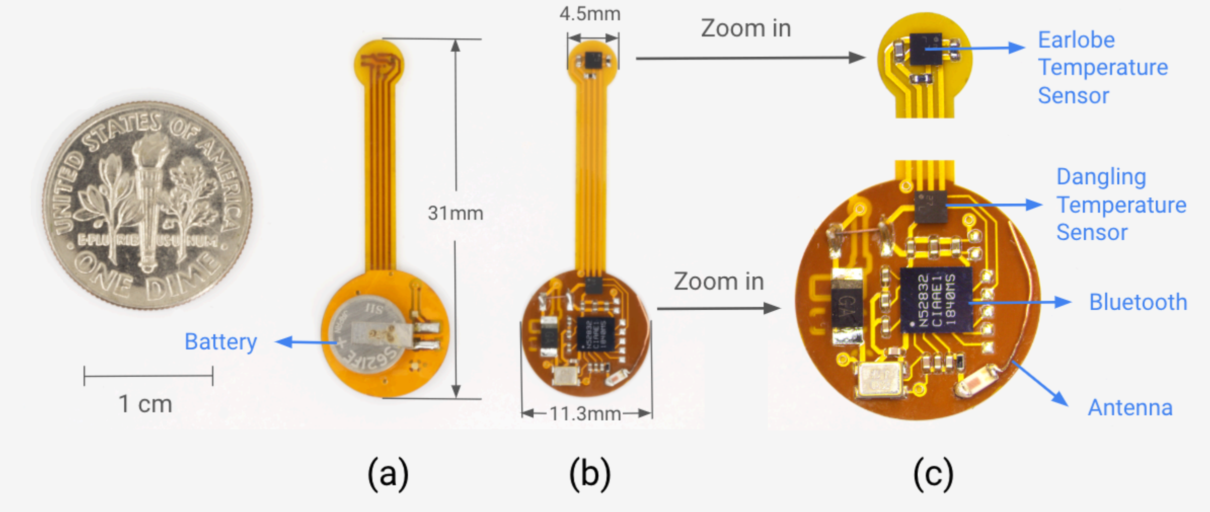


Figure 3.1. The Thermal Earring system with one dime coin as reference.
(a) The Back side of the Earring. (b) The front side of the Thermal Earring. (c) The zoomed-in view of the Thermal Earring components on the front side.

3.1 DUAL TEMPERATURE SENSORS DESIGN

The Thermal Earring features a dual temperature sensor design that can sense the earlobe and the ambient air temperature simultaneously. This design helps differentiate the user's body temperature changes from environmental changes. One temperature sensor is designed to directly contact the earlobe skin for sensing earlobe temperature, while the other one is embedded into the dangling part to sense the ambient air temperature around the ear. The addition of the dangling temperature sensor provides data to differentiate environmental changes, such as walking from a temperature-controlled building to outdoor environments, from body temperature changes. This design effectively overcomes the challenge that skin temperature changes with the environmental temperature and enhances its accuracy and utility in monitoring changes in body temperature.

We implement Thermal Earring's temperature sensing using the HDC2010 temperature sensor from Texas Instruments. We choose this sensor for its small size (1.49 mm x 1.49 mm), low-power consumption (0.9 uW), and high accuracy. The HDC2010 is capable of providing temperature accuracy within $\pm 0.2°C$ while consuming only 0.3 uA of average current when measuring temperature once per second. The two temperature sensors are connected to a Bluetooth microcontroller through the same I2C line but with different I2C addresses for synchronized data acquisition.

3.2 MICROCONTROLLER AND WIRELESS COMMUNICATION

The sensed data from the wearable requires wireless communication to a smartphone or a computing device for further computing and analysis. However, the microcontroller and wireless communication are orders of magnitude more power-intensive than the sub-microwatt temperature sensors, which can significantly impact the battery life of the wearable device. Wireless communication involves transmitting high-frequency RF signals in the GHz range, which typically constitutes the most power-consuming aspect of a wearable system. Therefore, it is critical to carefully select a wireless communication method that is both low power and compact in size for optimal performance in the Thermal Earring system.

Previous research has explored the use of backscatter communication for sending data from the wearable or Internet of Things (IoT) device to a computer. However, this method requires a customized carrier wave transmitter or a customized radio receiver, which makes it difficult to communicate directly to a user's smartphone. In contrast, Bluetooth chips offer a longer wireless range and compatibility with commercial phones, albeit with slightly higher power consumption. Considering these factors, we chose to develop wireless communication using the NRF52832 Bluetooth chip. This ultra-compact chip is packed in a wafer-level chip-scale package, measuring 3mm by 3mm in size and weighing 6.8mg. Furthermore, it incorporates an ARM Cortex M4 processor with a floating-point unit for computing tasks in the same compact package making it an ideal choice for Thermal Earring.

We utilize Bluetooth in advertising mode, which is well-suited for the Thermal Earring's short-temperature data transmission needs. Bluetooth advertising mode is a feature that enables Bluetooth devices to broadcast their presence and identity to other Bluetooth-enabled devices such as smartphones. This mode allows embedding customized data of up to 31 bytes in short advertising packets. Bluetooth advertising is significantly lower power compared to establishing a continuous Bluetooth connection which requires sending a series of packets to synchronize and negotiate the frequency hopping sequence as well as regular transmissions to keep the connection alive. The series of packets needed to set up the connection requires significant energy over a short period which is significantly greater than our small sub-centimeter battery can support. We observe the voltage begins to decrease upon transmitting a packet due to its current limits. Operating in advertising mode with sufficient time between packets enables the battery voltage to recover before the next transmission. Given that each temperature data point sent by the Thermal Earring can be compressed into two bytes, it is more energy-efficient to transmit the data using Bluetooth advertising mode instead of maintaining a constant Bluetooth connection with the smartphone.

The Bluetooth chip communicates with two temperature sensors via I2C and packs the temperature data into advertising packets. These packets adhere to the standard Bluetooth advertising structure, beginning with a fixed preamble pattern, access address, header, payload, and the Cyclic Redundancy Check (CRC). The payload of the Bluetooth packet contains the temperature data and the customized name of the Thermal Earring. Each temperature data is wrapped as service data, starting with a 2-byte Universally Unique Identifier (UUID) of 0x1809, which corresponds to health temperature data in the Bluetooth protocol. The customized name of the Thermal Earring typically ranges from four to ten bytes. For our experiments in this paper, we used names such as "Earring01" to "Earring14," which occupy nine bytes.

In the Thermal Earring system, there are several programming pins for programming the NRF52832 chip. Bluetooth can be configured to transmit advertising packets at different intervals to balance the need for visibility with power consumption. We also conducted experiments to explore how different Bluetooth advertising intervals affect the Thermal Earring's battery life. The results are presented in the System Evaluation section. Overall, our approach provides an efficient way to transmit temperature data in wearable devices using Bluetooth advertising mode without draining the battery.

3.3 BATTERY

In the development of wearable devices, the power source is a critical component that must have high power capacity while being compact and lightweight. The energy limits of currently available battery technologies make batteries the largest and heaviest components in such small centimeter-scale devices. To achieve our target form factor, we select the Seiko MS621FE lithium manganese battery for Thermal Earring. This rechargeable battery offers a capacity of 5.5 mAh, with a slim 6.8 mm diameter and a weight of 0.23 grams. Although it can generate a maximum output voltage of 3V, its standard discharge current is only 15uA with a maximum continuous discharge current of 0.25mA. While this is sufficient to support the temperature sensor and nRF52832 in sleep mode, it is not sufficient to robustly start-up or transmit Bluetooth packets which both require 5 mA of current. We observe however that both the startup and Bluetooth transmissions are transient operations that only require short pulses of high current. To address this, we add a low equivalent series resistance 100uF capacitor (F980G107MSA) in parallel with the battery. The 100uF capacitor buffers charge while the system is in sleep mode and can then provide a pulse of mA-level current by quickly discharging itself when needed. We note that in addition to size and capacity, this capacitor presents a trade-off between low Equivalent Series Resistance (ESR, the ability to source high current) and the leakage current when it is in sleep mode. We select this specific capacitor to minimize leakage while providing a sufficient buffer to reliably transmit Bluetooth packets.

3.4 SYSTEM OVERVIEW

The final prototype of the Thermal Earring is shown in Figure 3.1. Built on a flexible printed circuit board (PCB), the final prototype of the Thermal Earring can exhibit the same level of flexibility and movement as traditional earrings. The ambient temperature sensor and Bluetooth microcontroller are located on the front side of the earring's dangling part, while the battery is placed on the backside. The earlobe temperature sensor is situated on the small segment attached to the user's earlobe. The earlobe part and the dangling part are positioned approximately 3 centimeters apart, which falls within the dangling length of common earrings (2 to 6 centimeters) [31]. It is worth noting that the length of the dangling segment can be customized without impacting the system's performance. The earring is attached to the back of the user's earlobe using commercial magnetic earrings, with the PCB attached to the back magnet, and another magnet positioned on the front of the earlobe to hold the earring in place. To ensure user safety and comfort, we integrated a layer of Kapton to insulate the electronic components from the user's skin. The entire earring system is compact, measuring 4.5 mm in diameter for the part attached to the earlobe, and 11.3 mm in diameter for the dangling part. The length is 3cm including the thread in between, while the thickness is 3.46 mm. With a weight of just 0.335 grams, the Thermal Earring is significantly lighter than the average weight of commercial earrings, which is 3 grams [25] which allows for the integration of artistic enclosures and gemstones in future designs. In Section 6.1 we also showcase an example of fashion design for the Thermal Earring.

3.5 SYSTEM EVALUATION

3.5.1 *Battery Life*

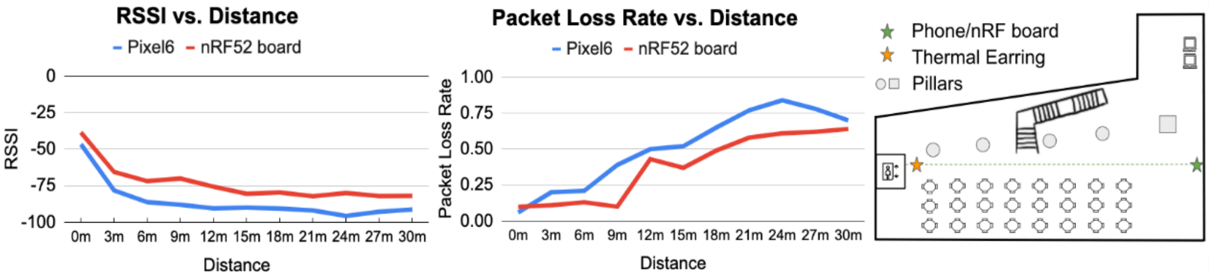
We investigate the impact of different transmission frequencies on the battery life of the Thermal Earring. Three Thermal Earrings were programmed to transmit temperature data at intervals of one second, five seconds, and ten seconds, respectively. The battery life was tested using the MS621FE coin battery as previously discussed, and the average current drawn by each Thermal Earring was measured using a Keysight U1282A multimeter over one hour. The time duration between the reception of the first and last Bluetooth packets on the smartphone was counted as the battery life, and the results were summarized in Table 3.1. These results provide valuable insights into the trade-off between transmission frequency and battery life in wearable devices, and suggest that slower temperature sensing and transmission rates, such as every ten seconds, can significantly extend the battery life of the device.

Table 3.1. Table of average current and battery life with different Bluetooth transmitting periods.

Transmitting Period	Average Current	Battery Life
1s	11.8 uA	5 days
5s	6.1 uA	17 days
10s	4.8 uA	28 days

3.5.2 *Wireless Communication Range*

We conducted several experiments in an indoor natural environment to test the Thermal Earring's wireless range. Miniaturization of the antenna and ground plane is known to affect antenna performance, and placement close to the body further detunes antennae by shifting their resonant frequency and reducing radiation efficiency. To evaluate whether our miniaturized earring can robustly send data to a phone, we evaluated the Received Signal Strength (RSSI) and packet loss rate of the Thermal Earring at distances ranging from 0 meters to 30 meters from two Bluetooth receivers: a Google Pixel 6 phone and an nRF52840 development board. The Google Pixel 6 represents a practical Bluetooth receiver while the nRF development board represents an ideal but less practical one illustrating a practical upper bound on the achievable range. To conduct the experiments, we placed the Bluetooth receivers at a fixed position marked as a green star in Figure 3.2 (c) and had a person wear the Thermal Earring, who moved away from the receiver at various distances. The Thermal Earring transmitted one Bluetooth packet per second, and we calculated the packet loss rate based on the number of packets received during a continuous 100-second interval.



(a) (b) (c)

Figure 3.2. Wireless communication evaluation of the Thermal Earring.
(a) The Received Signal Strength Indicator (RSSI) of the Thermal Earring Bluetooth packets. (b) The Thermal Earring's Bluetooth packet loss rate using Bluetooth receivers. (c) The floor plan of the space where we conducted the experiment.

Figure 3.2 presents the results of the experiments, showing the average RSSI and packet loss rate. The RSSI for the Google Pixel phone decreased to approximately -90 dBm at a distance of 12 meters and reached its lowest RSSI of -95.6 dBm at 24 meters. In contrast, the nRF52 board's RSSI decreased to -80 dBm at 15 meters and reached its lowest RSSI of -82 dBm at 30 meters. Similarly, the packet loss rate for the Google Pixel phone increased to 50% at a range of 12 meters, while the nRF52 board's packet loss rate exceeded 50% at 21 meters. It is noteworthy that the experiment environment had tables, pillars, and other Bluetooth devices causing interference. These factors contribute to the non-ideal change in packet loss rate over distance. Overall, our experiment results demonstrated that Thermal Earring could provide reliable wireless connectivity in indoor environments, especially in our close-range target use cases where the receiving smartphone is on the user's person.

In the Thermal Earring system, there are several programming pins for programming the NRF52832 chip. Bluetooth can be configured to transmit advertising packets at different intervals to balance the need for visibility with power consumption. We also conducted experiments to explore how different Bluetooth advertising intervals affect the Thermal Earring's battery life. The results are presented in the System Evaluation section. Overall, our approach provides an efficient way to transmit temperature data in wearable devices using Bluetooth advertising mode without draining the battery.

Chapter 4. DATA COLLECTION AND PROCESSING

As the temperature data captured by temperature sensors are transmitted by Bluetooth, we use smartphones to receive and store the data. After the data was collected, we apply data processing for further analysis.

4.1 SMARTPHONE APP

We developed an Android smartphone application to collect the temperature data from the Thermal Earring through Bluetooth. Figure 1.1 showcases an example screen of the application's user interface. The application continuously scans for Bluetooth devices filtered by the earring's specific Bluetooth name, enabling seamless and convenient data collection. Real-time temperature data is displayed in the app, along with a graph that plots the temperature changes over a 30-minute period. The collected temperature data is then saved to a local file on the smartphone for further analysis. The smartphone app serves as a tool for our experiments, enabling the users to log information related to their activities or oral temperature, meanwhile allowing us to collect and analyze users' temperature data in real-world settings.

4.2 TEMPERATURE SIGNAL PROCESSING

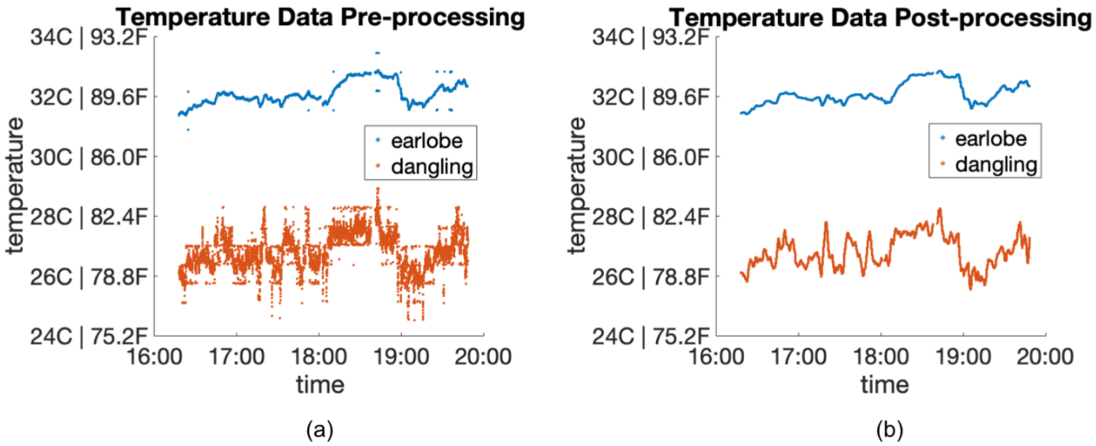


Figure 4.1. Example of temperature data pre-processing and post-preprocessing.
(a) The raw temperature data. (b)The corresponding temperature data after pre-processing.

Figure 4.1 (a) displays the raw temperature data collected from the Thermal Earring using the Android App. It is observed that the earlobe temperature remains stable over time and does not change significantly over a short period. In contrast, the dangling temperature sensor shows rapid changes due to the user's movements causing airflow around the earring. In addition, there are some outlier data points present in both the earlobe and dangling temperature data, which may be caused by temperature sensor malfunction or wireless communication errors. These outliers can be easily identified since human temperature and ambient temperature cannot change significantly in one second.

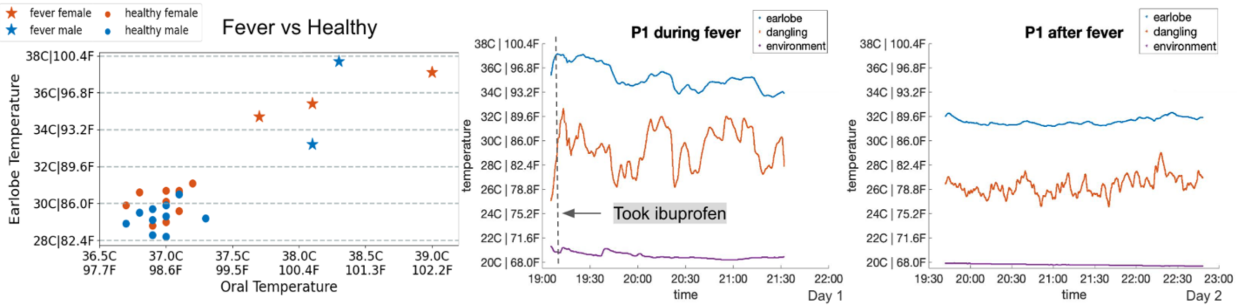
In order to improve the interpretability of the dangling temperature data and eliminate outliers, a moving-average filter with an empirical window length of 60 seconds is applied to both temperature data. Figure 4.1 (b) illustrates the temperature data after the moving-average filter is applied. A window length of 60 seconds is chosen to balance the trade-off between information detail and ease of interpretation for long-time series data. All figures presented in the next chapter are generated using this data processing method. All the data was saved to a local file on the smartphone first, then processed offline using MATLAB.

Chapter 5. REAL-WORLD EXPLORATION

In this section, we present the results of several real-world experiments conducted to investigate the effects of fever, eating, exercising, environmental changes, and stress on earlobe temperature. Throughout these experiments, participants were instructed to wear the Thermal Earring on their preferred ear, while the Thermal Earring was programmed to measure the temperatures every second for capturing comprehensive information. The results demonstrate that Thermal Earring is capable of distinguishing between changes in body temperature and environmental temperature. Our findings show that the Thermal Earring is a promising platform for a wide range of applications, including monitoring fever and detecting daily activities such as eating and exercising, as well as stressful events such as public speaking and exams.

5.1 EFFECT OF FEVER ON EARLOBE TEMPERATURE

Fever is a common physiological response to a variety of medical conditions, including infectious diseases such as COVID-19 and influenza, signifying a notable increase in core body temperature [20]. Clinically, fever is characterized by an elevated core body temperature exceeding 37.8°C (100°F) when measured orally. This experiment aimed to investigate the effects of fever on earlobe temperature and explore the feasibility of using the Thermal Earring to detect and monitor fever.



(a) (b) (c)

Figure 5.1. Fever exploration result and example plot.

(a)The Thermal Earring's earlobe temperature data on healthy and febrile people. (b) Day 1 when the participant was having a fever with an oral temperature of 39°C (102.2°F) at 19:10. (c) Day 2 after the fever was gone. The participant's oral temperature was 37.2°C (98.96°F) at 22:30.

We recruited a total of twenty-five participants, including four febrile individuals (two male, two female) with a core body temperature higher than 37.8°C (100°F), one individual (female) with a slightly elevated core body temperature of 37.6°C (99.7°F) in close proximity to fever, and twenty healthy individuals (ten male, ten female) with a core body temperature around 37°C (98.6°F). During the data collection process, each participant wore the Thermal Earring for a duration of five minutes to obtain earlobe temperature readings. Additionally, their oral temperature was measured while wearing the Thermal Earring. The measurements were conducted in a similar room environment with a temperature ranging from 20°C to 22°C (68°F to 71.6°F). Figure 5.1 (a) presents the results of the earlobe temperature measurements obtained from each participant. The febrile participants have an average earlobe temperature of $35.62 \pm 1.8°C$ ($96.12 \pm 3.24°F$), which is significantly higher than healthy participants' average earlobe temperature of $29.7 \pm 0.74°C$ ($85.5 \pm 1.33°F$). It was also observed that in general, healthy female participants have higher earlobe temperature of $30.11 \pm 0.78°C$ ($86.2 \pm 1.4°F$) than healthy male participants' average earlobe temperature of $29.26 \pm 0.70°C$ ($84.67 \pm 1.26°F$). The results are expected since women have slightly higher body temperatures in general. We also note that the lowest temperature among febrile patients was observed in an older study participant (age 71) who is known to have a lower body temperature baseline.

In addition to the aggregated results, we also present the Thermal Earring results of one participant over time during fever and after fever. Figure 5.1 (b) shows the Thermal Earring data of the participant during fever, including the changes observed after taking a common antipyretic to reduce fever. The participant's oral temperature was initially recorded at a high fever of 39°C (102.2°F) at 19:10 on day 1, with a corresponding high earlobe temperature of 37.1°C (98.8°F). At 19:20 on day 1, the participant took a capsule of ibuprofen, a common antipyretic, which resulted in a gradual decrease in earlobe temperature from 37.1°C (98.8°F) at 19:10 to 33.9°C (93°F) at 21:30. On day 2, the participant's earlobe temperature stabilized at around 31.4°C (88.5°F), which was significantly lower than her earlobe temperature during fever. The participant's oral temperature was measured at 37.2°C (98.96°F) at 22:30 on day 2, indicating a return to the normal temperature range. The limited oral temperature measurements were due to the participant's illness and unwillingness to take measurements. These results suggest that Thermal Earring temperature data could serve as a convenient and effective method for monitoring fever at home and in clinical settings, providing valuable information on the effectiveness of fever treatments.

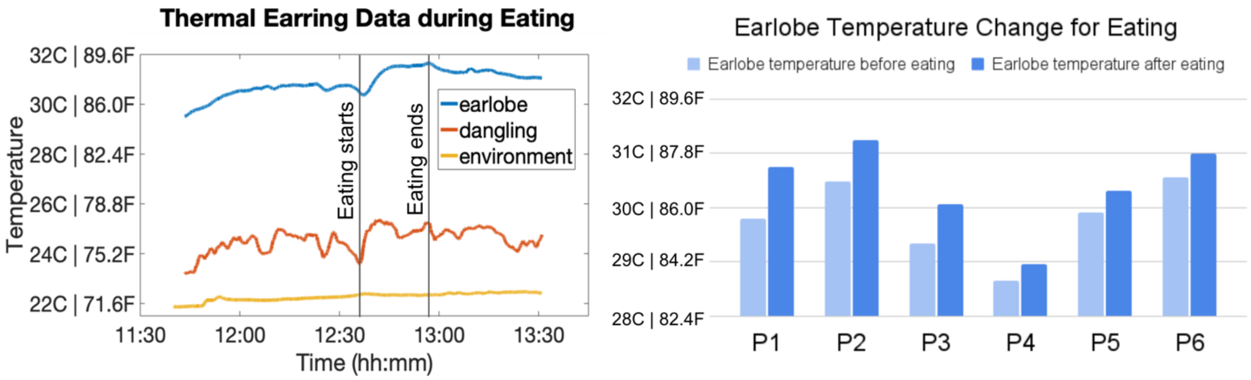
In conclusion, the findings of this experiment suggest that the Thermal Earring is an effective tool for detecting and monitoring fever non-invasively. Our study provides evidence that the Thermal Earring has the potential to be used in a variety of clinical and home-based settings to aid in the diagnosis and management of fever, particularly during outbreaks of infectious diseases.

However, further research is needed to validate the performance of the Thermal Earring in larger and more diverse populations.

5.2 EFFECT OF EATING ON EARLOBE TEMPERATURE

Eating is an important daily activity that is known to slightly increase body temperature. Generally, the core body temperature starts to rise within thirty minutes to an hour after eating a meal due to the increased metabolic rate associated with the digestive process. Furthermore, the act of chewing and the heat from the food can also elevate the earlobe temperature since the Thermal Earring is located close to the mouth.

In this experiment, we investigated the effect of eating on earlobe temperature. We recruited six participants (three males and three females) to participate in a semi-controlled lunch setting. The study began at 11:30 am, with participants sitting until 12:30 pm to establish a resting baseline temperature. The lunch session began at approximately 12:30 pm, with slight variations in duration across the participants. After they finished eating, they were asked to stay for another 30 minutes in the same room.



(a) (b)

Figure 5.2. The Thermal Earring temperature results for six participants during the eating session.

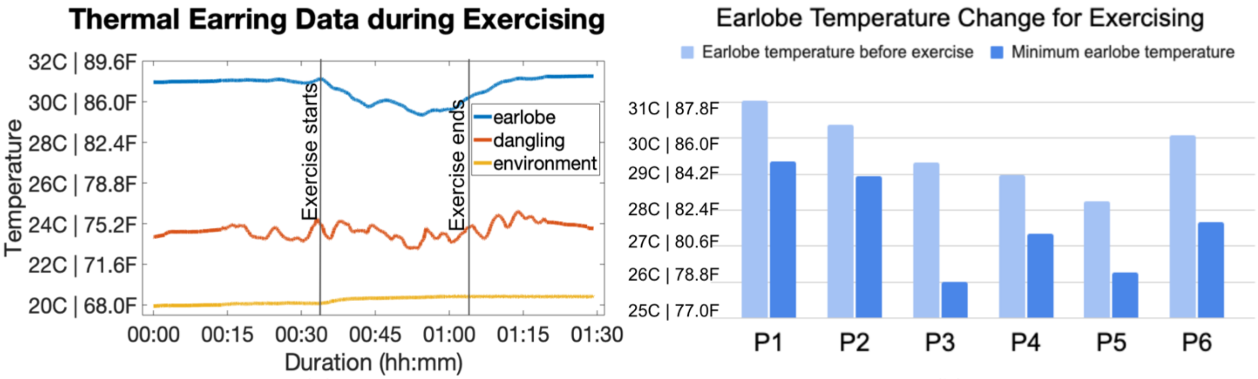
Figure 5.2 (a) illustrates a representative example of Thermal Earring data obtained from a participant during the eating session. The temperature data of all six participants exhibited a similar pattern, wherein the earlobe temperature exhibited a slight increase upon initiating the act of eating. Notably, some participants experienced a continued rise in earlobe temperature after finishing their meal, while others observed a stabilization or a slight decrease.

To provide an overall analysis, Figure 5.2 (b) presents the aggregated results of the average earlobe temperature for all six participants before and after 12:30 pm (the start of eating activity). The earlobe temperature showed an average increase of $0.60 \pm 0.25°C$ $(1.08 \pm 0.45°F)$ from the pre-eating resting baseline (11:30 am to 12:30 pm) to the post-eating (12:30 pm to 1:30 pm) average temperature. Furthermore, the earlobe temperature exhibited an average rise of $1.04 \pm 0.30°C$ $(1.87 \pm 0.54°F)$ from the pre-eating temperature to the maximum temperature observed after the initiation of eating. These experimental findings confirm the body temperature change associated with the act of eating and demonstrate the potential of utilizing Thermal Earring as a non-invasive detector of eating activities.

5.3 EFFECT OF EXERCISE ON EARLOBE TEMPERATURE

Exercise is another common activity that significantly impacts human core body temperature and skin temperature. During exercise, the core body temperature rises due to the increased metabolic activity of muscles. The thermoregulatory system is activated to dissipate heat and maintain a stable core body temperature through mechanisms such as vasodilation and sweating. Among these mechanisms, sweating plays a critical role in maintaining a relatively stable core body temperature. As sweat evaporates from the skin, it carries away heat, resulting in skin cooling and the maintenance of core body temperature.

The exercise experiment aimed to investigate the effect of exercise on earlobe skin temperature. We recruited six participants (three females and three males) to complete a 30-minute cardiovascular workout in a controlled room. The exercise study lasted for 90 minutes in total, which included a 30-minute rest before and after the exercise. Similar to the eating study, the participants were asked to rest or engage in sedentary activities during the rest periods to establish a baseline earlobe temperature in the room.



(a)

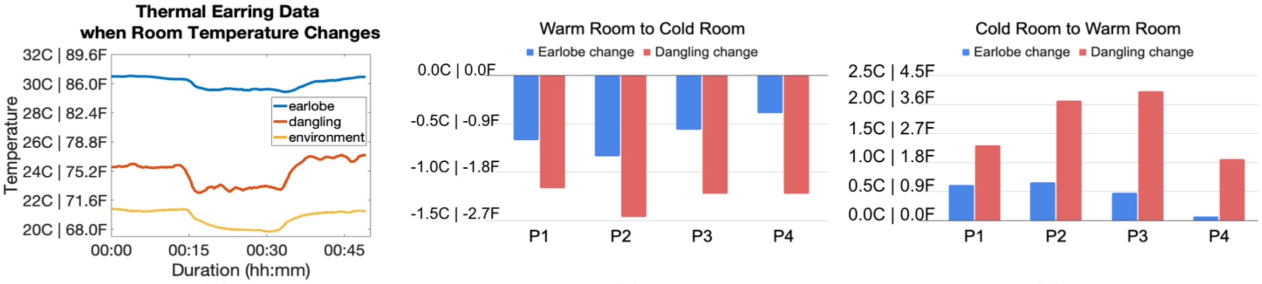
(b)

Figure 5.3. The Thermal Earring temperature results for six participants during the exercise session.

Figure 5.3 (a) shows a representative example of Thermal Earring data obtained from a participant during the exercise session. Consistent with our hypotheses, all six participants experienced a decrease in earlobe temperature during exercise, followed by a gradual recovery to their resting earlobe temperature after the exercise ended. Notably, one participant continued to experience a decreasing earlobe temperature for approximately ten minutes after the workout ended, likely due to ongoing sweating.

Figure 5.3 (b) presents the aggregated results of the six participants' average earlobe temperature before exercise and their minimal earlobe temperature during and after exercise. The earlobe temperature showed an average decrease of $2.08 \pm 0.70°C$ ($3.74 \pm 1.26°F$) from the pre-exercising resting baseline (duration 00:00 to 00:30) to the lowest earlobe temperature during and after exercise. These findings provide valuable insights into the influence of exercise on earlobe temperature and show the potential application of using earlobe temperature as a non-invasive biomarker for monitoring physiological responses to exercise.

5.4 Effect of Environment Temperature Change



(a) (b) (c)

Figure 5.4. The Thermal Earring temperature results when room temperature changes.

This section focuses on evaluating the ability of the Thermal Earring's dual temperature sensor design to detect changes in environmental temperature. To achieve this, we conducted an experiment involving four participants (two males and two females) to investigate the effects of slight indoor temperature changes. Specifically, we examined the transition from a warm room to a cold room and vice versa, which are typical scenarios encountered in daily life.

The two temperature change experiments were conducted in a continuous manner. Participants were instructed to spend 15 minutes in a warm room with an ambient temperature of 21.4°C (70.5°F), followed by 15 minutes in an adjacent colder room with an ambient temperature of around 19.9°C (67.8°F), and then return to the warm room for another 15 minutes.

Figure 5.4 (a) presents an example of temperature data obtained from one participant during this session, demonstrating the temperature pattern observed across all participants. When the environment temperature changed, the dangling temperature exhibited a similar change as the environment, while the earlobe temperature stayed relatively stable.

Figure 5.4 (b) presents the aggregated results from the amount of change in the earlobe and dangling temperature change when entered from a warm room to a cold room. And Figure 5.4 (c) presents the aggregated results of the amount of temperature change in the earlobe and dangling when the participants enter from a cold room to a warm room. All participants data showed significantly higher dangling temperature change than the earlobe temperature change. When participants entered the warm room from the cold room (1.5°C temperature difference), the dangling temperature increased by an average of $1.60 \pm 0.50°C$ ($2.88 \pm 0.90°F$), while the earlobe temperature only increased by $0.46 \pm 0.27°C$ ($0.83 \pm 0.48°F$). Conversely, when participants entered the cold room from the warm room (environment temperature increased 1.6°C), the dangling temperature experienced an average decrease of $1.27 \pm 0.13°C$ ($2.29 \pm 0.23°F$), while the earlobe temperature decreased only $0.61 \pm 0.19°C$ ($1.10 \pm 0.34°F$) on average.

These results indicate that the Thermal Earring's dangling temperature tends to mirror the changes in environmental temperature, while the earlobe temperature remains relatively stable with a consistent offset from the core body temperature. Therefore, the Thermal Earring demonstrates its effective ability to detect variations in environmental temperature. The subsequent section will delve into further analysis, showcasing how the Thermal Earring can differentiate between changes in environmental temperature and those related to human body temperature, such as during eating and exercising activities.

5.5 SUMMARY OF THERMAL EARRING RESULTS

This section provides a comprehensive summary and comparison of the results obtained from the previous experiments investigating the effects of fever, eating, exercising, and environmental changes. Figure 5.5 presents the temperature change patterns captured by the Thermal Earring across these different factors. The combined statistical results indicate that environmental changes, such as room temperature increasing or decreasing, exerted a more significant impact on the dangling temperature compared to the earlobe temperature. Conversely, alterations in core body temperature because of fever, eating, and exercising result in larger or comparable changes in the earlobe temperature, with the dangling temperature exhibiting a lesser impact.

Furthermore, the amplitude of temperature change is another informative metric. Our findings demonstrate that fever prompts a substantial increase in both earlobe and dangling temperatures, resulting in a significantly larger temperature rise compared to other activities such as eating.

Overall, our study provides valuable insights into the human body's earlobe temperature change patterns across various reasons and can have potential applications for detecting activities in daily natural settings.

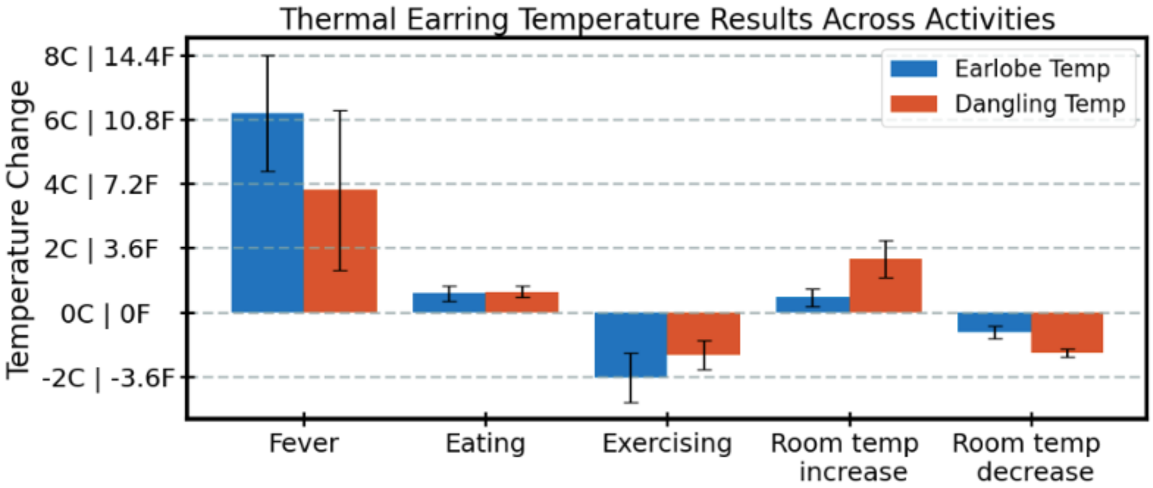


Figure 5.5. The Thermal Earring temperature results across activities.

5.6 FURTHER EXPLORATION

The Thermal Earring's compact form factor and long battery life enable longitudinal temperature sensing in real-world settings. In this section, we first show a data example of one day from the

Thermal Earring to demonstrate its performance in a longer and more natural setting. We then propose a heuristic algorithm for data analysis, followed by an accuracy evaluation on both Thermal Earring and a research-use smartwatch. Moreover, we also further explored the relationship between earlobe temperature and various stressors.

5.6.1 *In-the-wild Exploration*

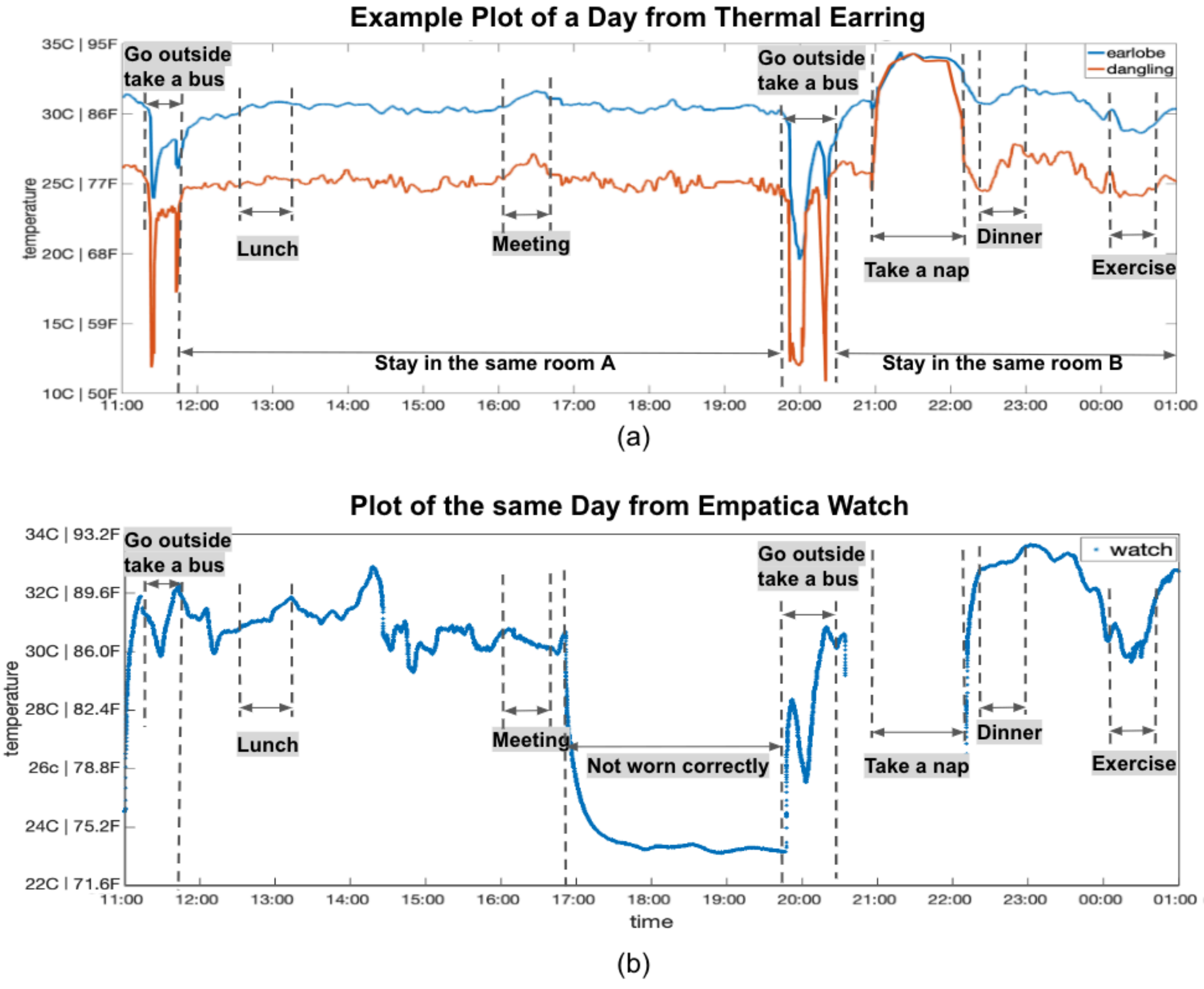


Figure 5.6. An example of the Thermal Earring data on a participant for a day.
(a) Data from Thermal Earring. (b) Data from Empatica Watch.

We further did an in-the-wild exploration by asking six participants to wear the Thermal Earring for one to three days with their natural daily routine. We also requested participants to wear an

Empatica EmbracePlus smartwatch [11], a health-tracking wearable for research that provides raw wrist temperature data continuously. To gather ground truth on activities, participants were further asked to self-report their activities using the Thermal Earring Android App.

Figure 5.6 shows an example of temperature data captured by the Thermal Earring and Empatica Watch over a day, with the participant's self-reported activity log as labels.

For the Thermal Earring data, there are three time periods showing significant effects from ambient temperature change: 1) going outside and taking a bus, and 2) during a nap. These periods can be identified by comparing the amount of dangling change with the corresponding earlobe temperature change with a heuristic detecting algorithm presented in the next section. After excluding the periods heavily affected by the ambient change, the participant's temperature data is relatively stable during indoor periods throughout the day. During the indoor time, the participant's earlobe temperature shows a similar pattern to our previous controlled experiments on eating and exercising. The participant's earlobe temperature increased by 1.0°C (1.8°F) when eating lunch, and 1.3°C (2.3°F) when eating dinner. During the exercise, the participant's earlobe temperature decreased to around 2.1°C (3.8°F) and then gradually recovered back after the exercise ended. In addition to the changes caused by eating and exercising, there is an additional noticeable earlobe temperature increase from 16:00 to 16:30, when the participant was in a stressful meeting with two professors. In the next section, a heuristic algorithm is presented to detect these events.

5.6.2 *Heuristic Algorithm on Thermal Earring Data*

Based on insights from this real-world data, we propose a threshold-based heuristic algorithm for activity presence detection using the combined temperature data from the Thermal Earring's earlobe and dangling sensors. The algorithm consists of two stages, as illustrated in Figure 5.7. In the first stage (a), we identify periods when the ambient temperature was rapidly changing and exclude these periods. To achieve this, we compute the temperature difference between the earlobe and dangling temperature, then use an empirical threshold of $\pm 0.2°C$ ($\pm 0.36°F$) on the computed temperature difference. This approach is guided by the insights highlighted in Section 5.4, which suggests that the magnitude of the dangling temperature change exceeds that of the earlobe temperature during changes in ambient temperatures. This approach successfully classifies rapid ambient temperature changes, such as from indoors to outdoors, with a 100% accuracy rate. Furthermore, we merge the detected ambient temperature change events occurring within a 30-minute time frame, since the second stage of the algorithm requires a 30-minute window during a stable indoor environment. These detected periods of unstable environmental temperature were excluded from further analysis.

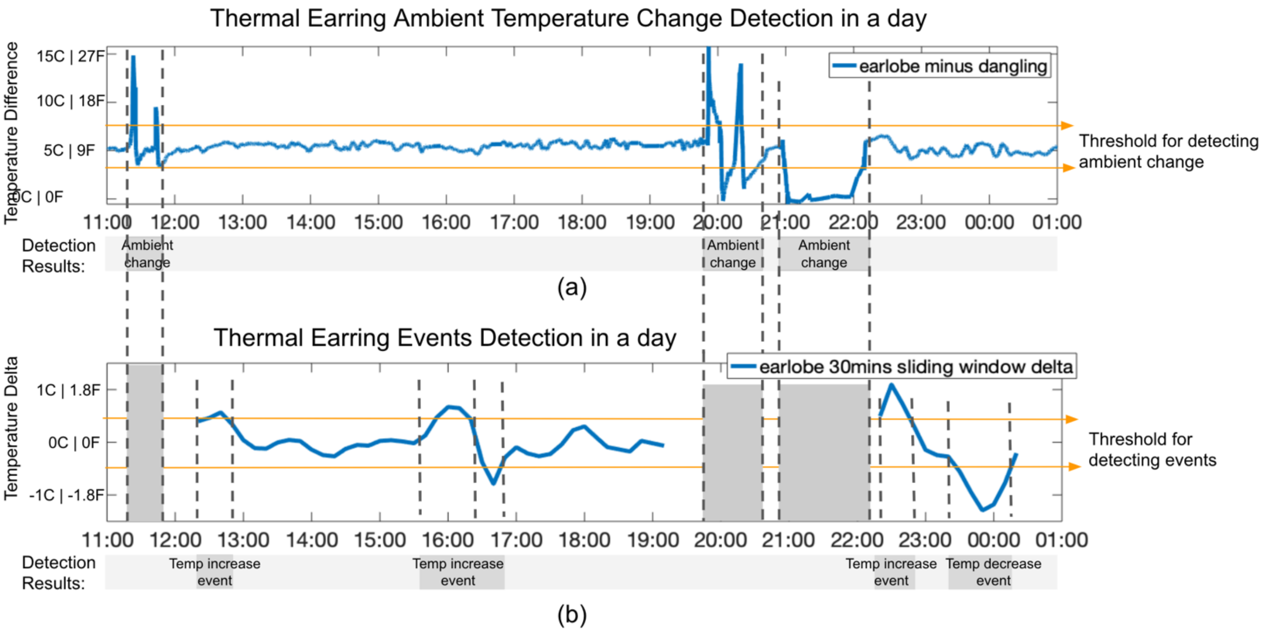


Figure 5.7. Heuristic algorithm result on the example one-day plot.

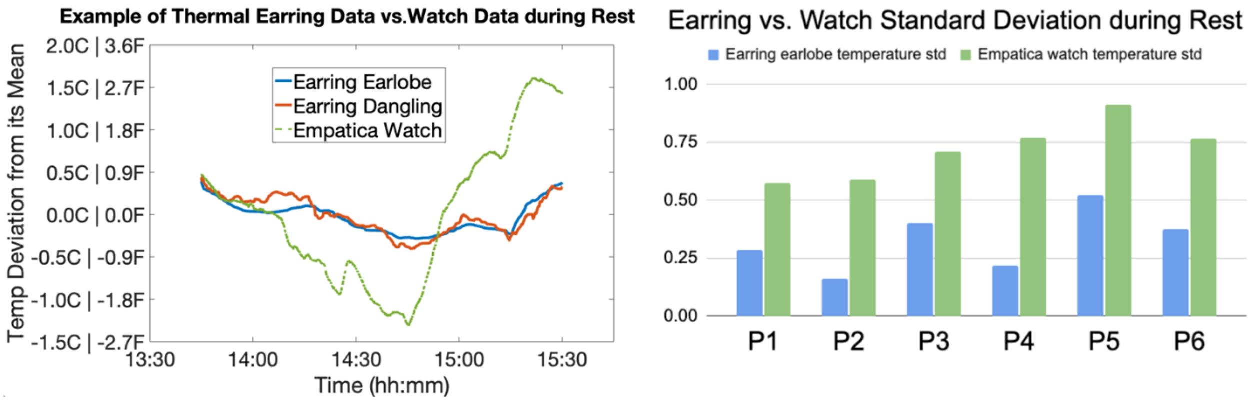
(a) A heuristic ambient temperature change detection model using a threshold. The empirical threshold is applied on the earlobe temperature minus dangling temperature. (b) A heuristic event detection model using user-specific model. The plot shows the earlobe temperature delta over time computed using the average in a 30-minute sliding window minus the average of the window 30 minutes ahead. The threshold is then applied to the computed results to detect the presence of various events.

In the second stage of the algorithm, we focus on identifying user activity-related events occurring while users were indoors. We achieve this by computing the temporal changes in earlobe temperature using a 30-minute sliding window. For each window, we consider the average earlobe temperature during the window 30 minutes ago as the baseline temperature for the current window to account for changes in the room or changes in body temperature. By subtracting the corresponding baseline from the current window's average earlobe temperature, we obtain the temperature delta. The computed sliding window results are shown in Figure 5.7 (b). We then apply a user-specific threshold of $\pm 1°C$ ($\pm 1.8°F$) to the computed data. In this way, we were able to detect temperature-increasing events (e.g., eating, meeting) and temperature-decreasing events (e.g., exercising) throughout the day.

It is important to note that this heuristic algorithm serves as a simple proof of concept based on empirical thresholds, and each user may have their unique threshold values. Similar to smartwatch-based activity detection, the Thermal Earring could be pre-trained and then gather user-specific data over time to learn a personalized model. Our hardware platform and experiments establishing relationships between ear temperature and various activities seek to provide a foundation for future earring-based activity recognition.

5.6.3 *Thermal Earring vs. Smartwatch*

As expected, the temperature data obtained from the wrist using a smartwatch tends to be noisier compared to the data collected from the earlobe using the Thermal Earring. This is potentially due to the effects of hand motions on the wrist temperature. As shown in Figure 5.6 (b), the Empatica Watch data appears significantly noisier than the Thermal Earring data on the same day. Firstly, because of the lack of a secondary ambient temperature sensor, the watch data cannot differentiate ambient temperature changes. Secondly, even during indoor periods, the watch data exhibits fluctuations of up to 3.6°C (6.48°F) without any apparent correlation to the participant's provided activity labels. Thirdly, the watch data is occasionally shown as "not worn correctly", potentially because of loose contact with the wrist, resulting in data reflecting the environmental temperature rather than the participant's skin temperature. Besides those limitations, the watch data demonstrate a similar pattern of temperature increase during meals and temperature decrease during exercise. However, these patterns are obscured by the noise in the watch data, making them difficult to identify.



(a) (b)

Figure 5.8. The Thermal Earring vs. Empatica Watch temperature data results during resting time.

To further analyze the noise levels of the smartwatch temperature compared to the Thermal Earring, we compared the data from the Thermal Earring and the Empatica Watch during six participants' resting periods, when no activity was recorded. Figure 5.8 (a) shows the temperature deviation of Thermal Earring data and Empatica watch data from its average temperature during a participant's resting period, where the participant was not engaged in any activities like eating, exercising, or talking. It is observed that the Thermal Earring data is more stable since the earlobe is less susceptible to motion effects, with a standard deviation of 0.18°C (0.32°F), whereas the watch data showed significant fluctuations for unknown reasons, resulting in a standard deviation of 0.82°C (1.48°F). Figure 5.8 (b) summarizes the aggregated results of the standard deviations for the Thermal Earring and Watch data during indoor resting periods from six participants. The average standard deviation from the Thermal Earring is 0.32°C (0.58°F), while the average standard deviation from the watch temperature is 0.72°C (1.3°F).

The Thermal Earring's reliable temperature readings have the potential to enable applications such as ovulation tracking, surpassing the capabilities of current smartwatches. During ovulation, a woman's body temperature typically rises by approximately 0.28°C to 0.56°C (0.5°F to 1.0°F) [40]. However, smartwatches struggle to accurately detect this temperature increase since their noise level exceeds the temperature change caused by ovulation. In contrast, the Thermal Earring provides a more reliable temperature reading, with a standard deviation close to the lower range of ovulation temperature rise. As a result, the Thermal Earring shows its theoretical potential for tracking ovulation.

In conclusion, Thermal Earring surpasses smartwatches in terms of noise levels and the ability to disambiguate ambient temperature changes. These advantages enable Thermal Earring to detect user activities effectively, and potentially support ovulation tracking.

5.6.4 *Emotion Exploration*

The activation across the human body would be different when feeling different emotions [50], we were inspired to study the relationship between earlobe temperature and emotional states. As a preliminary attempt, we had four participants go to a local cinema to watch a fantasy movie. The movie had a duration of 2 hours and 14 minutes with two main scary scenes that most people in the theater screamed about. Figure 5.9 shows the Thermal Earring data from all four participants with four labels indicating the start and end times of the movie, as well as the timings of the two scary scenes. From the plots, P1 and P2 had a small earlobe temperature increase approximately when the first scary scene showed up on the screen, while no similar change was observed for participants P3 and P4. Moreover, at the time when the second scary scene appeared on the screen, there was no obvious temperature change on the earlobe among all four participants. Thus, the movie exploration was not able to provide effective insights into the relationship between earlobe temperature and emotions. The potential reason behind it could be that the participants were informed of the movie's name in advance, which may have influenced their mental preparedness and potentially affected their reaction to the scary scenes. In addition, the labeling of scenes as "scary" may be subjective, as the perception and intensity of the scare can vary among individuals. In general, people have different emotional responses to different scenarios, making it challenging to generalize the emotional effects of a specific scene. In order to better explore the temperature changes related to emotional states, further experiments would need to be conducted thoughtfully with emotion evaluation surveys and more emotion-targeted activities.

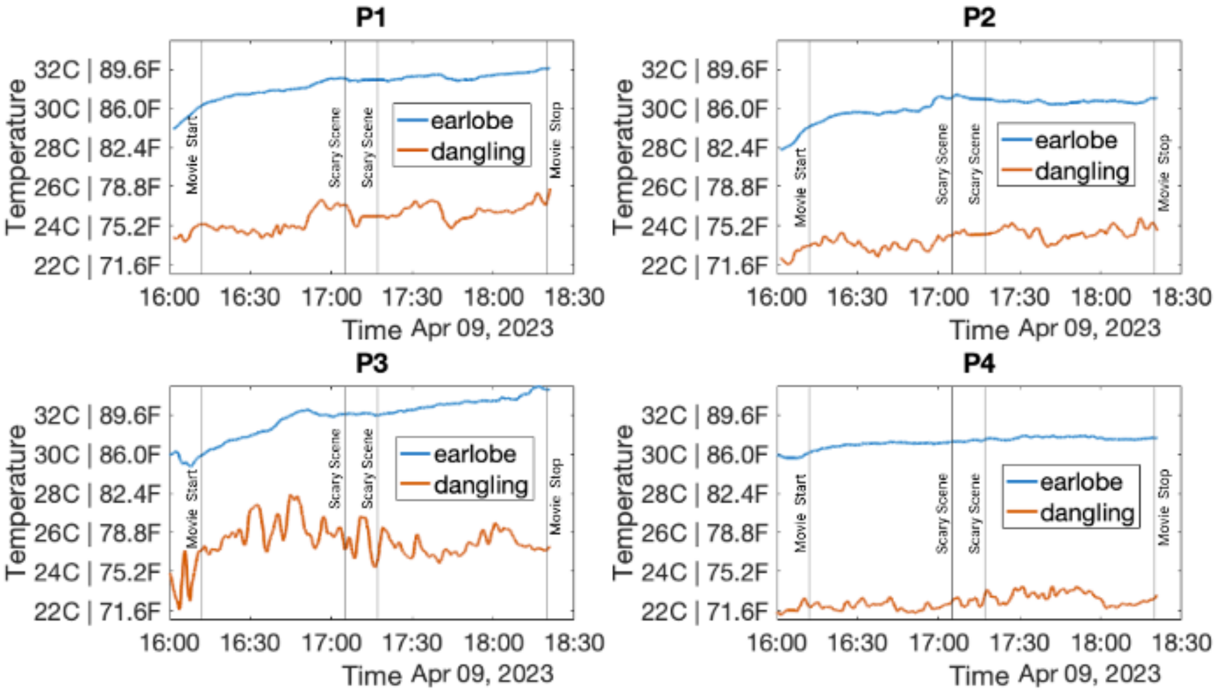


Figure 5.9. The Thermal Earring data for four participants during movie session.

5.6.5 *Acute Stress Exploration*

In our preliminary pilot experiments, we discovered significant changes in earlobe temperature during stressful events, such as public speaking. This temperature increase might be caused by the blood flow change within the superficial temporal artery and the posterior auricular artery during stressful events, as discussed in Section 2.2. While stress has been investigated using various physiological signals like heart rate, heart rate variability, blood pressure, and skin conductance, these metrics often struggle to differentiate between various types of events. For example, it is hard to differentiate stress from exercising solely based on an elevated heart rate. However, the measurement of earlobe temperature introduces a promising additional dimension that effectively aids in differentiating events.

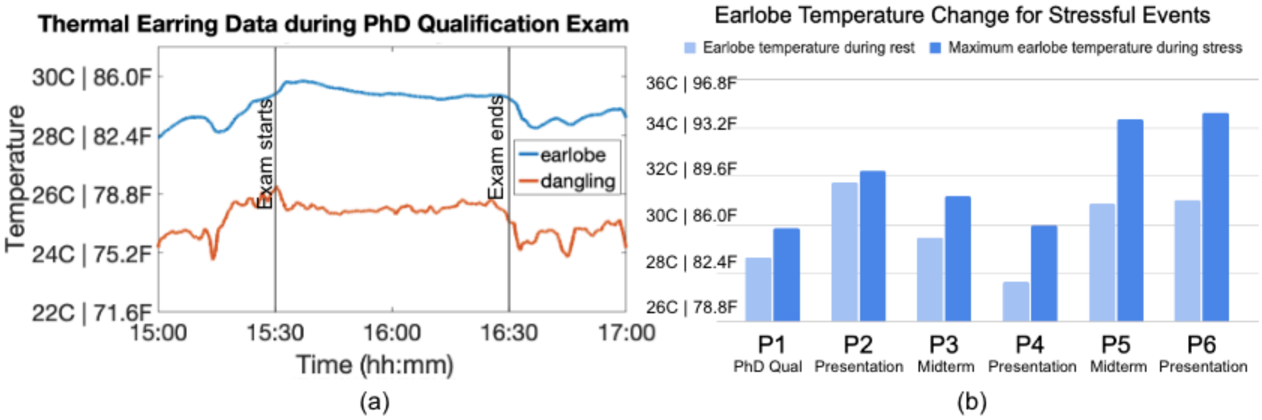


Figure 5.10. The Thermal Earring results for stressful events.

We conducted an experiment involving six participants who wore the Thermal Earring during various stressful events, such as PhD qualification exam, public presentation, and midterm. In Figure 5.10 (a), we present a representative example of the data obtained from one participant during their PhD qualification exam. The data clearly show a sustained increase in earlobe temperature throughout the exam. This pattern was consistently observed in all six participants, with the rise in temperature slightly before the stressful events and a subsequent decrease at the end.

Figure 5.10 (b) provides the aggregated results of all participants. An average of $2.12 \pm 1.25°C$ (3.81 ± 2.25°F) increase between the average earlobe temperature during rest and the maximum earlobe temperature during stressed time demonstrated the response related to the stressors. Aligned with our hypothesis, these exploration results show promising potential for using the earlobe temperature as an indicator for stressful or anxiety-related events. Further studies can be conducted in future work to extensively explore the relationship between earlobe temperature and stress or emotions.

Chapter 6. DISCUSSION

In this section, we discuss the potential of smart earring wearables, including the future directions of the Thermal Earring and its limitations. As smart earring is rising smart wearables that are promising for health sensing, we believe that further research work can focus on multiple directions, such as fashion design, system design, and detections of fever, activities, and stress.

6.1 FASHION DESIGN

It is also important for the Thermal Earring to be fashionable as smart jewelry. The small size and light weight of the Thermal Earring make it compatible with various drop earring designs. We showcase an example of fashion design here to indicate that the Thermal Earring can be both functional and fashionable. We chose to design a cherry blossom earring with resin as it is a popular material for making earrings and can be molded into various shapes and mixed with different pigments. Thermal Earring is flat, thin, and flexible, which makes it easy to be submerged in a resin pour. Figure 6.1 demonstrated the final design. The resin was poured into a cherry blossom-shaped silicone mold to encase the Thermal Earring. With different shapes of silicone molds and colors of resin, the Thermal earring can be personalized to various designs or styles.

Figure 6.1. An example of Thermal Earring with fashion design.

6.2 FUTURE DIRECTIONS

6.2.1 *Power Harvesting*

The Thermal Earring is currently powered by a lithium coin cell battery, which can provide continuous temperature monitoring for a month. However, to address the inconvenience of battery charging and replacement, alternative power sources can be explored. One promising option is to harvest energy from the ambient environment, leveraging the motion of the earring while it is naturally dangling when the user is moving. By harvesting kinetic energy from the earring's motion, a piezoelectric harvester can convert the vibrations into electrical energy to power the earring. Additionally, solar energy can also be used as an alternative power source by harvesting it from the ambient light. Even a small solar cell can provide microwatts of power for trickle charging compatible with Thermal Earring's low-power design.

6.2.2 *Detections*

In the previous sections under Chapter 5, we explore the effects of fever, daily activities, and stressors on earlobe temperature. With more data collected in the future, we could develop an algorithm to detect fever across individuals of different ages, gender, and Body Mass Index (BMI). Similarly, daily activity detection and stress assessment can be investigated with more data. Smart earrings can be more personalized and have more impact on healthcare and individual well-being.

6.3 LIMITATIONS

The earlobe temperature appears to be user dependent, which is expected as age, gender, body weight, and composition can all affect skin temperature. Similar to existing smartwatch temperature sensors [2, 14], Thermal Earring could leverage a calibration phase to identify a user's nominal earlobe temperature before making inferences.

During the evaluation of the Thermal Earring, the majority of tests were conducted indoors under normal air conditions, with temperatures ranging from 20 to 23 degrees Celsius (68 to 73.4 degrees Fahrenheit). For simplicity, outdoor measurements are disregarded. In future work, it would be valuable for future research to explore how the Thermal Earring performs in outdoor and extreme environments.

The Thermal Earring is currently only evaluated during daytime, to prevent participants' unconscious movement during sleep from harming the Thermal Earring or leading to noisy results. However, a more robust casing for Thermal Earring could enable studies during sleep to measure basal body temperature, which can be further used to track and predict menstrual cycles.

Chapter 7. CONCLUSION

We present Thermal Earring, a novel smart earring system designed for longitudinal temperature sensing from the earlobe. The Thermal Earring overcomes the challenges associated with developing a wireless smart wearable device in the form of an earring, resulting in a compact size (11.3 mm), lightweight (0.335 grams), and an impressive battery life of up to one month. Leveraging its proximity to the head and dual temperature sensor design, the Thermal Earring demonstrates reliable temperature sensing capabilities. We conducted extensive real-world evaluations to investigate the effects of fever, eating, exercising, and ambient temperature change on the Thermal Earring's data. Our results proved that the Thermal Earring can successfully disambiguate the temperature changes caused by the body from those caused by the environment. To further validate the practicality of the Thermal Earring in real-life scenarios, we explored the effectiveness in detecting activities like eating and exercising and stressful events within individuals' natural daily routines. We evaluated the advantages of Thermal Earring over existing wrist-worn smartwatches. Overall, Thermal Earring is a promising platform for continuous earlobe temperature sensing, which shows the potential in applications of fever monitoring, activity detection, and stress assessment.

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