Thermal Earring: Low-power Wireless Earring for Longitudinal Earlobe Temperature Sensing

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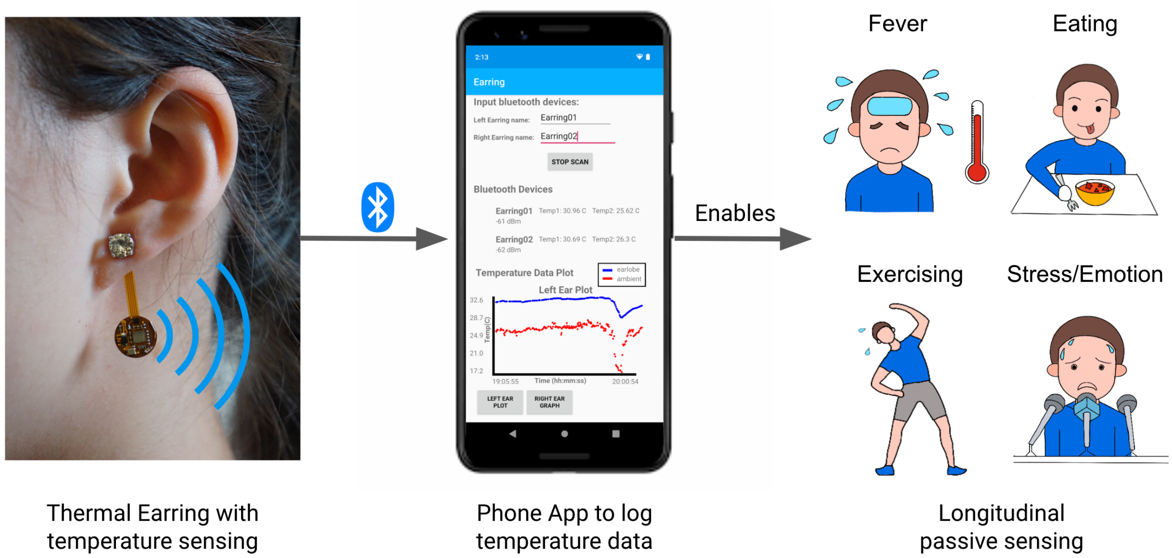

Fig. 1. Overview of the Thermal Earring.

Body temperature is an important vital sign which can indicate fever and is known to be correlated with activities such as eating, exercise and stress. However, continuous temperature monitoring poses a significant challenge. We present Thermal

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Earring, a first-of-its-kind smart earring that enables a reliable 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 a maximum width of 11.3 mm and a length of 31 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 its measured earlobe temperatures are stable within ±0.32 °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 and exams 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 automatic activity detection and earring-based wearables.

CCS Concepts: • **Human-centered computing → Ubiquitous and mobile computing systems and tools**; • **Applied computing → Consumer health**.

Additional Key Words and Phrases: Wearable Computing; Smart Jewelry; Health monitoring, Body temperature sensing

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1 INTRODUCTION

Wearable devices with sensors have gained significant popularity in recent years and are becoming a ubiquitous part of daily life. Nearly 40% of US households possess wearables like smartwatches [40]. Wearables which are often in contact with a user's body throughout the day offer unique opportunities for interaction, health sensing, and activity tracking. This has prompted exploration of various accessories for sensing, including smart rings [4, 33], smart glasses [47], fitness earbuds [15, 36], and smart clothing [42, 46]. 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, 76% of women have pierced earlobes which is nearly twice the current adoption rate of smartwatches and there is a growing trend of men embracing earrings, indicating its widespread acceptance as a fashionable choice [12].

Earrings, in particular, present a unique opportunity for continuous monitoring of physiological signals. Unlike headphones and earbuds, earrings are typically worn continuously for most of the day and could be used as a continuous sensing platform. Moreover, earrings have the further advantage of being tightly coupled to a user's body in contrast to watches which can easily move and shift against the skin. In addition to these form factor considerations, their attachment to a user's 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 an important vital sign but challenging to sense continuously. 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.

In this paper, we present Thermal Earring, a first-of-its-kind wireless, smart earring that enables a reliable wearable solution for continuous temperature monitoring. We develop a hardware prototype in the form factor of real earrings measuring a maximum width of 11.3 mm and a length of 31 mm, weighing 335 mg, and with a battery life of one month. We investigate the earlobe temperature's real-world use cases by gathering data from 5 febrile patients and 20 healthy participants, and demonstrated Thermal Earring's ability in fever detection. Further, we observed in our user testing that the relative change in earlobe temperature can identify activities such as eating and exercise, as well as, stressful events such as public speaking and exams. Rather than attempting to convert earlobe temperature into core body temperature, which generally remains around 37 °C (98.6 °F) except during fever, our focus centered on exploring novel applications based on relative changes in earlobe temperature within everyday contexts.

Achieving continuous body temperature sensing on wearables is challenging and remains an open problem in the research community. Although smartwatches and rings such as Apple Watch, Fitbit, and Oura Ring offer skin temperature monitoring on the wrist or finger, skin temperature data from extremities is noisy due to the distance from the core body [19] and is more susceptible to motion artifacts and contact with hot or cold surfaces. As a result, these devices only provide one average temperature reading per day, primarily from data during sleep. In contrast, Thermal Earring takes advantage of the unique position of earrings on the head and tight coupling to the earlobe to provide a reliable measurement of earlobe temperature. We find in initial trials across six users in the wild that earlobe temperature remains stable during periods of rest with a maximum standard deviation of 0.32 °C (0.58 °F) compared to a watch that varies by over 0.72 °C (1.3 °F). This is promising for future applications such as ovulation tracking which requires 0.28 to 0.56 °C accuracy [41].

Accurately measuring the earlobe skin temperature requires also isolating the effect of ambient temperature changes, which is one of the fundamental challenges in wearable body temperature measurement. One way to measure these effects would be to add a second temperature sensor solely dedicated to capturing 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 1 cm. We observe that common earring designs include 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 to capture the ambient temperature. This unique design enhances the reliability and accuracy of temperature measurements from wearable devices, surpassing the temperature accuracy achieved by existing smart watch devices.

Developing a wireless sensor in an earring form factor has many sensing advantages, but presents multiple technical challenges. The system must be small and lightweight for comfortable use. These constraints on size 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 support radios for transmitting the temperature data. To design a system within these strict form factor constraints we leverage the highly integrated nRF52 Bluetooth SoC which is available in a highly miniaturized 3 mm x 3 mm package and the 1.5 mm x 1.5 mm temperature sensor (TI HDC2010). We observe however that the battery and microcontroller consume a significant portion of the size, which may exceed the available space on a user's earlobe. Therefore, we positioned larger components, such as the microcontroller and battery, in the dangling part of the earring. In contrast, the small temperature-sensing unit is positioned directly on the user's earlobe. In addition, we optimize the power consumption of the system to operate on a miniaturized battery, capable of sustaining continuous discharge currents of 0.25 mA. Despite the 5 mA requirement during Bluetooth transmission, we demonstrate its ability to run continuously for a month.

To summarize, we present the following **contributions** in this paper:

- We design the first wireless smart earring platform for continuous temperature sensing, demonstrating a small and comfortable size (with a maximum width of 11.3 mm and a length of 31 mm), light-weight (335 mg), and ultra-low-power (14.4 uW, 28 days battery life), in a common dangling earring shape.
- We develop a novel dual temperature sensor design to differentiate human body temperature change from the environment temperature change. We further conduct experiments to demonstrate the Thermal Earring's ability to disambiguate the effects of environmental temperature change from valuable body temperature changes.
- We conduct real-world experiments in febrile patients demonstrating fever detection using earlobe temperature.
- 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, exercise, and periods of acute stress. In addition, we perform in-the-wild experiments and confirm the temperature changes caused by these daily activities in natural scenarios. The initial exploration results provide a basis for future automatic activity detection.

2 RELATED WORK

In this section, we first review the literature on related wearable devices including smart jewelry and on-ear wearable devices for health monitoring. We then discuss various techniques for core-body temperature sensing.

2.1 Smart Jewelry and On-ear Wearable Devices

Smart jewelry is an emerging class of wearable devices that seeks to combine fashion and function by integrating sensing into jewelry accessories. Previous work exploring smart jewelry items include smart necklaces which have been used for silent speech recognition [51] and medication adherence detection [29], bracelets for user interaction [18, 45], health monitoring and intervention [1, 17], and rings for interaction [4] and health monitoring [33]. While prior works have explored earrings for wellness tracking [27, 37] these works do not investigate temperature measurement. Additionally, we demonstrate the first dangling earring design and leverage this feature to improve our temperature sensor accuracy. By integrating various sensors and communication technologies, smart jewelry enables a variety of applications for health sensing, user interaction, and information sharing.

On-ear wearable devices have seen a significant increase in popularity following the widespread sale and adoption of wireless earbuds. The ear has emerged as a compelling location for wearables [39], offering unique opportunities for health sensing [36, 43], activity tracking [5, 27, 43], and interactions [10]. Researchers have explored the potential of earbuds for detecting heart rate signals using in-ear photoplethysmography (PPG) [15, 36], in-ear pressure sensing [14, 34], and in-ear acoustic sensing [43]. Previous on-ear wearable devices focused on physiological sensing however [6, 37] are large and heavy making them impractical for daily wear and difficult to integrate as part of fashion accessories. In contrast, we specifically optimize the design of Thermal Earring for wearability by reducing the form factor to the size and weight of a typical earring, while still offering a month battery life. Additionally, our thin, flexible circuit can be easily incorporated into fashionable designs.

2.2 Human Body Temperature Monitoring

Body temperature is a crucial vital sign that can be measured or estimated using a variety of methods. Specifically, elevated core-body temperatures were found to be the primary predictive symptom for many viral infections including influenza and COVID-19 [7, 21, 22]. Although invasive techniques such as arterial catheters [25] or e-pills [30] 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 [35].

Past research has attempted to develop more accessible and ubiquitous methods of temperature sensing by incorporating temperature sensors into wearable devices [2, 6, 13, 24], utilizing thermal cameras [31, 48], or leveraging existing temperature sensors on smartphones [8]. Wrist-mounted temperature sensors have been extensively explored for core-body temperature sensing [2, 13, 24], but they have struggled to provide accurate measurements due to noisy temperature signals from the wrist. Infrared thermopile sensors mounted on headphones have been used to monitor tympanic temperature directly and longitudinally [6], 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 [31, 48]. However, these sensors are expensive and not suitable for personalized health sensing applications. In addition to dedicated hardware, researchers have developed software models that map smartphone temperature to core-body temperature when the phone is in contact with the user's head [8]. However, this method requires a dedicated interaction to make spot estimates rather than passively sensing temperature longitudinally.

3 BACKGROUND ON EARLOBE SKIN TEMPERATURE

3.1 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, ensuring relative stability despite external temperature changes. The average core body temperature for a healthy adult is around 37 °C (98.6 °F).

Skin temperature, distinct from core temperature, exhibits variability influenced by environmental temperature, core body temperature, and physiological changes. While core temperature remains at 37 °C (98.6 °F), skin temperature is lower than core temperature, fluctuating across body regions. The skin plays a vital role in thermoregulation through insulation, blood flow control (vasodilation and vasoconstriction), and sweating [50]. Vasodilation increases blood flow to the skin and aids heat dissipation, while vasoconstriction reduces blood flow to the skin and conserves core temperature. Sweating facilitates heat evaporation, cooling the skin. Overall, the skin responds to internal and external temperature changes to keep the core body temperature stable.

Moreover, recent studies suggest that skin temperature changes indicate stress, with elevated temperatures noted in facial and forehead regions during stress and decreased temperatures in finger and nose skin [20]. As a result, monitoring skin temperature changes can offer valuable insight into an individual's physiological and emotional state.

3.2 Earlobe Temperature

The human ear is one of the acral regions that help regulate body temperature. The earlobe has a large blood supply that aids in maintaining temperature balance by controlling blood vessels. As shown in Figure 2 (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. Given its proximity to the head and minimal susceptibility to motion artifacts, the earlobe serves as a promising location for temperature monitoring.

In addition, the earlobe's close proximity to the brain presents the possibility of capturing changes related to stress and emotions. Notably, emotional changes such as embarrassment, anxiety, and anger can cause the ears and face to turn red, due to the autonomic nervous system's response. This response involves 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 the ear and face [23]. Consequently, the earlobe temperature has the potential to serve as a valuable biomarker for tracking changes in emotional and physiological states.

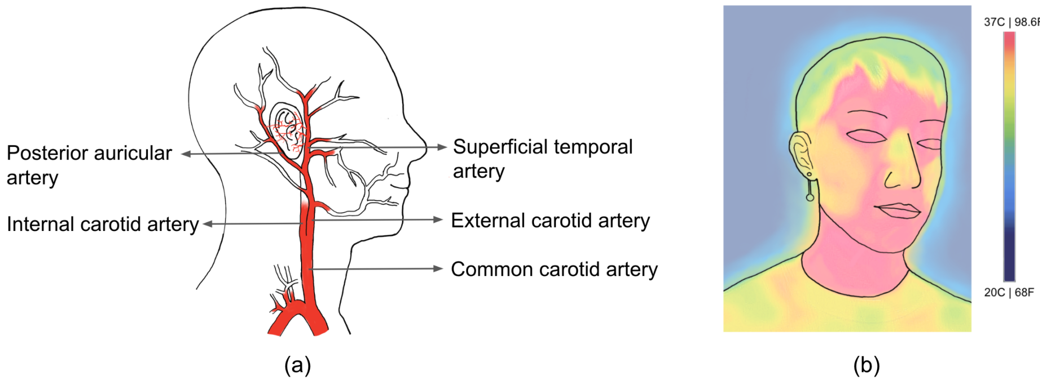


Fig. 2. (a) The blood vessels around the ear. (b) The heat distribution around the ear, head, and neck.

3.3 Dangling Temperature

To distinguish changes in the earring temperature signal due to body temperature from changes caused by environmental temperature, we add a second temperature sensor to the Thermal Earring's dangling part, 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 (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 information for detecting changes in environmental temperature, which we will evaluate and discuss further in the later Section 6.4.

3.4 User Dependence

While the body is very good at maintaining a nominal core-body temperature of 37 °C (98.6 °F), both core and skin temperature vary from user to user. Numerous factors, including but not limited to age, gender, body weight, and metabolic rate, can affect body temperature[38]. Subcutaneous fat, acting as insulation, influences skin temperature [9]. For example, women, with higher subcutaneous fat content, exhibit enhanced skin insulation compared to men [28, 50], resulting in slightly elevated skin temperatures [44], which is also reflected in our experiments.

4 THERMAL EARRING SYSTEM DESIGN

When designing a smart earring, it is crucial to consider various constraints, including size, weight, and power consumption. The earring should fit comfortably, be lightweight, and have a long battery life to avoid frequent charging or battery replacement. However, the limited battery capacity due to size and weight limitations requires careful co-design for a low-power and small-size system.

Inspired by dangling earrings, the Thermal Earring adopts a similar design. The small temperature-sensing unit is placed on the earlobe, while larger components like the microcontroller and battery are discreetly placed in the dangling part. This design ensures a compact and comfortable structure that maintains 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, microcontroller, wireless communication, and battery. We also evaluate the system's battery life and wireless performance.

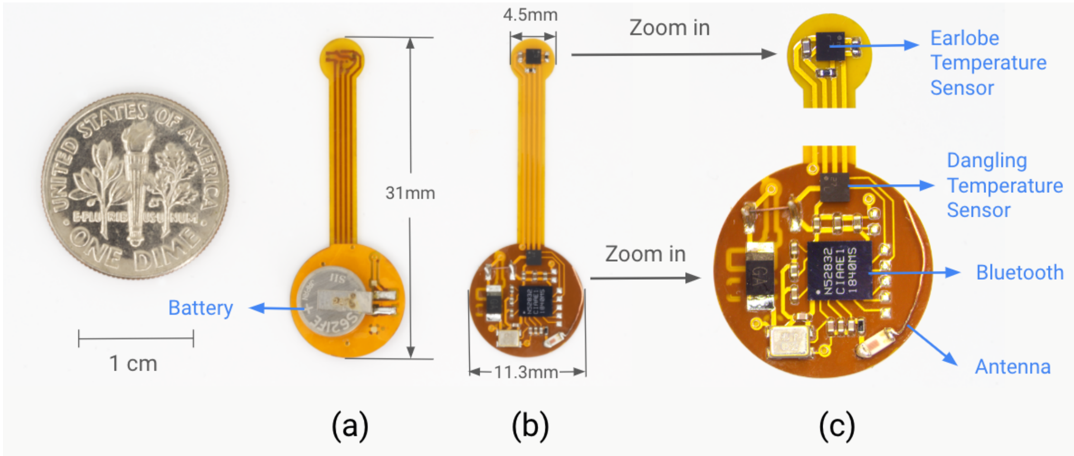


Fig. 3. The Thermal Earring system with one dime coin as reference. (a) The back side of the Thermal Earring. (b) the front side of the Thermal Earring. (c) The zoomed-in view of the Thermal Earring components.

4.1 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 × 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.

4.2 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.

4.2.1 Bluetooth Advertising. 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 time 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 limitation. Operating in advertising mode with sufficient time between packets enables the battery voltage to recover prior to 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 section 4.5.1. Overall, our approach provides an efficient way to transmit temperature data in wearable devices using Bluetooth advertising mode without draining the battery.

4.3 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. While hearing aid batteries offer higher capacities they are not rechargeable. Although MS621FE 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 transmit Bluetooth packets reliably.

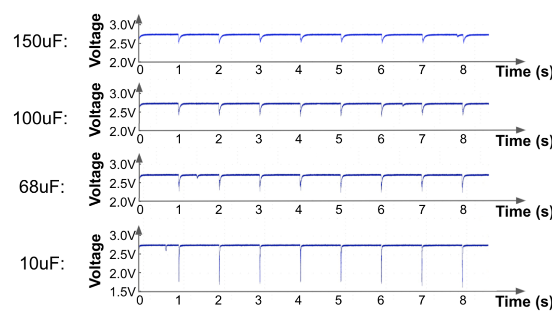
4.4 The Final Earring System

The final prototype of the Thermal Earring is shown in Figure 3. 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)[32]. It is worth noting that the dangling length of the Thermal Earring can be customized without compromising system performance. However, setting it too short may affect the accuracy of environmental temperature sensing, as it brings the dangling temperature too close to the body. 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 31 mm 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 a commercial earring (around 3 grams) [26], which allows for the integration of artistic enclosures and gemstones in future designs. In section 8.1 we also showcase an example of fashion design for the Thermal Earring.

4.5 System Evaluation

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

(a)



(b)

Fig. 4. (a) The table of average current and battery life with different Bluetooth transmitting periods. (b) The plot of battery voltage drop during transmission with four different capacitors connected in parallel.

4.5.1 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 Figure 4 (a).

The average current compromises periodic high pulses (approximately 5 mA for 400 us) during Bluetooth transmission and sleep current (approximately 2.4 uA). A lower transmission frequency reduces the instances of high current, bringing the average current closer to the sleep current. Nevertheless, even with the parallel capacitor, the system still draws up to 0.8 mA from the battery during transmission, surpassing the battery's maximum continuous discharge. The battery can still source it due to the very short duration (400 us), but it reduces the actual capacity[49], resulting in a shorter battery life than ideal.

Moreover, to assess the parallel capacitor's effectiveness and provide design insights for capacitor selection, we also demonstrate the battery's voltage change during high current pulses. Figure 4.5.1 (b) illustrates the battery voltage with four different capacitors. During Bluetooth transmission every second, the battery with larger capacitors (150 uF, 100 uF) exhibited a temporary up to 0.3V drop, which quickly recovered after the transmission was completed. Conversely, the 10uF capacitor led to a significant battery voltage drop to 1.5V, making the battery unable to recover and power the system after approximately 20 seconds. Despite better current supply, larger capacitors are larger in size and weight. After careful trade-off consideration, we chose the 100 uF capacitor (Kyocera F980G107MSA) for our final design.

Overall, the results presented in Figure 4 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. In addition, we also explored the trade-off between the parallel capacitor's performance and its size, and hope to provide design insights for future research when designing wearable systems with limited-capacity batteries.

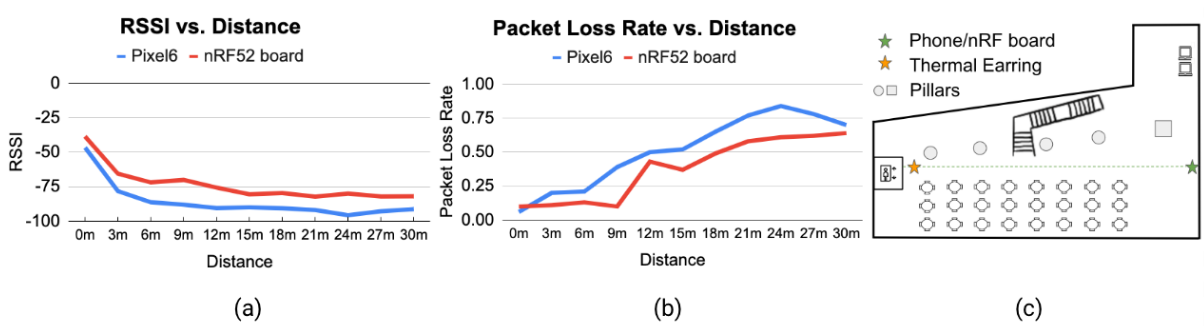


Fig. 5. (a) The Received Signal Strength Indicator (RSSI) of the Thermal Earring Bluetooth packets. (b) The Thermal Earring's Bluetooth packet loss rate using Bluetooth receiver. (c) The floor plan of the space where we conducted the experiment.

4.5.2 Wireless 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 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 5 (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.

Figure 5 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 dropped 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. The packet loss rate even at 0 meters is 0.06 and 0.10 for the Pixel phone and nRF board respectively. This is expected since 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.

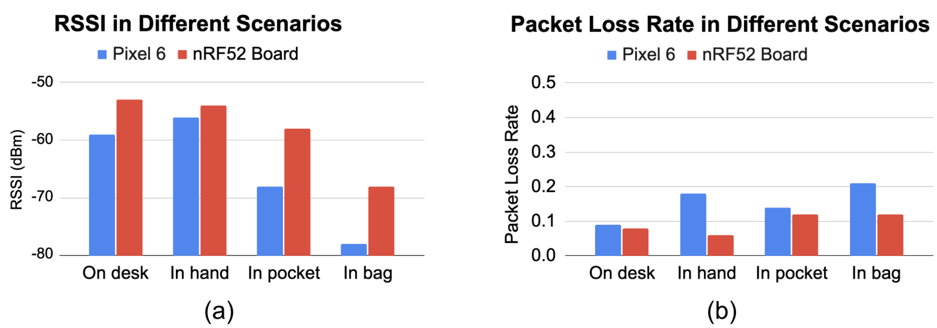


Fig. 6. (a) The Received Signal Strength Indicator (RSSI) of the Thermal Earring Bluetooth packets. (b) The Thermal Earring's Bluetooth packet loss rate using Bluetooth receiver.

4.5.3 Wireless Performance in Daily Scenarios. To assess Thermal Earring's wireless performance in real-life situations, we conducted experiments to investigate the RSSI and packet loss rate when the Bluetooth receivers (Google Pixel 6 and nRF52840 board) were positioned in various scenarios, including being placed on a desk, held in hand, kept in a pocket, or stored in a bag (backpack). Consistent with our prior wireless experiments, The Thermal Earring was worn by a user and was programmed to transmit one Bluetooth packet per second. We calculated the packet loss rate based on the number of packets received during a continuous 100-second interval.

Figure 6 shows the RSSI and packet loss rate results. Both Google Pixel 6 and nRF board had RSSI exceeding -60 dBm on the desk or in hand, and further decreased when obstructed in the pocket or bag. Google Pixel 6's packet loss rates were 0.09, 0.18, 0.14, and 0.21 for desk, hand, pocket, and bag, respectively. Higher loss when held in hand could be due to human body interference. In contrast, the nRF board consistently had lower packet loss, with highest (0.12) when in the pocket or backpack likely due to its better antenna performance. While phone antennas cannot be changed, this suggests a path to improving the link budget by improving the earring's transmit antenna. It is important to acknowledge that the experiments were conducted in a real-world office environment, with factors like desks, people moving, and other actively transmitting Bluetooth devices introducing possible interference. Additionally, it is worth noting that the loss of some data points does not significantly impact our temperature sensing applications because temperature data does not fluctuate rapidly, as discussed in Section 5.2. Overall, the experiments confirm Thermal Earring's robust wireless communication in daily scenarios, even with smartphones in pockets or bags.

5 SMARTPHONE APP AND SIGNAL PROCESSING

5.1 Smartphone App

We developed an Android smartphone application to collect the temperature data from the Thermal Earring through Bluetooth. Figure 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.

5.2 Temperature Signal Processing

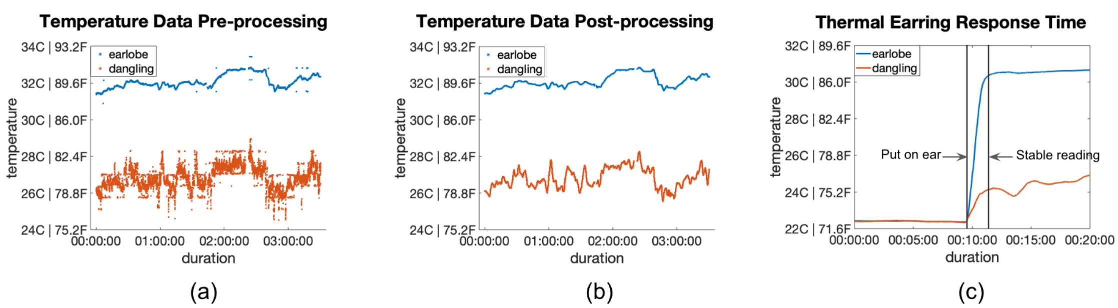


Fig. 7. (a) Example of temperature data pre-processing. (b) Example of corresponding temperature data post-processing. (c) Example recording showing Thermal Earring's response time to temperature change from indoor environment temperature to earlobe temperature.

Figure 7 (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 of time. 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 7 (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 study section 6 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.

Table 1. Table of the demographic information about the participants involved in the experiment.

Experiment	**Gender**	**Average Age**	**Race**
Fever Experiment Febrile	2 male, 3 female	39.6 ± 18.20	1 Asian, 1 Latino, 3 White
Fever Experiment Healthy	10 male, 10 female	23.55 ± 4.03	14 Asian, 1 Black, 5 White
Eating Experiment	3 male, 3 female	25.7 ± 1.6	4 Asian, 2 white
Exercising Experiment	3 male, 3 female	23.67 ± 3.01	4 Asian, 1 Black, 1 White
Ambient Change Experiment	2 male, 2 female	25.75 ± 2.06	3 Asian, 1 White

5.3 Thermal Earring Temperature Response Time

Since heat requires time to transfer from a surface to the sensing element, temperature sensors experience a delay in their response to temperature changes. We conducted an experiment to evaluate Thermal Earring's response time to obtain a reliable earlobe temperature reading. Figure 7 (c) displays an illustrative recording, depicting the Thermal Earring's data as it transitions from being placed on a desk to being worn on a user's earlobe. The Thermal Earring was moved from the desk to the user's earlobe at 00:09:30, and it attained a reliable earlobe temperature reading around 00:11:20. This result indicates that the Thermal Earring requires approximately 2 minutes to establish a reliable reading when first placed on a human earlobe.

6 REAL-WORLD EXPLORATION

In this section, we present the results of several real-world experiments conducted to investigate the effects of fever, eating, exercising, and environmental changes on earlobe temperature. All the experiments were conducted under Institutional Review Board (IRB) approval, and the participants were compensated differently depending on the experiments they were involved in. Table 1 summarizes the demographic information about the participants who were involved in each experiment. 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 to capture 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.

6.1 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, characterized by a core body temperature above nominal 37° C [22]. Clinically, fever is defined as 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.

We recruited a total of twenty-five participants, including four febrile individuals 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 with a core body temperature around 37 °C (98.6 °F). The demographic information of the participants is shown in Table 1. During the data collection process,

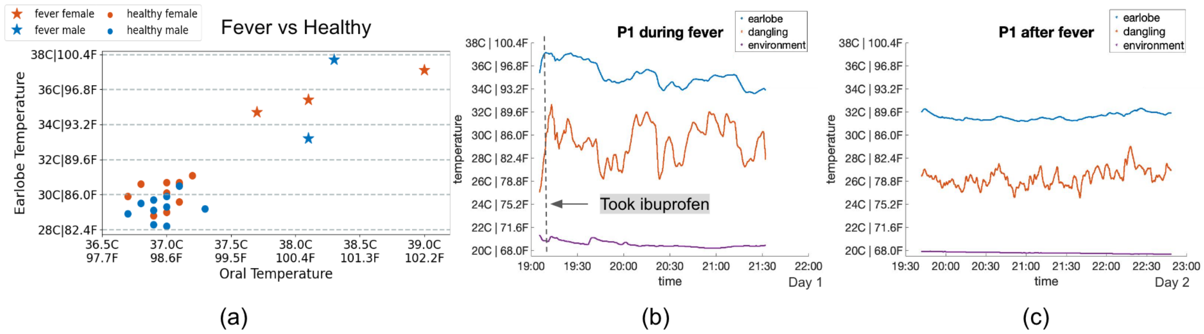


Fig. 8. (a) The Thermal Earring's earlobe temperature data on healthy and febrile people. (b) Day 1 when the participant was having a fever with an oral temperature of 39C (102.2F) at 19:10. (c) Day 2 after the fever was gone. The participant's oral temperature was 37.2C (98.96F) at 22:30.

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 8 (a) presents the results of the earlobe temperature measurements obtained from each participant. The febrile participants have an average earlobe temperature of 35.62 ± 1.8 °C (96.12 ± 3.24 °F), which is significantly higher than healthy participants' average earlobe temperature of 29.7 ± 0.74 °C (85.5 ± 1.33 °F). It was also observed that in general, healthy female participants have a higher earlobe temperature of 30.11 ± 0.78 °(86.2 ± 1.4 °F) than healthy male participants' average earlobe temperature of 29.26 ± 0.70 °C (84.67 ± 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 a participant (P1) over time during fever and after fever. Figure 8 (b) shows the Thermal Earring data of P1 during fever, including the changes observed after taking a common antipyretic to reduce fever. P1'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 move. 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 a promising 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.

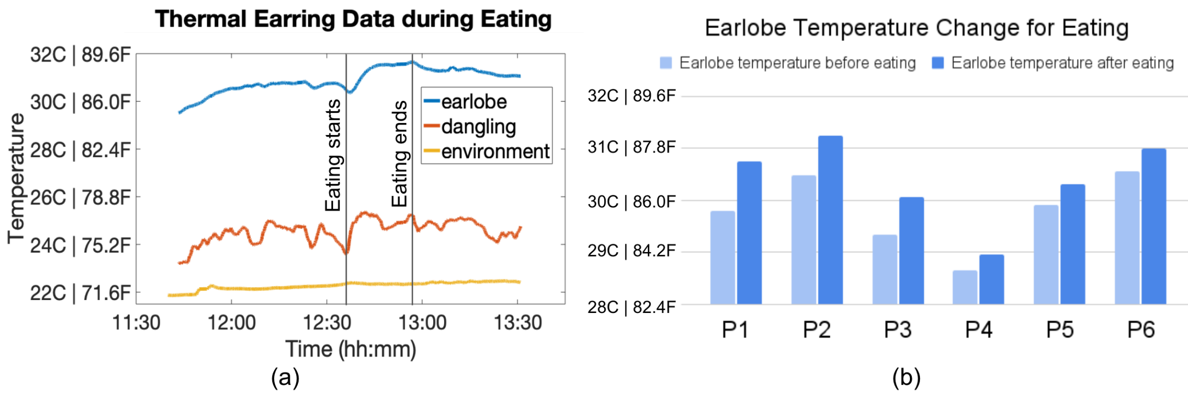


Fig. 9. The Thermal Earring temperature results for six participants during the eating study.

6.2 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, with an average age of 25.7 ± 1.6) to participate in a semi-controlled lunch setting. The study began at 11:30 a.m., with participants sitting until 12:30 p.m. to establish a resting baseline temperature. The lunch session began at approximately 12:30 p.m., with slight variations in duration across the participants. During lunch, all participants ate warm food that they chose.

Figure 9 (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 as depicted in Figure 9 (a), 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 9 (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 ± 0.25 °C (1.08 ± 0.45°F) from the pre-eating resting baseline (11:30 am to 12:30 pm) to the post-eating (12:30 p.m. to 1:30 p.m.) average temperature. Furthermore, the earlobe temperature exhibited an average rise of 1.04 ± 0.30 °C (1.87 ± 0.54 °F) from the pre-eating temperature to the maximum temperature observed after the initiation of eating. We conducted a paired t-test on the average earlobe temperature before and after eating starts. The test statistic is 5.67, and the corresponding p-value is 0.0024, which proves the earlobe temperature is very statistically different before and after eating starts. 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.

6.3 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.

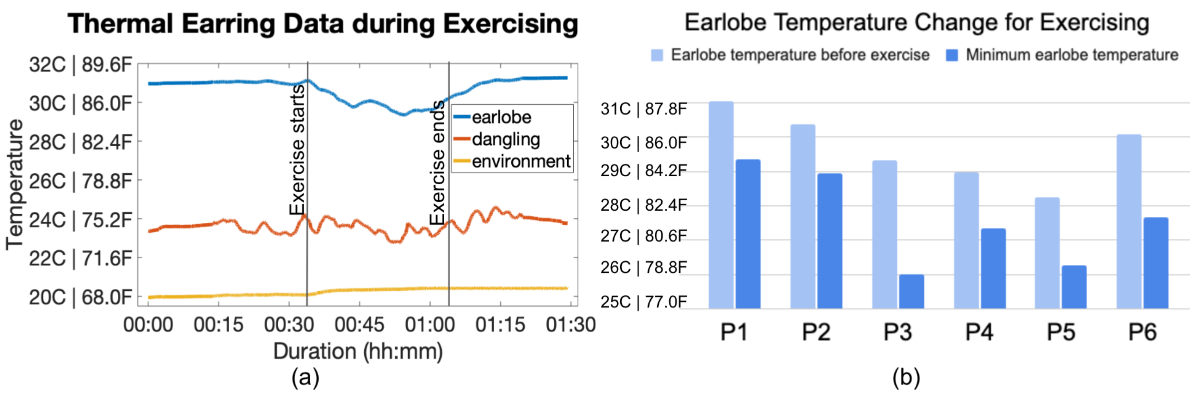


Fig. 10. The Thermal Earring temperature results for six participants during the exercise study.

The exercise experiment aimed to investigate the effect of exercise on earlobe skin temperature. We recruited six participants (three females and three males, with an average age of 23.7 ± 3.0) to complete a 30-minute cardiovascular workout (with 4-minute stretching at the end) following a YouTube video in a controlled room. Two of the six participants also participated in the previous eating experiments. 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.

Figure 10 (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 10 (b) presents the aggregated results of the six participants' average earlobe temperature before exercise and their minimal earlobe temperature during exercise. The earlobe temperature showed an average decrease of 2.08 ± 0.70 °C (3.74 ± 1.26 °F) from the pre-exercising resting baseline (duration 00:00 to 00:30) to the lowest earlobe temperature during exercise. We conducted a paired t-test on the average earlobe temperature before and during the exercise. The test statistic is 6.52, and the corresponding p-value is 0.0013, which proves the earlobe temperature is very statistically different before and during 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.

6.4 Effect of Environment Temperature Change

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, with an average age of 25.8 ± 2.1) to investigate the effects of slight indoor temperature changes. All of the four participants also participated in either the experiment for eating or exercising. Specifically, we examined the transition from a warm room to a cold room and vice versa, which are typical scenarios encountered in daily life.

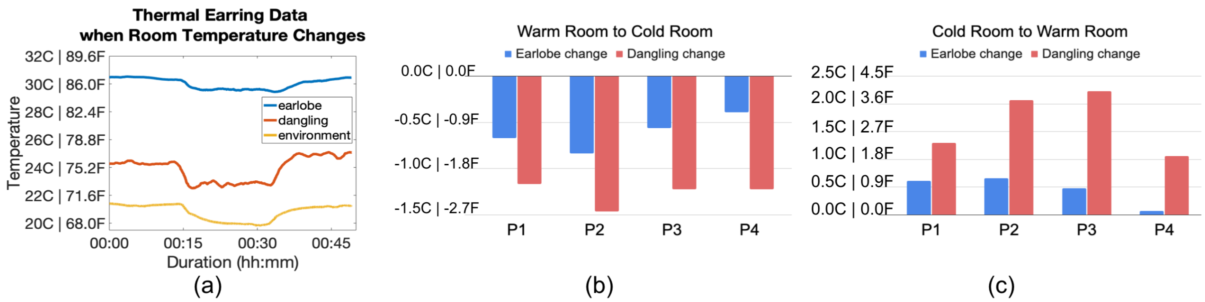


Fig. 11. The Thermal Earring temperature results when room temperature changes.

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 11 (a) presents an example of temperature data obtained from one participant during these sessions, demonstrating a consistent 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 11 (b) presents the aggregated results from the amount of change in the earlobe and dangling temperature change when entering from a warm room to a cold room. Figure 11 (c) presents the aggregated results of the amount of temperature change in the earlobe and dangling data 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 (the environment temperature decreased by 1.5 °C), the dangling temperature increased by an average of 1.60 ± 0.50 °C (2.88 ± 0.90 °F), while the earlobe temperature only increased by 0.46 ± 0.27 °C (0.83 ± 0.48 °F). Conversely, when participants entered the cold room from the warm room (environment temperature increased by 1.6 °C), the dangling temperature experienced an average decrease of 1.27 ± 0.13 °C (2.29 ± 0.23 °F), while the earlobe temperature decreased only 0.61 ± 0.19 °C (1.10 ± 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.

6.5 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 12 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 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.

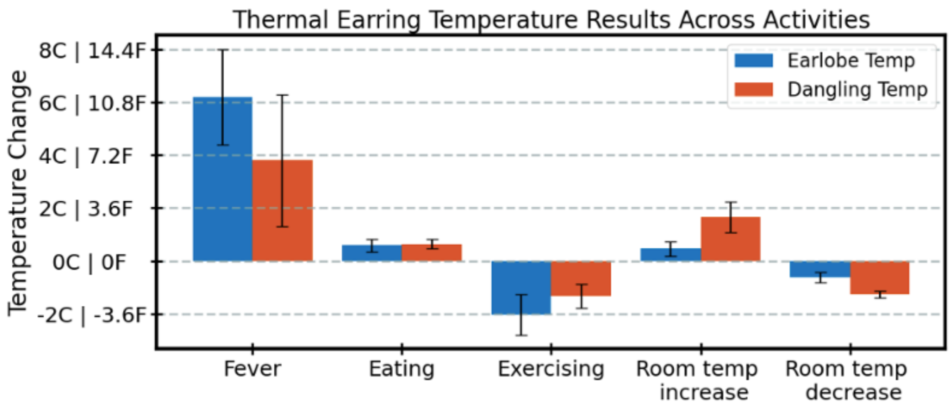


Fig. 12. The Thermal Earring temperature results across activities.

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.

7 IN-THE-WILD EXPLORATION

The Thermal Earring's compact form factor enables longitudinal temperature sensing in real-world settings. We conducted an in-the-wild exploration with six participants. The six participants are 3 male and 3 female, with an average age of 24.83 ± 2.86. The racial composition consisted of five individuals identifying as Asian and one as White. Five of the six participants have also participated in either the eating experiment or the exercising experiment in Section 6. The six participants conducted the in-the-wild experiment on different days without any overlap. We asked the participants to wear the Thermal Earring for one day in their natural daily routine. The participants were asked to remove the Thermal Earring when sleeping, taking a bath, or any time they did not want to wear it. We also requested the participants to wear an Empatica EmbracePlus smartwatch [13], which provides raw data on continuous wrist temperature every second. To gather ground truth on activities, participants were further asked to self-report their activities using the Thermal Earring Android App when they did any activity or went outside.

Figure 13 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 of time showing significant effects from ambient temperature change: 1) going outside and taking a bus, and 2) during a nap. During the napping period, both the earlobe and dangling temperature sensors were covered by a blanket which formed a warm chamber. As a result, the earlobe and dangling temperatures became almost the same and also higher than their usual values during indoor conditions. These periods can be identified by comparing the amount of dangling change with the corresponding earlobe temperature change, which we will show a heuristic detecting algorithm 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 lab-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

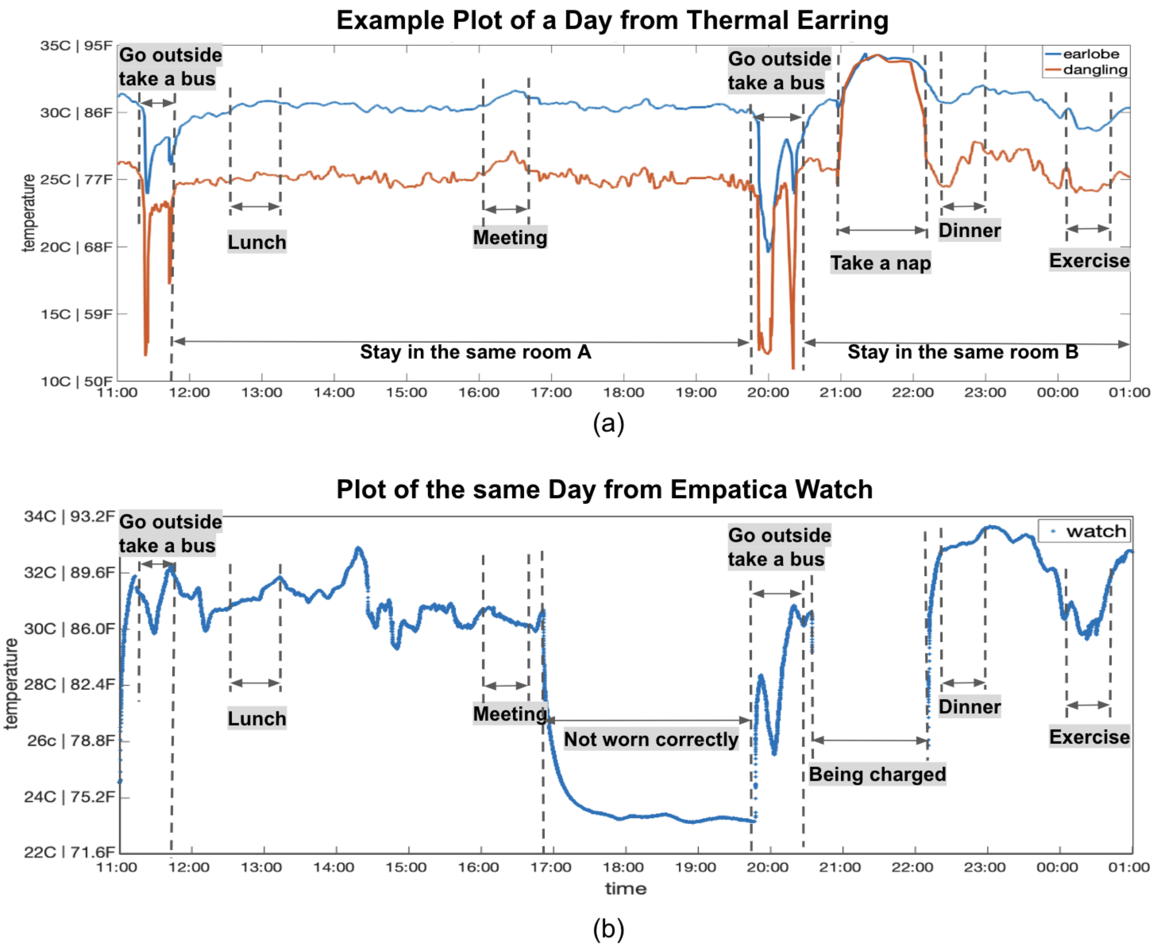


Fig. 13. An example of the Thermal Earring's data on a participant for a day: (a) from Thermal Earring, (b) from Empatica Watch.

dinner. During the exercise, the participant's earlobe temperature decreased by around 2.1 °C (3.8 °F) and then gradually recovered 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, we will present a heuristic algorithm to detect these events.

7.1 Heuristic Algorithm on Thermal Earring Data

Based on insights from this real-world data, we propose a threshold-based heuristic algorithm for activity events detection using the combined temperature data from the Thermal Earring's earlobe and dangling sensors. We will first explain this heuristic algorithm on the example participant's data, then present the heuristic algorithm results on all six participants. The algorithm consists of two stages, as illustrated in Figure 14. In the first stage (Figure 14 (a)), we identify periods when the environment's ambient temperature is rapidly changing and exclude these periods. To achieve this, we compute the temperature difference between the earlobe and dangling temperature and use an empirical threshold of ±2 °C (3.6 °F) on the computed temperature difference. This approach is guided

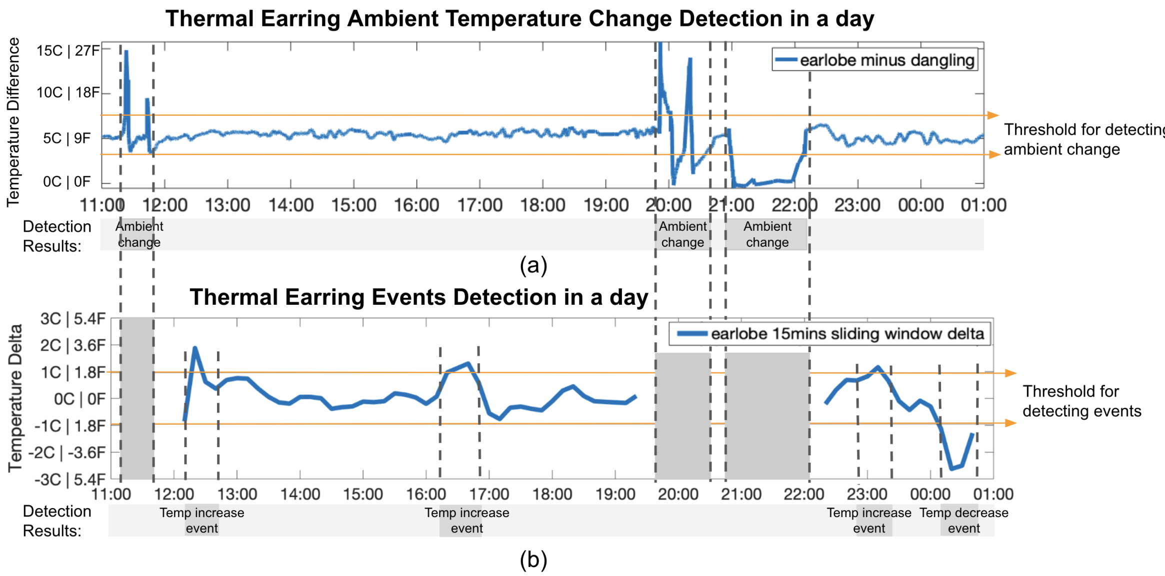


Fig. 14. (a) A heuristic ambient temperature change detection model using a threshold. The empirical threshold is applied on the earlobe temperature minus dangling temperature. (b) A heuristics event detection model using the user-specific model. The plot shows the earlobe temperature delta over time computed using the average in a 30-minute sliding window minus the average in the window 30 minutes prior. The threshold is then applied to the computed results to detect various events.

by the insights highlighted in Section 6.4, which suggests that the magnitude of the dangling temperature change exceeds that of the earlobe temperature during changes in ambient temperatures. The empirical threshold was determined leveraging the significant environment temperature change (>10 °C) observed in the experiment while ensuring it remained higher than the maximum fluctuation induced by activities like eating or exercising. This approach successfully detected all rapid ambient temperature changes for this participant shown in the example, such as when the participant transitions from indoors to outdoors. Furthermore, we merge the detected ambient temperature change events occurring within a 15-minute time frame, since the second stage of the algorithm requires a 15-minute window during a stable indoor environment. These detected periods of unstable environmental temperature were excluded from further analysis.

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 15-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 slow 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 14 (b). We then apply a threshold of ±0.96 °C (±1.7 °F) to the computed data. The threshold was determined by calculating three times the average standard deviation (0.32°C) of earlobe temperature during non-activity periods across all six users, which we will discuss in the next section 7.2. We note that future studies with larger scale datasets can explore more complex methods. In this way, we were able to detect temperature-increasing events (e.g., eating, stress) and temperature-decreasing events (e.g., exercising) throughout the day.

We employed our heuristic algorithm on the six participants, utilizing consistent window lengths and thresholds as described above. Figure 15 (a) shows the aggregated results of detecting ambient temperature change events among the six participants. Most changes were accurately identified, while two false positives were observed

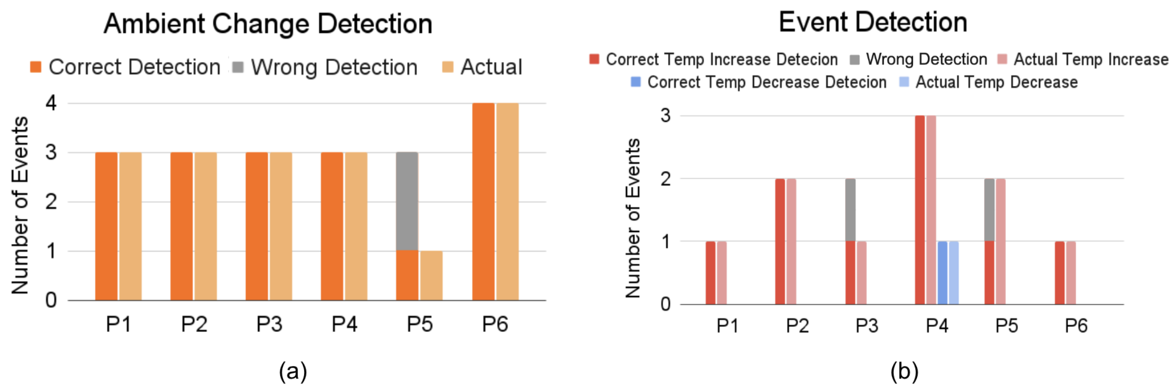


Fig. 15. (a) Heuristic algorithm results on detecting ambient temperature change. (b) (a) Heuristic algorithm result of detecting temperature-increasing events (eating and stress), and temperature-decreasing events (exercising).

in participants P3 and P5, along with one false negative in participant P5. We followed up with P5 and the participant explained that she occasionally sat on her bed covered by a blanket, potentially leading to temperature fluctuations that were attributed to the Thermal Earring errors. Figure 15 (b) shows aggregated results for detecting temperature-increasing (eating or stress) and temperature-decreasing (exercising) events across participants. Notably, only one participant exercised during the experiment, and it is possible that certain participants might not have worn the earring while eating, leading to fewer than three actual eating events per day. For P3, a distinct earlobe temperature increase lasting approximately 40 minutes, peaking at 1.8°C (3.24°F), was observed. However, no user activity log was provided for this period, potentially implying additional factors contributing to earlobe temperature changes that were not logged. For P5, there were two eating events logged, with only one being correctly detected, and the other remaining undetected. In addition, there is also a falsely detected temperature increase event for P5 where the participant self-reported as having no activity.

In summary, our results demonstrate the Thermal Earring's ability to detect temperature changes triggered by eating, stress, and exercise in dynamic real-world scenarios. However, instances of temperature increases not directly related to known events require further exploration. Furthermore, the Thermal Earring's threshold-based heuristic algorithm demonstrates limitations, occasionally miss-identifying eating-related events. It is important to note that this heuristic algorithm serves as a simple proof of concept method. The algorithm can be further improved by utilizing pattern matching on the time-series temperature data or employing a machine learning classification model. However, a more extensive dataset is required for a robust model. By integrating the heuristic algorithm with the hardware system and our exploratory experiment, we establish a foundation for future endeavors in earring-based activity recognition.

7.2 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. The watch lacked data during the napping period because it was being charged during that time.

As shown in Figure 13 (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 without any apparent correlation to the participant's provided activity labels. Thirdly,

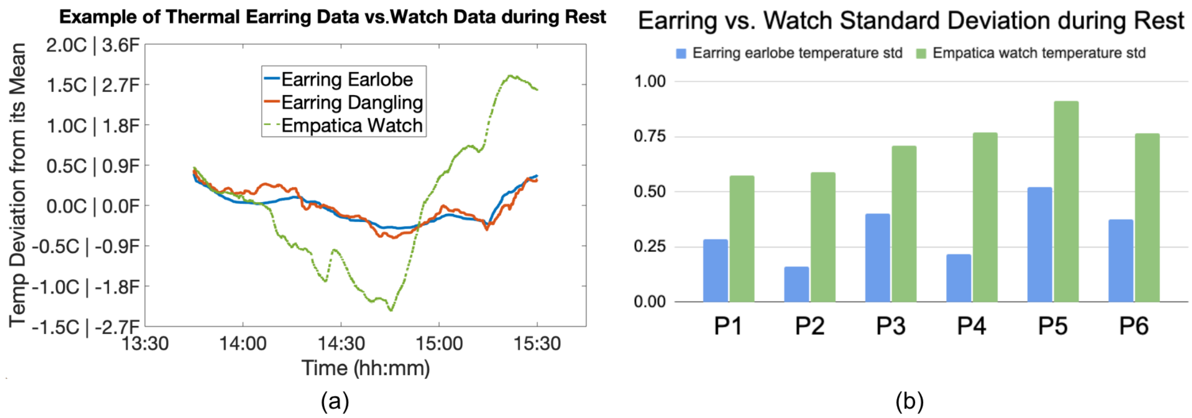


Fig. 16. Thermal Earring temperature data vs. Empatica Watch temperature data during resting time.

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.

To further analyze the noise levels of the smart watch temperature compared to the Thermal Earring's, we compared the data from the Thermal Earring and the Empatica Watch during six participants' resting periods, when no activity was recorded. Figure 16 (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 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 16 (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 smart watches. During ovulation, a woman's body temperature typically rises by approximately 0.28 to 0.56 °C (0.5 to 1.0 °F) [41]. However, smart watches 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 smart watches 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.

7.3 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 3.2.

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.

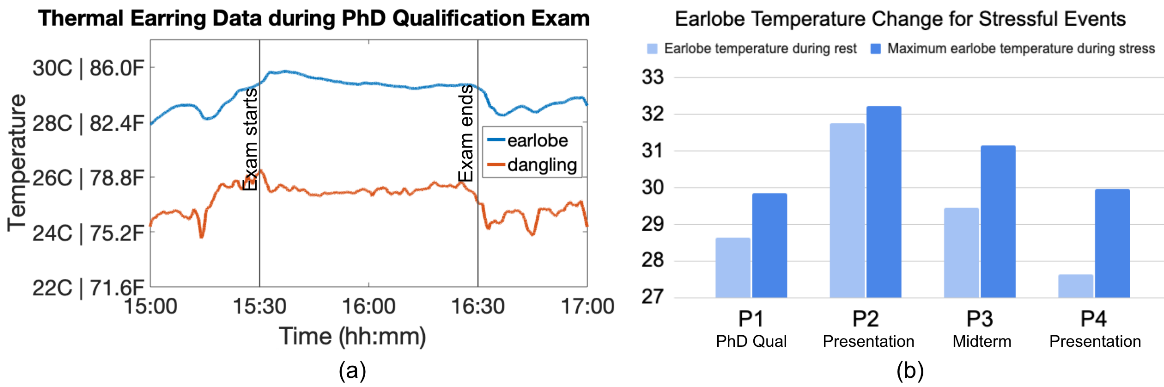


Fig. 17. The Thermal Earring temperature results from stressful events.

Besides the stressful meeting event shown in Figure 13, we extracted one more stressful event (P1 taking PhD qualification exam) from the in-the-wild experiment and further recruited three participants (P2, P3, and P4) who were known to experience potentially stressful events. The four participants are two male and two female, with an average age of 22 ± 3.65. The racial composition consisted of three individuals identifying as Asian and one as Black. For the specific stress experiment involving P2, P3, and P4, they were instructed to begin wearing the Thermal Earring at least thirty minutes before the stressful event and to continue wearing it for at least thirty minutes after the event ended.

In Figure 17 (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 four participants, with the rise in temperature slightly prior to the stressful events and a subsequent decrease at the end.

Figure 17 (b) provides the aggregated results of all participants who wore the Thermal Earring during various stressful events, including PhD qualification exam, public presentation, and midterm. An average of 1.42 ± 1.07 °C (2.56 ± 1.93 °F) increase between the average earlobe temperature during rest and the maximum earlobe temperature during stressed time demonstrated the response related to the stressors. We conducted a paired t-test on the average earlobe temperature before and during the stress. The test statistic is 3.55, and the corresponding p-value is 0.0381, which proves the earlobe temperature is very statistically different before and during stress events. Aligned with our hypothesis, these exploration results show promising potential for using the earlobe temperature as an indicator of stress or emotion-related changes. Further studies can be conducted in future work to extensively explore the relationship between earlobe temperature and stress or emotions.

8 DISCUSSION

8.1 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 fashion 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

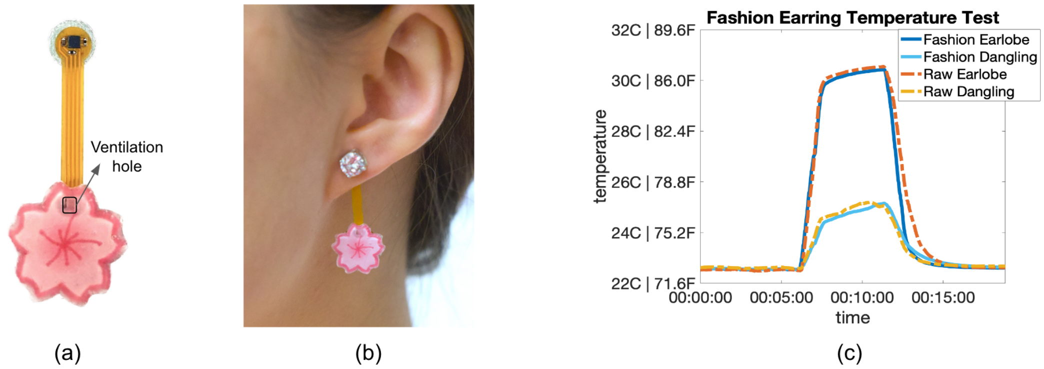


Fig. 18. An example of Thermal Earring with fashion design.

blossom earring with resin, a popular material for making earrings due to its ability to 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 18 (a) and (b) demonstrate the final design. The resin was poured into a cherry blossom-shaped silicone mold, encasing the Thermal Earring. We incorporated a ventilation hole around the dangling temperature sensor to ensure precise ambient temperature sensing. The dangling temperature sensor was covered by a piece of pink paper instead of resin. Future works could also use alternative coverings such as gas-permeable membranes in air quality sensors [11].

To validate the functionality of the Thermal Earring after integrating the resin fashion design, we conducted a comparative test. A Thermal Earring with the fashion design was placed alongside an uncovered Thermal Earring on a table for approximately seven minutes. Subsequently, they were placed on a person's left and right ear for approximately six minutes and then returned to the table. The temperature data results, shown in Figure 18 (c), prove that the Thermal Earring with the resin design performs temperature sensing as effectively as an uncovered Thermal Earring.

It is worth noting that this resin-based design represents a simple showcase of the Thermal Earring's compatibility with diverse fashion concepts. There are numerous alternative methods for incorporating fashion design into Thermal Earring. For example, techniques like welding or attaching precious metals can be explored. By employing molds of varying shapes and utilizing materials (whether resin or metal) in different colors, the Thermal earring can be personalized to various designs or styles and even incorporate gemstones like normal jewelry.

8.2 Estimating Core Body Temperature from Earlobe Temperature

While we have shown that an increase in core body temperature can be reflected in earlobe temperature measurements made by Thermal Earring in section 6.1, directly estimating the core body temperature from the earlobe temperature requires further study. It is known that skin temperature, including earlobe temperature, is affected by a number of factors beyond core body temperature such as ambient temperature, gender, age, metabolic rate, body mass index, etc. While the Thermal Earring can provide information to exclude the ambient temperature effect, resolving these other factors such as user dependence or metabolic rate remains an open challenge. We expect that with a larger and more representative data set, it would be possible to develop a model to predict user's core body temperature using their earlobe temperature and corresponding demographics. In future work, Thermal Earring may be deployed in a larger study in conjunction with other physiological sensors to build a model for computing the core body temperature from the earlobe temperature.

8.3 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.

8.4 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 [3, 16], Thermal Earring could leverage a calibration phase to identify a user's nominal earlobe temperature before making inferences.

Recent smartwatches like the Apple Watch Series 8 also feature a dual temperature sensor design that offers improved accuracy of 0.1°C. However, the components of the smartwatch are primarily confined to the skin surface or within the watch's thickness (approximately 15 mm). In contrast, the Thermal Earring's unique form factor detects environmental temperature differently, providing better isolation from body heat.

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.

Regarding eating detection, the observed earlobe temperature rise results from factors like increased metabolism during digestion, food temperature, and chewing movements. Mouth motion, inherent to eating, also occurs in other activities, e.g., talking. To further delve into the effect of mouth motion on eating events, a future experiment comparing natural speech and dedicated eating sessions could offer insights.

While the Thermal Earring signifies temperature changes, it faces challenges in distinguishing events causing temperature elevation, like eating vs. public speaking. Integrating physiological signals like heart rate in the future could enhance its ability to differentiate these events more effectively.

9 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 (with a maximum width of 11.3 mm and a length of 31 mm), lightweight (0.335 grams), and a battery life of 28 days. 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 changes in ambient environment temperature 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. Moreover, our results demonstrate significant earlobe temperature changes related to eating, exercise, and periods of acute stress. The initial exploration results provide a basis for future automatic activity detection. 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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