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Ear-Based Temperature Probing: Sensor Placement and Fusion for Wearable Applications

Master's Thesis

by

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Zusammenfassung

Aufgrund der steigenden Nachfrage im Bereich der Gesundheitsfürsorge wird die Überwachung biophysiologischer Signale des Körpers immer wichtiger. In den letzten Jahren sind zahlreiche Arbeiten in diesem Bereich entstanden, woraus sich ein neues Forschungsgebiet gebildet hat: den Wearables. Earables (am Ohr getragene Wearables) wurden aufgrund ihrer kompakten Größe, deren komfortablem Fit und der einfachen Handhabung sehr beliebt. Ihre Nähe zu den Körperöffnungen und kritischen Organen, wie dem Gehirn, bietet eine einmalige Gelegenheit für eine verlängerte Datenerfassung von Vitaldaten, einschließlich der Körpertemperatur.

Aufgrund dessen wurde die am TECO bereits verfügbare Plattform OpenEarable um sechs Temperatursensoren erweitert, welche die Temperatur an verschiedenen Positionen in und um das Ohr messen können. Daraus entsteht ein eigens in dieser Thesis erstellter Prototyp, welcher anschließend zur Datenaufzeichnung für zwei Studien verwendet wird.

In der ersten Studie wurden 12 Probanden eingesetzt, um die Temperatur, sowie deren Schwankungen an den ausgewählten Sensorpositionen zu untersuchen. Dabei wurden die Sensoren unter kontrollierten Bedingungen, sowie unter dem Einfluss externer Umweltbedingungen. Die Beobachtungen deuten darauf hin, dass die Sensoren im hinteren Bereich des Ohrs niedrigere Temperaturmesswerte liefern und im Vergleich zu den anderen Positionen eine höhere Varianz aufweisen. Wichtig ist, dass diese Abweichungen zunahmen, wenn sich die Probanden im Freien bewegten. Bei allen Sensoranordnungen wurde eine ausgeprägte Korrelation unter dem Einfluss von Umweltfaktoren beobachtet. Die zuverlässigsten Messungen wurden erzielt, wenn die Sensoren auf das Trommelfell ausgerichtet waren. Darüber hinaus wurde ein interessanter Zusammenhang zwischen der Bewegung, die durch die Signale der Inertialmesseinheit (IMU) dokumentiert wurde, und den relativen absoluten Änderungen der Temperaturwerte festgestellt.

Die zweite Studie wurde mit einer kleineren Stichprobengröße von 5 Probanden durchgeführt und war auf die Erkennung von stressbedingten thermischen Veränderungen ausgerichtet. Das Experiment ergab, dass die festgestellten Temperaturänderungen nicht ausreichend erkennbar waren, um Stress definitiv zu identifizieren. Die vorliegenden Daten legen nahe, dass zukünftige Studien mit einer größeren Stichprobengröße und dem Einsatz des Trier Social Stress Tests (TSST) für differenzierte Analysen erforderlich sind.

Diese Erkenntnisse sind besonders relevant für die Entwicklung von Wearables, welche den Fokus auf Stresserkennung oder weitere sich durch Temperatur erkennbare physiologische Zustände haben. Die Thesis schließt erfolgreich die Lücke zwischen Theorie und Praxis und liefert eine solide Grundlage für zukünftige Forschungen, einschließlich der Erkennung von zirkadianen Rhythmen, der Zykluserkennung für Frauen oder auch beispielsweise die Früherkennung von Krankheiten.

Abstract

Due to the increasing demand in the field of healthcare, the monitoring of biophysiological signals of the body is becoming more and more important. In recent years, a great deal of work has been done in this area, resulting in the formation of a new field of research: wearables. Earables (wearables worn on the ear) have become very popular due to their compact size, comfortable fit, and ease of use. Their proximity to body orifices and critical organs, such as the brain, provides a unique opportunity for prolonged data collection of vital signs, including body temperature.

Because of this, the OpenEarable platform already available at TECO has been expanded to include six temperature sensors that can measure temperature at different positions in and around the ear. This will result in a prototype created specifically in this thesis, which will subsequently be used to record data for two studies.

In the first study, 12 subjects were used to investigate the temperature, as well as its fluctuations, at the selected sensor positions. This was done under controlled conditions, as well as under the influence of external environmental conditions. Observations indicate that the sensors at the back of the ear provide lower temperature readings and have higher variance compared to the other positions. Importantly, these variances increased when subjects moved outdoors. A pronounced correlation under the influence of environmental factors was observed for all sensor arrangements. The most reliable measurements were obtained when the sensors were aligned with the tympanic membrane. In addition, an interesting correlation was found between the movement documented by the inertial measurement unit (IMU) signals and the relative absolute changes in temperature values.

The second study was conducted with a smaller sample size of 5 subjects and was focused on the detection of stress-induced thermal changes. The experiment revealed that the detected temperature changes were not sufficiently detectable to definitively identify stress. The present data suggest that future studies with a larger sample size and the use of the Trier Social Stress Test (TSST) are needed for more sophisticated analyses.

These findings are particularly relevant for the development of wearables that focus on stress detection or other temperature-detectable physiological states. The thesis successfully bridges the gap between theory and practice and provides a solid foundation for future research, including circadian rhythm detection, cycle detection for women, or even, for example, early disease detection.

Contents

1. Introduction

1.1 Motivation

With the increasing world population and the growing demand for healthcare, monitoring various biophysiological signals of the body has become more and more important. As a result of increased research and development in this field, several wearable and implantable systems have been developed [72]. The revolution began with smartphones, followed by other wearables such as watches and now includes earables. Earables have emerged as a particularly promising technology for the future of healthcare and lifestyle [112, 66]. The global earable market size was valued in 2022 at around USD 58 million and is expected to rise by another 12.6% until 2030 [47]. Most wearables are equipped with various sensors, which are intended to replace a modern medical laboratory through analysis [72].

Capturing data using earables has become very popular due to their compact size, their comfortable fit, their easy reachability by hands and their ability to capture lots of physiological data of the human body [102]. The fact that they are very close to the body, especially on a body opening, and can be worn over a long period of time without any issues is a huge advantage compared to other positions to capture such data. Furthermore, many earables are designed to be discrete, making them a practical option for individuals who want to monitor their health without drawing attention to themselves. Earables are located near the brain and the major blood vessels on the head and neck. They can be worn in or around the ears capturing a variety of biometric data to revolutionize the way our health such as heart rate, oxygen saturation and body temperature is monitored and understood.

An important aspect of sensing data with earables is the ability to detect changes in body temperature [37, 22, 1]. Earables equipped with temperature sensors can provide accurate measurements of body temperature throughout the day, which can be used to track patterns and identify potential health issues [99]. By monitoring core body temperature over time, individuals can gain valuable information about their health and physiological state, allowing for early identification of potential issues [85]. For example, core body temperature can be an important indicator of fever as well as infection or inflammation. Monitoring this data can provide early insights and enable rapid treatment steps [1]. Furthermore, core body temperature can also be used to classify the circadian rhythm of the body [69, 60]. This controls many physiological processes, revealing possible disturbances when core body temperature is measured continuously. Athletic performance can also be monitored using core body temperature [20]. Temperature can indicate changes in the body's thermoregulatory system that can affect the performance and increase the risk of heat illness [42, 107]. Hormonal changes also affect core body temperature. These can, for example, trigger fluctuations in body temperature due to changes in estrogen levels during the menstrual cycle. By constantly monitoring body temperature, hormonal changes can be detected and their effects studied [48, 29, 53]. In addition, core body temperature monitoring can be useful in diagnosing and treating various medical conditions such as hypothermia, hyperthermia and sepsis [54, 52, 100]. Overall, continuous core body temperature monitoring can provide valuable insight into a person's health and physiological state and has many potential applications in clinical and research settings.

The ear canal is a promising location for body temperature measurement because it provides a stable and easily accessible measurement location [38]. In addition, this location is less susceptible to body movement [51, 62]. In the ear canal, the tympanic membrane is located. The tympanic is supplied with blood by the branches of the internal carotid artery, which supply blood to the thermoregulation center in the hypothalamus of the brain [83]. Therefore, the ear provides high potential in measuring body temperature.

Nevertheless, the sensor placement and measurement methodology for ear-based temperature monitoring is still an open research question. The optimal position for temperature measurement on the ear is quite obvious: the tympanic membrane [31, 65, 86]. However, it is not easy to align the infrared sensor with the tympanic membrane. In addition, influencing factors such as earwax can affect the measurement results. This raises the question of how measurement results differ at different measurement points on and in the ear, and whether various characteristics, activities, or health features can also be detected via other sensor positions. Another question is how temperature measurements at the ear behave when not performed under controlled conditions in the laboratory. For example, one could ask how great the influence of motion artifacts is. With additional sensors, e.g., an IMU, it would be possible to detect motion and integrate this knowledge into the erroneous temperature measurement and possibly correct it.

1.2 Problem

Recent research studies have revealed various problems in measuring temperature in the ear. Discrepancies in temperature-based measurement in the ear have been reported due to factors such as sensor location, skin contact and calibration [104, 45, 2, 56, 25]. The main problem is that the accuracy and reliability of ear temperature measurements can be affected by several factors [45]. Measuring temperature at the tympanic membrane is quite complicated to set up since the temperature sensor in the ear canal must be properly aligned [2, 45]. Due to the wide variety of ear canal shapes of different individuals, this cannot always be guaranteed. In addition, influencing factors such as earwax can affect the path to the tympanic membrane and thus also the temperature measurement as well as all the advantages of measuring the temperature there [45].

1.3 Question

This master's thesis examines temperature sensors, each placed at different locations in and around the ear canal, and compares the sensor measurements to those of a medically certified thermometer (BRAUN Thermoscan 7), which is the ground truth here. The research goal is to compare different positions for temperature measurement in and around the ear and how this affects the accuracy and stability of the measurements. Additionally, it will be interesting to see if other sensor information can be used to filter potential errors and optimize results. This includes, for example, an IMU signal. The resulting location of the measurement is then used as a basis for detecting a temperature-dependent event of the body and evaluating whether this provides conclusive results. The temperature dependent event is stress in this thesis. Stress activates the sympathetic nervous system by activating the fight-or-flight mode. This leads to increased heart rate, increased blood flow, and thus increased body temperature, which should be detected by the sensors. Various metrics such as mean square deviation and correlation are used to measure the accuracy and stability of the measurements.

In particular, it is unclear how different measurement positions affect measurement accuracy and reliability. To address these issues, several hypotheses are tested. In addition, it is conceivable that other signals such as IMU could be used to detect measurement errors, sports activities or the like. Several metrics are used to evaluate the accuracy and reliability of ear temperature measurements, such as mean square deviation and correlation. With our studies, we hope to contribute to improving the accuracy and reliability of ear temperature measurements and thus contribute to medical diagnostics.

1.4 Planned Approach

In order to position the temperature sensors at the selected positions and to record the temperature values with them, a prototype is built for this master thesis. Subsequently, two studies will be conducted, the first of which will look at and compare the positions and the second of which will compare the temperature behavior under stress at the different sensor positions.

The OpenEarable platform is used as a basis, which makes it possible to attach various temperature sensors to the ear canal in an uncomplicated manner. The sensors are placed at various locations, including the concha, inside the ear canal, at a location facing the tympanic membrane, and behind the concha. The exact locations can be explored in Figure 1.1. Two circuit boards will be designed for this purpose, furthermore a case for comfortable wearing during the study. Participants will be asked to wear the sensors in a study under similar conditions on the right ear. The resulting data will be collected and then analyzed to compare sensor positions for ear-based temperature measurement. These positions will then be used to classify body stress induced in the second study based on body temperature. To gain additional insights, it is planned to perform temperature measurements during

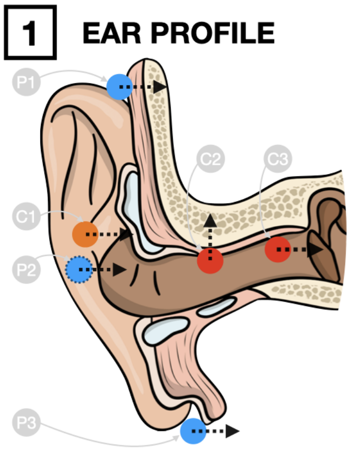

Figure 1.1: Here the temperature measurement points are shown visually from different angles (profile view (1), ear from behind (2), ear from the side (3)). $P1$-$P3$ are three measuring points behind the ear, which measure the skin temperature at the mastoid. $C1$ is a measuring point that measures the temperature at the concha. $C2$ and $C3$ measure the temperature in the ear canal, where $C3$ is directed at the tympanic membrane and $C2$ is directed at the edge of the ear canal. The arrows at each measuring point show the measuring direction. In addition, a measuring point is outlined with a dashed line if it is located behind the ear. The sensor used is the MLX90632, which is an infrared temperature sensor. This is connected to the OpenEarable and the sensor values can be received and persisted using the I2C protocol.

different activities in a first study to see how the measurements behave in different situations. In addition, it is planned to conduct a second study to observe the temperature readings at the different sensor locations under stress. This results in two independent studies from which the following hypotheses emerge:

Study 1

H1: The temperature measured by sensors located behind the ear is lower compared to the other locations.

H2: The variance in temperature readings differs between indoor and outdoor settings.

H3: Relative changes in temperature readings across different sensor locations will be interrelated.

H4: The temperature at the tympanic membrane has the greatest stability compared to other sensor locations.

H5: Subject movement leads to significant changes in the temperature readings across various sensor locations.

Study 2

H1: A measurable rise in temperature occurs during stress-inducing activities.

H2: There will be variability in temperature changes across different types of stress tests.

1.5 Expected Results

The study is expected to provide insights into the placement of sensors for temperature monitoring in or directly on the ear. Possible variations in temperature measurements at different positions in the ear canal will be identified to adequately detect temperature at the ear in everyday situations. The results will support the development of more accurate and reliable wearable devices for biometric applications. In addition, the optimally determined position will serve as a new basis for the analysis of various body temperature changing events. The second study, which is being conducted as part of this work, will demonstrate small-scale temperature increases under stress and provide preliminary findings.

2. Background & Related Work

This chapter first introduces important aspects of body temperature and then continues with sensing with earables. For body temperature, a distinction is made between core body temperature and skin temperature. In addition, the focus is on how temperature can be measured. In the subchapter on sensing with earables, the recording of data on the ear is generally introduced. Here, a division of Röddiger [102] is explained.

2.1 Body Temperature

In medical practice, temperature is one of the most frequently measured physical quantities. By measuring temperature, one gains information about the internal energy of an object. From the biophysical point of view, temperature measurement determines the changes in physical quantities that occur in a thermodynamic system [36]. Temperature can be expressed in different scales. These include Celsius, Fahrenheit, Kelvin and Rankine [50]. The human body temperature range is usually between 36.5-37.5$°C$ [57], varies constantly and depends on many influencing factors such as gender, age, time of day and many others [110]. Likewise, the state of consciousness and emotions are a decisive factor that significantly influences the body temperature [9]. Furthermore, the position at which body temperature is measured is crucial [97]. In order to keep the body temperature within the normal temperature range through internal and external factors, the body uses thermoregulation, through which the temperature is constantly adjusted by signals from the central nervous system.

2.1.1 Thermal Regulation

A vital body function is the possibility of regulation of the exchange of body heat [50]. Regulation occurs through a neural feedback system. In many body parts, sensory means detect cold and heat, and transmit them via the central nervous system to the hypothalamus, reacting to potential temperature adjustments by triggering physiological activity. This can be associated with a gain or loss of heat, which maintains body temperature. Major players in regulating body temperature are the cardiovascular system, the sudomotor control system and skeletal muscles. The goal is to maintain body temperature within the range of $35°C$ to $41°C$ [98]. An excessive increase in body temperature (hyperthermia or hyperpyrexia), in which temperature regulation is no longer working, must be treated as a medical emergency. The same applies if the body temperature drops below $35°C$.

2.1.2 Core Body Temperature

Core body temperature is the temperature of the body's internal organs, such as the heart, liver and brain. It is a commonly used indicator of human health and endurance performance. Unlike the core body temperature, the body surface temperature is more easily influenced by the ambient temperature and therefore cannot reflect the changes inside the body as well as the core body temperature. Core body temperature can be measured invasively rectally, orally (oesophagus), in the pulmonary artery (with the use of a catheter) or in the urinary bladder [83]. However, the gold standard is different. The core body temperature of a healthy human body differs almost little from the temperature of the blood flowing in the pulmonary artery [67, 55]. This is exactly what is used as the gold standard for measuring core body temperature [67, 55, 41, 79]. However, this comes with a few critical points. Measuring the temperature of the blood flowing in the pulmonary artery involves an invasive and risky procedure that requires the insertion of a pulmonary artery catheter [116]. This is strongly recommended in a medical hospital and nowhere else. All of the previously mentioned methods are not comfortable for humans when measuring over a long period of time in everyday life.

Body temperature can also be measured non-invasive. The following methods are much more convenient, but the measurement accuracy suffers somewhat. Measuring the body temperature non-invasive can be done on the axilla, the tympanic membrane and the body surface [83]. Usually, core body temperature is constant only in the core body and consequently cannot be determined outside only by temperature sensors [91]. Due to this, it is necessary to use several other values for the calculation of the core body temperature in order to approximate the true temperature value. These can include, e.g., skin temperature and skin heat fluxes or the heart rate. Niedermann achieved a root mean square deviation (rmsd) ranging from $0.28°C$ to $0.34°C$ for all environmental conditions in 2014 [91]. Therefore, a principal component analysis (PCA) was performed to extract uncorrelated variables that were subsequently used in a linear regression model. Six parameters, consisting of three skin temperatures, two skin heat currents and heart rate, were selected as input variables to generate two principal components. The predictive power of these components for estimating core body temperature was evaluated using multiple regression analysis.

2.1.3 Skin Temperature

Skin temperature is often used to measure body temperature. In general, it is the result of a dynamic equilibrium between the heat released during metabolic processes and transferred to the skin layer by thermal conduction and convection, the heat extracted from the environment and the heat transferred to the environment by radiation, convection and evaporation [36]. Various sensors are used to measure skin temperature. These include the infrared sensors, but also the thermistors. Both are equal for purposes of clinical electrodiagnostic readings. Thermistors offer better responsiveness and sensitivity in measurements. Infrared thermistors, on the other hand, are more convenient in terms of speed and maneuverability [24]. As the skin is exposed to external influences, temperature differences can quickly occur. This can be caused by cold or warm ambient air, but also by rain or other influences. Measurements on the skin that cannot be easily influenced, such as the armpits, are suitable here.

2.1.4 Temperature Measurements

In general, the temperature of a human body will be measured with a thermometer. There are multiple techniques available based on which the temperature value will be calculated. They are divided into contact and non-contact thermometers. For a detailed overview, take a look at Chapters **??** and **??**. Body temperature is often measured in the armpit, mouth, rectum, ear or forehead. The temperature in the armpit is typically $36.6°C$, in the mouth $36.9°C$ and $37.1°C$ in the ear [36]. The rectal temperature testing method is the most accurate of all measurements, while non-contact forehead thermometers are considered the least accurate. Measurements taken with them should be confirmed by other methods. The minimum value of the standard error for the above methods is $0.1°C$ [9]. Ear readings are assumed to be of similar accuracy compared to the rectal method, which is most commonly used for infants. The value for ear based measurement readings is usually $37.1°C$ [36].

Ear-based temperature measurement uses a sensor to measure the temperature of the ear canal. The approach has a number of advantages over other measurement positions. First, it is a non-invasive measurement procedure, which allows measurement nearly inside the body with the least amount of hematoma. Second, the measurement is much more promising compared to other non-invasive alternatives, where many factors can contribute to falsify the final result [43, 33]. However, it is essential to note that the accuracy of temperature measurement may depend on factors such as the positioning of the thermometer and the presence of earwax or other obstructions in the ear canal.

The tympanic membrane is a thin membrane that separates the middle ear from the external auditory canal. The artery called the external carotid artery runs near the external auditory canal and radiates heat, which is why measuring the temperature at the tympanic membrane has a promising chance of determining body temperature [116].

Since measuring body temperature at the tympanic membrane is a non-invasive measurement method, it is already being investigated as a possible replacement for currently accepted methods. This could be a safe and very convenient way of measuring core body temperature, but to date it is not de-facto due to unresolved problems. These include the accuracy and stability compared to measurements at other locations [79, 41, 86, 105]. Benzinger first demonstrated the feasibility of tympanic membrane measurement as an indicator of core body temperature using a thermocouple temperature probe that engages the surface of the tympanic membrane with the ear canal sealed from the environment [14, 13, 15]. For this, Benzinger made measurements of the tympanic membrane temperature with his probe and measurement approach and showed them to be stable, reproducible and responsive to thermal stresses of various types. However, there are other studies at a later date

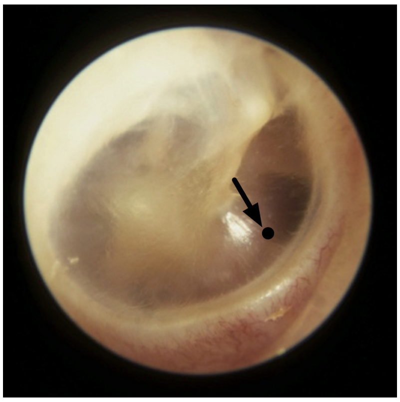

Figure 2.1: Measuring point on the tympanic membrane [23]. Tympanic membrane of the right ear with a temperature measuring point in the lower front quarter (see arrow).

that refute individual assumptions of this study. McCaffrey et al. [80] and Nielsen [92] showed that head cooling reduces the core body temperature when measured exactly with the procedure of Benzinger. McCaffrey et al., however, also showed that by heating and cooling localized regions of the head, infrared measurement of the temperature at the tympanic membrane of human subjects was not proportionally affected by changes in head skin temperature. This suggests a contradiction, which means that this method may not be a good predictor of core body temperature because it depends on other, as yet unknown, variables. Brinnel and Cabanac [23] and Sato et al. [106], however, provided data showing that measurements for this purpose are still reliable if the measurement point on the tympanic membrane is carefully chosen. Brinnel and Cabanac proposed that the lower anterior quarter of the tympanic membrane (Figure 2.1) has a higher temperature on the surface of the tympanic membrane and temperature measurement from a point in this area is the least sensitive to head cooling.

Temperature sensors are used to measure the temperature of a particular object or environment. They are widely used in many applications, such as industrial, medical or scientific contexts. Temperature sensors detect changes in temperature and convert this into a measurable signal. There are various types of temperature sensors, including contact and non-contact sensors. Contact sensors measure temperature by maintaining physical contact with an object and measuring the temperature there. Contact sensors can be divided into three types: Thermocouples, Thermistors and Resistance Temperature Detectors (RTDs). Thermocouples measure the voltage generated by two different metals when they are exposed to different temperatures. RTDs measure changes in the electrical resistance of a metal wire when it has temperature changes. Thermistors are semiconductor devices whose electrical resistance changes with temperature. Non-contact sensors, on the other hand, do not require contact with the object being measured. Non-contact sensors are divided into infrared thermometers, pyrometers, thermography, and acoustic pyrometers. Infrared thermometers measure the infrared radiation from a surface, while pyrometers measure radiation over a specific wavelength range. Thermography uses a thermal imaging camera to create a temperature map. Acoustic pyrometers measure temperature by using the velocity of sound waves in a medium. Most often, the sensors are used when contact with an object is not desirable or practical, as is often the case in medical or scientific research, for example. This is also the case in this work, since contact with the tympanic membrane, for example, is not desired. When selecting the right sensor for a particular application, a number of things need to be considered. Accuracy, response time and range are important variables. Depending on the requirement profile, the right sensor can be selected based on the parameters. In the following, the infrared sensor will be described in more detail, as this is the sensor used in this work.

2.1.5 Infrared Sensors

Infrared temperature sensors measure the temperature of an object by detecting the emitted infrared radiation. The sensor contains a thermopile, an array of thermocouples that absorbs the incoming infrared radiation. Through the Seebeck effect, the thermopile generates a voltage proportional to the temperature difference between the absorbing "hot" side and a "cold" reference side. This voltage is now amplified and converted into a digital signal, from which the temperature is subsequently calculated. Calibration factors and the ambient temperature are also taken into account here. An important factor for the accuracy of the measurement is the emissivity of the target object, as well as the wavelength range for which the sensor is sensitive. The emissivity depends on the type of object to be measured. The emissivity, or emission factor, is a dimensionless quantity between 0 and 1 that indicates how efficiently a material emits thermal energy in the form of infrared radiation. The emissivity defines the ratio to ideal blackbody radiation. Human skin is a relatively good emitter of infrared radiation, which is an advantage when measuring fever. The factor here is 0.98. Some sensors also measure the ambient temperature to adjust the final calculation. Infrared sensors have the advantage of non-contact measurement, making them ideal for applications where the object being measured is moving or difficult to access. However, they also have disadvantages, such as some sensitivity to external conditions such as smoke or fog. In addition, the accuracy of the measurement can be affected by the emissivity of the target material. Since the target material in this thesis is limited to the skin, this is an ideal sensor for measuring temperature at different positions of the ear.

2.1.5.1 MLX

The MLX90632 sensor is an infrared thermopile temperature sensor. Temperature without requiring contact with the skin is measured. This is done by means of an infrared sensor. The sensor is based on a microelectromechanical system (MEMS), which is used to detect thermal radiation in the infrared spectrum emitted by the object to be measured [81]. The MLX90632 has a small form factor and low power consumption, which is well-suited for small devices. In addition, the sensor has a very high accuracy of $\pm 0.2°C$ from $35°C$ to $42°C$. In the range of $-20°C$ to $100°C$ the sensor reaches an accuracy of $\pm 1°C$. Here the sensor can resolve in $0.02°C$ steps. In order to be able to integrate the sensor optimally into a system, an I2C interface is available so that a microcontroller can communicate easily. Overall, the MLX90632 sensor provides a versatile and accurate solution for non-contact temperature measurement in a variety of applications, including medical, industrial and consumer electronics.

2.1.6 Stress and Its Effects on Body Temperature

This section is intended to provide a scientific basis for later studies on the detection of stress by measuring temperature at the ear. To this end, the relationship between stress and body temperature will be explained in order to later test whether stress can be detected by changes in body temperature. Stress is a physiological and psychological response to challenging tasks or threatening situations [58]. Stressors can be acute or chronic. An acute stressor (e.g., a near-accident with a car) triggers a stress response directly, but the stress subsides immediately after the event. A chronic stressor, on the other hand, lasts over a longer period of time. This includes, for example, financial problems or persistent illness. Here, there are no quick fixes and the problems are not quickly forgotten [12]. Stress can have positive and negative effects. On the one hand, stress can make you rise above yourself in dicey situations. On the other hand, it can have a negative impact on mental and physical health if the stress is excessive or lasts for a long time [58]. In this context, prolonged stress can cause, for example, digestive and gastrointestinal problems, hypertension, diabetes, cardiovascular disease, bone mineral loss, immune suppression and asthma [82, 35, 95].

Stress activates the body's fight-or-flight mechanism, which leads to various physiological changes, including an increase in body temperature [74]. This chapter focuses on the effects of stress on body temperature. The goal is to provide the scientific basis for a study of stress detection through temperature measurements at the ear. The human body's response to stress is complex and involves multiple systems, including the endocrine system, the nervous system and the immune system [58]. One of the immediate physiological responses to stress is hyperthermia, a transient increase in core body temperature [113]. This phenomenon is part of the body's acute stress response, often referred to as the fight or flight response [113]. The increase in body temperature during stress has already been demonstrated in several studies. In a study by Nakata in 2021, a passive heat stress test resulted in an increase in the internal temperature of about 1.2°C and impaired cognitive function [89]. This study suggests that heat stress may have a significant impact on neuronal activity related to cognitive function. In another study, stress was inflicted on subjects using the Trier Social Stress Test (TSST) [113]. In this study, subjects had to perform a 5-minute interview with a preparation time of three minutes in front of a panel with a microphone. Additionally, mental arithmetic tasks were performed afterwards. Subjects were informed at the beginning that everything would be videotaped. In this study, an increase in heart rate, in skin temperature and in respiratory rate, among others, were noted. This is caused by the aforementioned fight-or-flight system, which is the activation of the sympathetic nervous system. When stressed, this system turns on and releases adrenaline and other hormones that prepare the body to respond to a threat [59]. Among other things, these hormones cause an increase in metabolic rate, which leads to an increase in body temperature [49].

In summary, this chapter has laid out the scientific basis for the relationship between stress and body temperature, which will provide the foundation for future research on stress detection through ear-based temperature measurements. The complexity of the human body's response to stress, involving multiple physiological systems, underscores the potential of temperature as a reliable biomarker for stress detection. The present studies demonstrate that both acute and chronic stress can lead to measurable changes in body temperature mediated by activation of the sympathetic nervous system and release of specific hormones.

2.2 Sensing with Earables

Earables belong to the class of wearables and are a type of wearable device that is worn in or around the ears. They typically have a number of sensors that allow them to collect data about the wearer's physiology and activity. The most common sensors in earables include accelerometers, gyroscopes and heart rate monitors. These sensors can be used to track the wearer's movements, monitor their heart rate and provide other types of health data. Earables are portable, lightweight and small, which allows them to be worn easily for long periods of the day [102]. Thus, data can be tracked over a longer period of time. In addition, earables have the advantage of being worn on the ear, which together with the head are automatically stabilized during movements and thus have less motion disturbances and artifacts [51, 62]. The position on the ear provides a lot of potential. For one thing, the ear is very close to the brain and blood vessels, which allows accurate measurement of brain activity, cyclic blood flow and related properties [39]. In addition, it is possible to detect the perception of a variety of facial, neck and eye muscle activations [3] as well as the input of head movements [3], facial gestures [78], mouth movements [109] and instantaneous [19, 96]. Due to the ease of accessibility [64, 115], interactions in the ear can be used to trigger actions [71]. In summary, earables are capable of triggering a variety of processes in the skeleton (e.g., gait [4]), muscles (e.g., facial expressions [78]), nerves (e.g., brain activity [34]), endocrine system (e.g., emotions [7]), cardiovascular system (e.g., blood pressure [6]), respiratory system (e.g., breathing [103]) and digestive system (e.g., food intake [44]).

In 2022, Röddiger et al. noted the current state of research on sensing with earables [102]. A systematic literature review of 271 peer-reviewed research articles was made receiving a better understanding of the current state of research on this topic. The research area was divided there into four categories (Figure 2.2), which will now be explained in more detail.

2.2.1 Physiological Monitoring and Health

The first categorical classification of sensing with earables is physiological parameters and health [102]. The use of ear-worn sensors to track and maintain personal health by monitoring various physiological parameters is considered. The parameters are categorized according to human body functions such as the cardio-respiratory system, nervous system, thermoregulation, mental status and health monitoring. The cardio-respiratory system is divided into the areas of heart rate, blood oxygen saturation, respiration and blood pressure. All these areas can be classified, for example, with a PPG (photoplethysmography). When determining the heart rate, a microphone, an accelerometer, an infrared thermometer, a piezoelectric or an EEG (electrocardiography) can be used. The nervous system includes the classification of brain activity, sleep or drowsiness. All can be determined using an EEG. When classifying sleep, an infrared thermometer can also be used. The most researched area in the context of earables is brain activity. The third subcategory in the area of physiological parameters and health represents the mental state. This has not

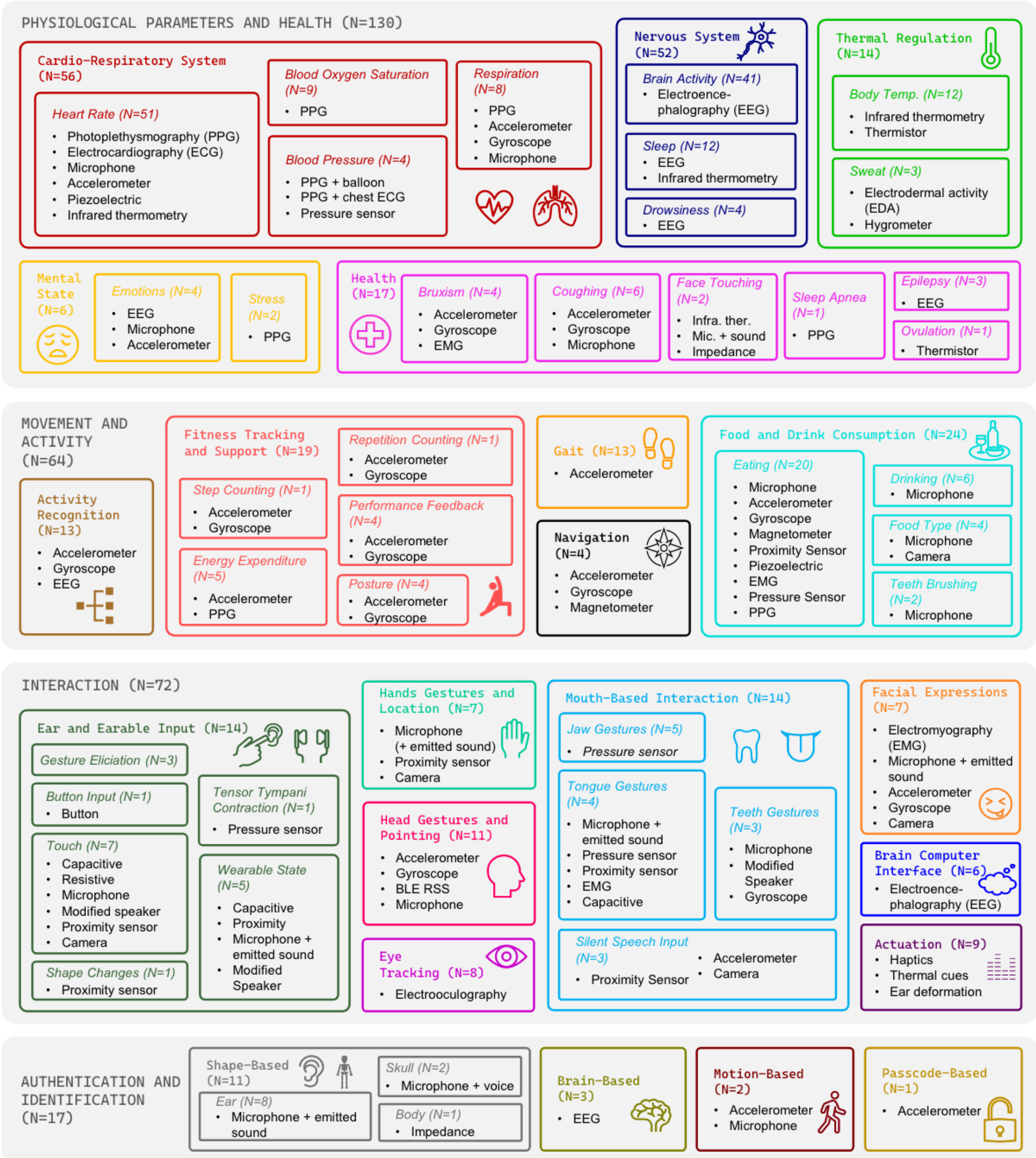

Figure 2.2: Overview map of sensing with earables. The map displays all phenomena current research is about divided into the main four categories. For each phenomena, there is a number (N), which describes the available articles and all the used sensors used to detect these phenomena are listed [102].

yet been researched that far in the context of earables with only six reference papers. Emotions can be recognized using an EEG, a microphone or an accelerometer, and even stress using a PPG. Another subcategory is health, which is divided into bruxism, coughing, face touching, sleep apnea, epilepsy and ovulation. Sensors such as an accelerometer, a gyroscope, a microphone, an EEG, a PPG or an infrared thermometer are used here. For further details, please refer to the original paper [102]. The last part of physiological parameters and health is thermal regulation. Here, a distinction is made between body temperature and perspiration. An EDA (electrodermal activity) and a hygrometer are used for sweating. When classifying body temperature, an infrared thermometer and a thermistor are used. Due to body temperature being the most crucial part of this thesis, this part will now be focused in more detail.

Body Temperature

Bestbier and Fourie applied the principle to a wearable form factor and achieved a small mean error of only $0.02 \pm 0.52°C$ [16]. They used the TMP006 infrared sensor, which points directly at the tympanic membrane. The thermophilic voltage and the temperature sensor were made digitally available via hardware registers from which the object temperature can be calculated. This reflects the temperature of the tympanic membrane after calibration. However, the accuracy varies greatly between individual positions, which is attributed to the orientation of the sensor due to a wide variety of auditory canals. This problem was solved by implementing intra-participant calibration. This should allow the sensor to self-calibrate automatically and improve the standard error by 56% (from $0.5125°C$ to $0.29°C$) and the correlation coefficient from 0.4667 to 0.8684.

However, user-defined calibration is needed because the shape of the ear canal is different for each individual [16, 73, 77]. Luken et al. integrated TI's TMP007 into the proposed measurement system to obtain information about human core temperature variation at a rate of $33Hz$ [73]. For individual calibration purposes, the voltage difference of the thermopile element and the chip temperature was transmitted in addition to the recorded object temperature. However, the temperature was not further calibrated or processed in this work [73]. Alternatively, surface skin temperature at the mastoid can be determined with high accuracy ($0.03°C$ mean error) [5]. A known factor for changes in body temperature is considered in earable research to be the response to external weather conditions [10, 20, 27] and during physical activities [20, 28, 27, 77, 108]. These findings enable a number of applications that perform some important functions, such as alerting or vital signs and parameter tracking based on the identified relationships.

2.2.2 Movement and Activity

Another categorical classification of sensing with earables is movement and activity [102]. Here, the focus is on detecting user movements and deriving insights about activities performed by the user. Movements detected at the ear can be classified into discrete classes, such as a user's posture, their movement and also the type of activity. Beyond simply classifying sensor data, the project also explored how physical quantities can be derived from the user's movement to provide useful information for a variety of applications, including fitness tracking, gait analysis, food and beverage consumption and inertial navigation. Most of the findings are recorded with the accelerometer and the gyroscope. Activity recognition is done with it, but also with an EEG. Accelerometers and gyroscopes are also used as a basis for fitness tracking and support subcategory and the EEG for sensor performance. When measuring the gait, the signal from the accelerometer is sufficient. Significantly more sensors are used for classification when eating. While only one microphone signal was used for the drinking detection, a series of signals is used for the eating detection. Here, the microphone, accelerometer, gyroscope, magnetometer, proximity sensor, piezoelectric, EMG, pressure sensor and also the PPG is used. When brushing teeth is detected, a microphone signal is evaluated. In addition, the accelerometer and gyroscope signal as well as a magnetometer are also used for navigation.

2.2.3 Interaction

Interaction is another categorical classification of sensing with earables [102]. Since earables have a lot of different sensors, there are exciting possibilities for unique and novel interactions. So far, attempts have been made to recognize inputs on the ear, but also inputs on other parts of the body can be recognized by sensors on the ear. Subfields of interaction include ear or earable input, hand gestures or hand position, head gestures or orientations, eye tracking, mouth-based tracking, facial expressions, brain-computer interface and actuation. The most common tracking techniques are pressure or proximity sensors, accelerometer and gyroscope, the microphone and EEG and EMG. There are various input options for the ear-based or earable-based input. These include button inputs, touch or shape changes and others. Mouth-based interactions can be divided into jaw activities, tongue gestures, tooth activities and silent speech input.

2.2.4 Authentication and Identification

The final categorical classification of sensing with earables is authentication and identification [102]. For secure access to sensitive data, mobile devices often use biometrics such as fingerprints. Earable technologies have explored biometric authentication based on the unique ear, skull or body features as well as brain activity and body movement. Passcode-based authentication methods that use rhythmic patterns have also been proposed. The two main approaches are verification and identification, where performance is often measured using an equal error rate (ERR) to balance false acceptance and false rejection rates. In this categorical classification, the microphone and emitted sound are used as the basis for shape-based authentication and identification at the ear as well as the microphone, voice at the skull and impedance at the body. The EEG is the basis for recognition in brain activity-based authentication and identification. For authentication and identification by individual motion, accelerometer and the microphone are used. If password-protected authentication takes place, the accelerometer signal is also used.

2.2.5 Sensing Platforms

Ear-based sensing platforms have gained considerable attention in the wearable technology field due to their potential for multiple applications and benefits. This chapter examines different types of ear-based sensor platforms, discusses their technical aspects and characteristics, captures their application and examines the challenges and future directions in this field.

One type of ear-based sensor platform is the in-ear sensor, in which sensors are placed directly in the ear canal. Examples of in-ear sensors are earphones with integrated sensors that can monitor various physiological parameters [76, 16, 73]. Another type is the on-ear sensor, which is placed on the outer ear or earlobe. These sensors can be in the form of clip-on devices or wearable ear accessories to collect specific data.

Behind-the-ear sensors represent another category of ear-based sensor platforms [96, 46, 18]. These sensors are positioned behind the ear and are often found in hearing aids or smart ear tags. Finally, there are ear-worn wearables, which are wearable devices designed to be worn on the ear [18, 46]. These include smart earbuds or earbuds that have sensors to monitor various health and activity-related metrics.

Technical aspects and features play a critical role in ear-based sensor platforms. Sensor technologies vary by platform and each has its own advantages and limitations. Connectivity and data transfer methods are essential for seamless integration with other devices or networks [94]. Power management strategies are used to optimize battery life and ensure the longer use of ear-based sensor platforms [90]. Ear-based sensor platforms find applications in various fields. In the area of health and wellness monitoring, these platforms enable the tracking of vital signs such as heart rate and body temperature [103, 5, 76, 99]. They also facilitate the monitoring of sleep quality, stress levels and other health-related parameters [73, 114]. In human-computer interaction, ear-based sensor platforms can serve as input modalities for gesture recognition or control interfaces, making them suitable for augmented reality, virtual reality and gaming environments. In addition, ear-based biometrics are being explored for biometric identification and secure authentication purposes, offering an alternative to traditional authentication methods [102].

Despite the potential benefits, ear-based sensor platforms face certain challenges. These include ensuring the accuracy and reliability of measurements, addressing convenience and usability concerns as well as addressing privacy and data security issues [21, 103, 22, 45, 2, 38, 28]. Future research and development efforts will focus on overcoming these challenges, exploring new applications and advancing the capabilities of ear-based sensor platforms. In summary, ear-based sensor platforms have emerged as promising tools in wearable technology. They offer a range of applications, from health monitoring to human-computer interaction to biometric authentication. By leveraging the unique properties of the ear, these platforms provide valuable insights and contribute to the advancement of wearable technology as a whole.

Earables: Temperature Measurement

The research area of ear based temperature probing is not a new territory. As early as 2010, infared tympanic thermometers (IRTTs) were used to compare temperature at the tympanic membrane with a rectal and oral sample [8, 11, 17, 40, 32, 61, 87, 84, 68, 63]. However, the tympanic membrane is not the only relevant measurement point in previous work.

In 2018, Atallah et. al attached sensing devices to the mastoid to measure temperature [5]. According to Atallah, skin temperature is easy to measure there, which is significantly different elsewhere on the body. Skin temperature differs by as much as $2°C$ depending on the body position measured. Atallah et. al placed three sensors on the lower area behind the ear, which was used to measure the heat flow for temperature. In addition, the three sensors help to detect and eliminate potential measurement errors. In this work, an 18 series thermistor from Murata was used to measure temperature.

Already in 2016 Nakada et. al have developed a method to also measure temperature at the outer ear canal [88]. Here, different positions on the external ear canal were measured to determine the temperature of the esophagus. The results showed that the temperature differed by about 1-$2°C$ from the comparative measurements at the tympanic membrane. In addition, the variation in measurements at the external auditory canal is also significantly larger than the variation in measurements at the tympanic membrane ($\pm 0.78 - 2.82°C$) [88]. This is explained by the ambient temperature and other radiations. With increasing ambient temperature and reduced radiation, the difference from the comparison measurement and also the fluctuations could be minimized. However, the most commonly used measurement point on the ear for temperature is the tympanic membrane. The advantages of measuring temperature at the tympanic membrane have already been explained in Chapter 2.1.4.

Already in 2013, Boano et. al used the tympanic membrane to measure temperature with an ear-based wearable [20]. Here, the progression of temperature during a marathon run was tracked. The advantage for the runner is that knowing their temperature can help them perform better, get fewer injuries and also reduce the risk of heart attacks. The design was one of the biggest issues here, as the orientation of the sensor needs to be robust against strong physical movements. In addition, there are constantly changing climatic conditions during a run that can potentially have a strong impact on the results. A waiting period of at least 20 minutes was observed before the run to reduce fluctuations and erroneous readings [28]. During the measurement, there was an initial drop in temperature at the beginning of the run, then an increase in body temperature, as also initially expected. The drop was explained by the wind conditions there. In addition, there was a considerable data loss during the marathon, which together with the cold outside temperatures led to massive influences. In the end, this resulted in few dependencies among the test subjects. The temperature conditions that prevailed on site. After the end of the run, the temperature dropped back to normal. In addition to the temperature observation of the marathon run, the temperature was also observed over a whole day [20]. Body temperature is significantly lower at night than during the day, even with nearly $1°C$ difference at peak. Other increases in temperature were detected during eating (about $0.4°C$) and when the outside temperature was $0°C$ during walking.

Another work measuring the temperature at the tympanic membrane is from Bestbier in 2018 [16]. Bestbier has developed a wearable that uses a self-built device on the ear to measure temperature with an infrared sensor (TMP006) pointed at the tympanic membrane. The rest of the components were attached to a headband, such as the battery and also the computing units. Accuracy varies significantly from person to person due to different ear canals. However, Bestbier has solved this with an in-person calibration by having the sensor self-calibrate. This improves the standard error by 56% from $0.5125°C$ to $0.29°C$. The interclass correlation coefficient (ICC) also improves from 0.4667 to 0.8684. Lueken designed an earplug in 2017 that also measures temperature using an infrared sensor on the tympanic membrane [73]. In addition to temperature, ACC and PPG were also measured. However, the ACC signal was used to optimize the PPG signal rather than the temperature signal. This is to make the signal resistant to head motion. Lueken integrated TI's TMP007 into his system to obtain information about variations in human core temperature. Here, the temperature was recorded at $33Hz$. For individual calibration purposes, the voltage difference between the thermopile element and the chip temperature was recorded in addition to the acquired object temperature.

In another study in 2018, Chaglla E. et. al looked at developing a novel sensor to measure core body temperature [28]. The sensor is based on a graphene-inked infrared thermopile sensor positioned on the tympanic membrane. The graphene coating on the active surface of the sensor improves sensitivity and performance. The measurement principle is based on the acquisition of electrical signals from the sensor. Two different studies were conducted in this regard. In addition to a laboratory study, a field study with physical activity was also conducted. In the laboratory study, seated and resting test subjects were examined for a period of 10 minutes with 60 seconds rest using a total of four different devices. The in-house device with the graphene-inked thermopile sensor and an infrared drum thermometer (IRTT) ThermoScan 7 Age Precision-IRT6520 (Braun GmbH, Kronberg, Germany) were referenced. In the field study, a 26-year-old man was examined during activity on a cross-trainer in an outdoor gym. The measurements lasted 25 minutes and took place on a cloudy day at a temperature of $21°C$. Additionally, the temperature information of the cross trainer was recorded as well, the Cosinuss One (Cosinuss GmbH, Munich, Germany) was used for this purpose. The results showed that the graphene-inked thermopile sensor measurements provided better results than the Cosinuss One [28]. The latter seemed to be more sensitive to external parameters. It was noted that the sensors were very comfortable during wear. Additionally, it was observed that the sensors required a calibration period at the beginning and provided relevant measurement results after about 8 minutes. However, in the laboratory study, the measurements were taken only for a period of 10 minutes.

In another work in 2020, the temperature at the ear was also measured [30]. Here, an infrared sensor recorded the temperature. The focus of this work was to design a wearable device that can be worn over a longer period of time. The focus was on size, weight and battery life. An app was developed to transfer the data. The ground truth was a conventional thermometer on the ear. During activities, the results were $0.15°C$ below those of ground truth, but the presence of sweat explains this. The range of error was $\pm 0.16°C$. The correlation was 0.9438 and the average accuracy was 99%.

OpenEarable Platform

The OpenEarable serves as the core sensing platform for this thesis. It is an open source hardware and software platform for the development of multisensory audible devices, originally introduced by Röddiger et al. in 2021 [101]. The OpenEarable was developed at Karlsruhe Institute of Technology (KIT) and enables rapid prototyping and exploration of novel earable applications. It was not developed as a finished product, but serves as a platform for future projects.

The OpenEarable hardware design is based on the Arduino Nano33 BLE, which includes the Bluetooth SoC nRF52840 from Nordic Semiconductor. This chip integrates a 32-bit ARM Cortex M4F processor with 256 KB of RAM and supports Bluetooth 5.4 connectivity. For audio detection, the OpenEarable features high-performance STMicroelectronics LSM6DSRTR low-power digital microphone. This enables high dynamic range audio sampling up to 44 kHz. Motion and orientation tracking is provided by the 9-axis inertial measurement unit (IMU), which combines a 3-axis gyroscope, a 3-axis accelerometer and a 3-axis magnetometer. In addition, a push button and a controllable LED are built into the circuit board. Besides the main circuit board, an earpiece has also been designed. This features an ear canal pressure and temperature sensor, an inward-facing ultrasonic microphone and a speaker. However, the earpiece was not used in the context of this master thesis. Finally, a rechargeable 90 mAh lithium-ion polymer battery powers the platform. This combination of sensors enables the OpenEarable device to collect and analyze audio, motion, environmental and biometric data in real time. The nRF52840 SoC also provides sufficient processing capabilities for integrated machine learning inferencing. Multiple peripherals can be connected via the available GPIOs and I2C bus. An integrated microSD card slot enables storage and buffering of sensor data. By building on the OpenEarable hardware and software architecture, the development time to create a custom multimodal ear sensing device can be dramatically reduced compared to designing a new platform from scratch.

OpenEarable can be used for a variety of applications, such as health monitoring, authentication, identification and human-computer interaction. The platform is still under development, but has the potential to be used for a wide range of applications. OpenEarable's capabilities for rapid prototyping, flexible extension and sensor fusion were key enablers for the research presented in this paper.

3. Design and Analysis

This master's thesis aims to compare different positions on the ear for measuring body temperature. For this purpose, a prototype was developed that allows temperature measurements at different positions in and around the ear. Studies were then conducted to collect temperature data at different locations in and around the ear, then temperature changes under stress were observed. The data collected from both studies were then analyzed and evaluated. This chapter first focuses on the OpenEarable platform, which is the cornerstone of the prototype. Next, the sensors critical to temperature measurement are discussed. After laying the groundwork for understanding the prototype, the development and approach to designing the prototype are explained. In addition, the methodology and process of the two studies are described in detail. The results of the studies are presented in Chapter 5.

3.1 Platform: OpenEarable

In Chapter 2.2.5, the OpenEarable platform is thoroughly introduced, emphasizing its interaction with other components. The OpenEarable was designed for rapid prototyping and exploration of novel earable applications. This thesis successfully utilized it as the foundation for the prototype. Figure 3.2 illustrates the seamless collaboration between all components. The OpenEarable uses an Arduino Nano 33 BLE and enables the use of Arduino-based software. It connects to the PCB and FlexPCB via a 4-pin connector. The developed software collects data from the temperature sensors and effectively utilizes the resources of the OpenEarable. In addition, the IMU data already available on the OpenEarable is read out. The study data is permanently stored on the SD card and the termination of the study is triggered by a double click on a push button. In summary, the OpenEarable platform proved to be a versatile and effective foundation for the prototype, allowing seamless interaction between its components and facilitating data collection from the temperature sensors. By leveraging Arduino-based features and user-friendly design, OpenEarable was successfully used in this study to explore novel earable applications and conduct the user study easily and efficiently.

3.2 Sensors

Based on research and experience at the TECO Institute, the MLX90632 sensor was selected for its suitability for the project.

The MLX90632 sensor is an infrared temperature sensor known for its high accuracy in temperature measurements. This enables reliable applications where precise temperature tracking is needed. Furthermore, non-contact temperature measurement is a huge advantage. The MLX90632 can measure temperature without physical contact with the object or body part, providing a non-invasive and convenient ear temperature monitoring option. In order to place the temperature sensors in the necessary locations to measure temperature, the sensors must be appropriately small. Since the MLX90632 has a small form factor (3x3mm), this is optimal for the application needed. Additionally, the MLX90632 is readily available on the market and has existing Arduino libraries. This availability and compatibility with Arduino simplify the integration process and save valuable development time. In addition, the sensor is designed for low power consumption, making it suitable for battery-powered devices. Given the small battery size in the developed prototype, low power consumption is critical for extended operation during the study. The MLX90632 offers fast response times and allows for real-time temperature monitoring and fast updates. Some difficulties arose when writing the EEPROM, so the default value was left at 2Hz. The measurement rate was adjusted due to implementation details of the library, because the library waits the time until a new measurement value arrives. Since this failed, the library was modified. This process is described in more detail in Chapter 4. The high sensitivity to temperature changes allows the MLX90632 to accurately detect even minor variations. This sensitivity is advantageous for precise temperature tracking. In addition, the sensor has applications in both the consumer and industrial markets due to its accuracy and reliability. This versatility makes it an excellent choice for this master's thesis project, which involves working with an Arduino Nano 33 BLE.

The MLX90632 has 4 pins that must be connected. Beside 3.3V and Ground the MLX90632 has a SCL and SDA connector. SCL stands for the clock signal and SDA for the data flow.

Overall, infrared temperature sensing capabilities, accuracy, easy availability, non-invasive measurement, compact size and compatibility with Arduino make the MLX90632 an ideal choice for developing an ear temperature monitoring system.

3.3 Prototype

To measure the temperature as planned in Section 1.4, a custom-built prototype was developed as part of this master's thesis. The prototype consists of two components: an earpiece that resembles an in-ear headphone and a component placed behind the ear that resembles a hearing aid. TECO's OpenEarable platform for ear-based observations is integrated into the behind-the-ear component. This component serves as the central interface and houses the Arduino on which all code is executed. Additionally, a circuit board with three temperature sensors is connected to measure the temperature behind the ear. The second component is placed in the ear and is also controlled by the OpenEarable via the Arduino Nano33 BLE installed there.

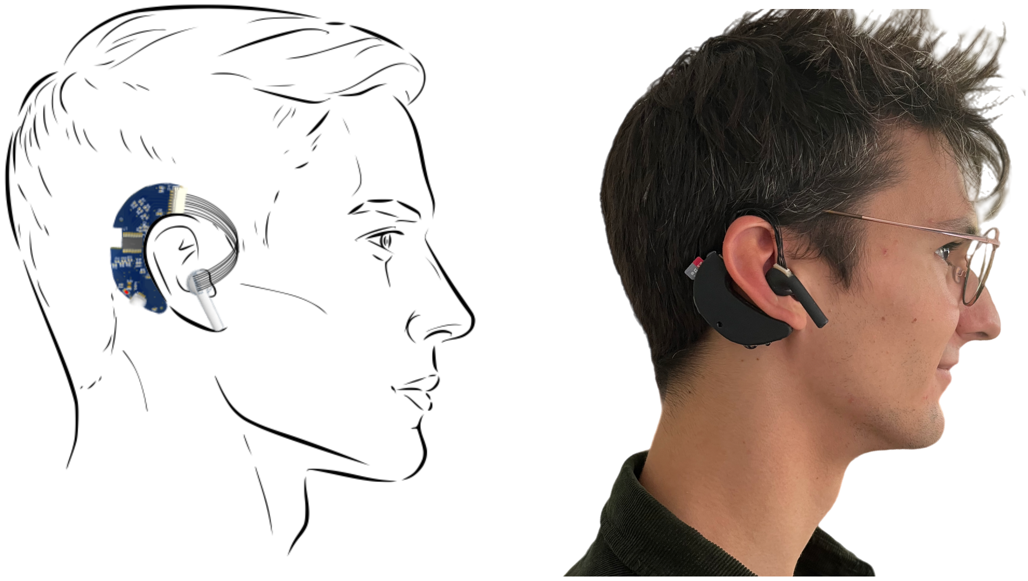

Figure 3.1: Sketched view while carrying the components, next to it a real view. The PCB behind the ear measures in three positions (bottom, middle, top) and is connected via an 8-pin connector to the FlexPCB, which is already wrapped in the case here in the right picture. In the ear is the second component, which is used to measure at the concha, the ear canal and the tympanic membrane. The wiring of the two components results in good stability when worn, so that the device cannot fall off.

The OpenEarable acts as the basis for reading and storing data from the sensors connected via I2C. The relationship and interaction of the components are visually represented in Figure 3.2. To ensure functionality and protection of the hardware, custom 3D-printed enclosures were created for both the behind-the-ear component and the in-the-ear component. Figure 3.1 shows the final result, worn by a participant and also visually demonstrates the positioning of the components. As shown in Figure 3.1, the custom cases add durability and a high-end appearance to the product, improving its overall usability and aesthetics. The use of the 8-pin cable effectively connects the two components, additionally ensuring good comfort and fit.

3.3.1 Temperature Measurements Behind the Ear

The temperature behind the ear is measured at three positions, as can be seen in Figure 3.3 on the back of the PCB and conceptually in Figure 1.1. To position the temperature sensors at the locations chosen in Section 1.4, a PCB was developed that has the sensors installed at the appropriate locations. The PCB has been designed so that only the temperature sensors are placed on the back. This allows the PCB to be placed entirely in the bottom of the case, while the temperature sensors peek out through matching openings in the case. On the front of the PCB are all the other components, including a 4-pin connector and an 8-pin connector. The 4-pin connector is used to connect to the OpenEarable. This connection allows the OpenEarable to communicate with the PCB via I2C, as the OpenEarable also has a special 4-pin connector for exactly such a purpose. To be able to control the second component (the earpiece) via I2C later on as well, the 8-pin connector was added to establish a connection to the second component. Via I2C, the built-in

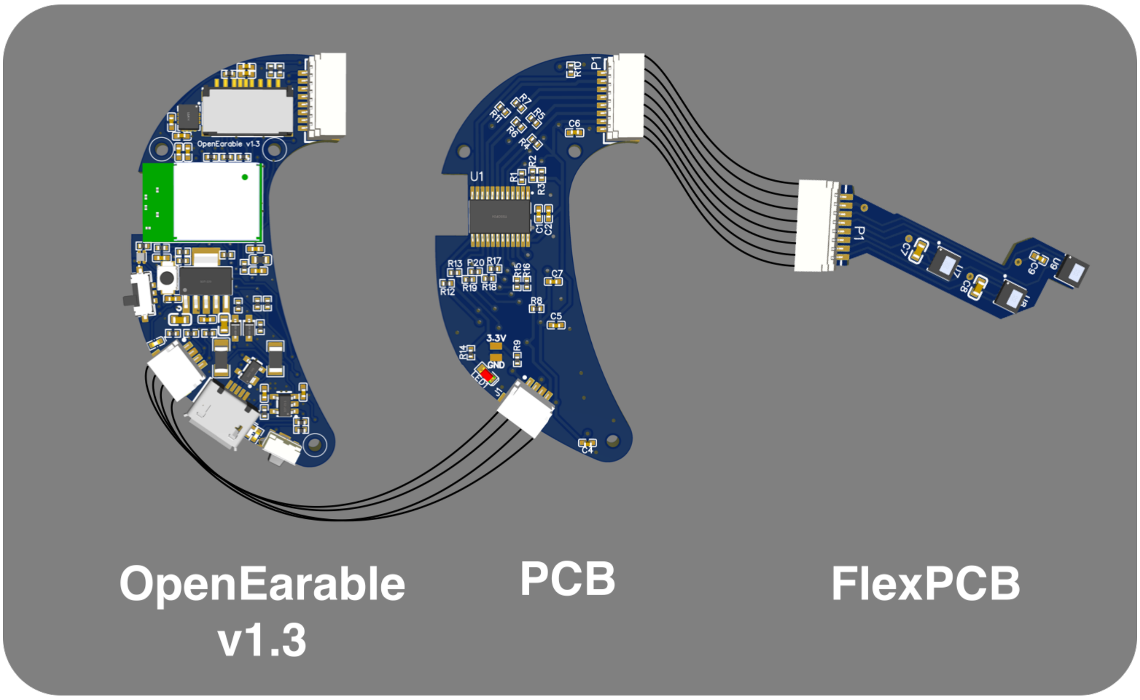

Figure 3.2: Visual representation of the prototype and the interaction of all components. The PCB is connected to the OpenEarable v1.3 with a 4-pin connector. In the OpenEarable is an Arduino Nano33 BLE, with which it is possible to control the multiplexer (TCA9548A) via I2C. Through this, every sensor value on the PCB and also on the FlexPCB can be read out, since the FlexPCB is also connected to the multiplexer via the 8-pin connector.

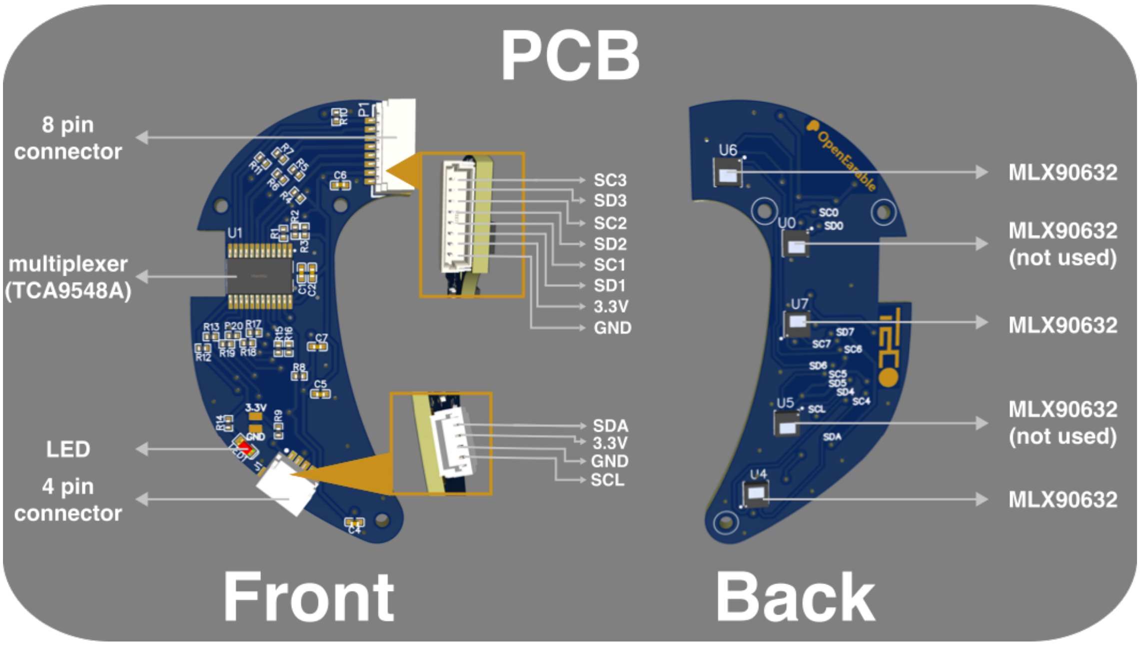

Figure 3.3: Representation of the front and back of the PCB. The multiplexer can be seen on the front, which is controlled by the OpenEarable via the 4-pin connector. The three other MLX90632 are then connected by the FlexPCB via the 8-pin connector. In addition, an LED is connected to the front, which lights up green if no short circuit is generated. The temperature sensors can be seen on the back, but only three of the five connections visible in the design are used.

multiplexer is addressed, with which one of the eight possible applied lines can be switched and read out. The eight possible through-connections of the multiplexer are connected to all temperature sensors, including those of the FlexPCB via the 8-pin connector. In addition, an LED is installed on the PCB to directly indicate a possible short circuit. For each temperature sensor, the signals Ground, Power (3.3V) as well as SCL (clock signal) and SDA (data transmission) are required, as shown in Figure 3.3. Communication with the multiplexer can be handled through the 4-pin connector. To connect the three temperature sensors of the FlexPCB, a total of 12 signals are required, which can be reduced somewhat. For this purpose, the ground and power signals can be used together, resulting in a total of 8 signals being transmitted.

A case has now been developed around the OpenEarable and the custom-made PCB to enable a comfortable fit. Above the PCB, the battery is placed in the enclosure so that no long cables are needed for the power supply to record the data in the study conducted. The OpenEarable is placed above this. The dimensions of the PCB are exactly the same as the OpenEarable to keep the case as small and compact as possible. The sensor used requires an angle of 50° around itself for the temperature to be reliably measured. This was taken into account.

3.3.2 Temperature Measurements in the Ear

The second component now enables temperature measurement in the ear area. The FlexPCB itself is only equipped with components on the front side. Thereby, the 8-pin connector that connects the FlexPCB to the PCB is located, as described in Section 3.3.1. Additionally, three temperature sensors are placed on the FlexPCB to sense the positions in the ear and Concha described in Section 1.4 and Figure 1.1. The FlexPCB was designed to extend through the component. On the one hand, the 8-pin connector extends outward to connect to the PCB. On the other hand, the PCB extends along the outside of the case to the earbud, allowing the FlexPCB to snake through. The tip of the FlexPCB also contains a temperature sensor mounted in the earplug and aimed directly at the tympanic membrane. Another temperature sensor is aimed at the ear canal and is located on the outer edge of the earplug. The third temperature sensor is aimed at the concha. The component was modeled on the design of an AirPod, but heavily modified afterward. The original AirPods design is freely available on TinkerCAD and was used as the basis for the component shape. The inside of the design was completely hollowed out to allow cables to be routed through the case. Additionally, an adapter was added to the side to fit the redesigned earpod. An earbud can be attached here to ensure that the earbud penetrates further into the ear than usual compared to conventional in-ear headphones. This enables precise temperature measurement in the direction of the tympanic membrane. A temperature sensor is attached to the tip of the earbud to perform basic temperature measurements. The three temperature sensors on the FlexPCB can be switched via the multiplexer that is connected to the PCB. This allows for precise selection and acquisition of the desired measurements. Figure 3.4 shows a sketch and other images of the final component.

3.4 Study

In this master's thesis, the temperature is to be measured at different positions of the ear in order to enable temperature measurement over a longer period of time.

Figure 3.4: Sketch and real view of the earpiece from different perspectives. The sketch shows the first idea of how the FlexPCB has to be designed so that it gets through the earplug to the tip to measure in the direction of the tympanic membrane. The real views provide an impression of how the component is composed. On the bottom right picture, you can see the sensors on the concha and ear canal, on the top right picture the sensor directing to the tympanic membrane. The bottom left picture displays the 8-pin connector.

For this purpose, a study is to be carried out in which the temperature is measured at different positions and then compared. For this purpose, a prototype has been developed, which has been described in detail in the previous chapters. With this prototype it is possible to measure the temperature at three positions behind the ear, at the auricle, in the ear canal and on the tympanic membrane. The goal is to compare the different positions after recording the data. Within the context of this master's thesis and related studies, several hypotheses arise that have the potential to clarify important aspects of ear temperature measurement. To this end, two studies were designed to provide evidence for the hypotheses previously described in Section 1.4. In addition, the issue of reproducibility and consistency of measurements is of interest. The hypothesis is that the measurement results will remain the same in different subjects despite differences in human physiology. The importance of the initial acclimation time of the sensors is also considered. Here, it is assumed that the 20-minute acclimation period is sufficient to ensure a stable temperature measurement citechagllae.MeasurementCoreBody2018. The role of environmental variables is also considered. The results can be used to define further research questions and applications in the field of temperature measurement by wearables.

3.4.1 Study 1: Localized Ear Temperature Measurement Study Procedure: Baseline Surveys and Environmental Influences

Two studies are conducted as part of this master's thesis. The first study deals with the comparison of temperatures at the different sites. For this purpose, a study is designed to test the different hypotheses and to provide the best possible data basis. The study begins by giving the subject an introduction to the study. After the subject has signed the privacy statement, as well as the informed consent form, a temperature measurement of the right ear is taken with a thermometer (BRAUN ThermoScan 7) to obtain a reference value for the temperature in the ear. This measurement is taken again at the end of the study. The prototype is then attached to the subject's ear. This phase is critical because the correct positioning of the sensors is crucial for the quality of the recorded data. Since the component behind the ear tends to protrude a bit from the skin after a while, it is taped behind the ear to ensure that it is securely in place and would not slip even during light activity. This is observed during preliminary testing. Care is also taken to ensure that this did not affect the temperature measurement of the sensors. This also includes external influences, such as wind, sun or other. To ensure that the prototype's battery would last throughout the entire period, a power bank is attached, as initial results suggested that battery life is between one and two hours. After the prototype is installed, an acclimation phase of 20 minutes follows, during which data is already being recorded. The test subject is now sitting alone in a chair in a room at the TECO Institute. This phase is to ensure that the sensors have enough time to adapt to the physiological conditions of the test subject and to allow stable measurements. After the acclimatization phase is completed, the study investigator entered the room and pressed the prototype button to classify the next phase in the data as well. Subsequently, the subject is again alone in the room. The subject spends another 20 minutes in a seated position in a room at the institute where all other subjects have also conducted the study. The room is not air-conditioned and the windows are closed before the measurement. In addition, the room temperature and humidity are noted between phases and at the beginning and end of the measurement. Subsequently, the subject answers the questionnaire and thus ends the study. The purpose of this phase is to establish a baseline for the temperature measurements and to check the consistency of the sensors under stable conditions. Due to this, the phase is called baseline phase. The next step is to investigate the influence of environmental variables. Subjects will be asked to walk outdoors for 20 minutes. This phase was called outdoor phase. This is done to analyze the response of the sensors to sudden changes in temperature and environment and to evaluate the adaptability of the system. After returning to the room, the subjects take their seats again in their original places and remain in a seated position for another 20 minutes. This phase (relaxation phase) allowed for quantification and

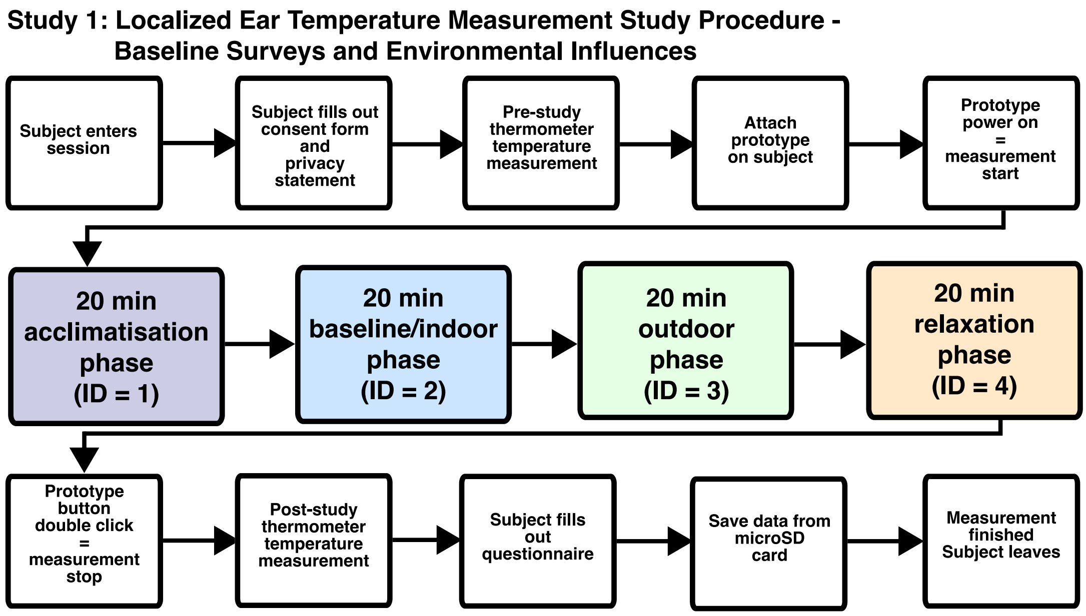

Figure 3.5: Figure illustrating the procedure of Study 1, consisting of four 20-minute phases: acclimatization, sitting, outdoor walking, and relaxation. Ground truth temperature is recorded using a BRAUN Thermoscan 7 thermometer before and after the study.

analysis of variations in sensor readings due to being outdoors. Throughout the time in the room, subjects are allowed to watch animal documentaries that elicited no or minimal anxiety or happiness. Subsequently, subjects still answer a questionnaire that answers important information such as demographics, health, current weather conditions, and prototype comfort. After answering the questionnaire, the study is finished for the subject. A total of 12 subjects will be used in the study to provide a sufficient database for statistical analysis. A visual diagram of the procedure of Study 1 can be seen in Figure 3.5.

Through the design it should be possible to analyze the established hypotheses. The baseline should provide a general feeling for the temperature measurements at the different positions. In addition, through Phase 2 (baseline phase), it is hoped to better assess the temperature differences during Phase 3 (outdoor phase). In the relaxation phase (Phase 4), it should be observed how the sensors settle back to their normal level.

For Hypothesis 1, that the sensors behind the ear measure lower temperatures than the sensors at the tympanic membrane, the ear canal and the concha, this design of the study is an ideal prerequisite, because besides the baseline also external influences of the outdoor phase can be considered. Also for Hypothesis 2, which considers the variance differences between the controlled and uncontrolled environment, the study design provides a good basis, because both phases are covered. For Hypothesis 3, which tests whether certain sensors behave more or less similarly, the study design provides a good basis. In the outdoor phase (Phase 3), the correlation is expected to be very high, as the test subjects move into a colder environment and thus the correlation between the sensors is expected to be very high. Likewise, Hypothesis 4 can be perfectly considered and evaluated. Here it has to be shown that the temperature of the sensor directed to the tympanic membrane is the most stable. It is expected that the subjects are exposed to external conditions in the outdoor phase (Phase 3) and a clear difference can be seen especially in this phase. Since the IMU data are always recorded in parallel, Hypothesis 5 can also be analyzed well with the study design. Here, it is examined whether increased human movements lead to temperature changes. However, a distribution is not directly clear. Since the movement is clearly higher in the outdoor phase, the temperature change can be tested here, but this can also be caused by external environmental influences and not only by the pure movement.

However, a further subdivision into two phases (movement and walking oudoors) is beyond the scope of the study. Through this carefully designed procedure, the study should help test the formulated hypotheses and provide valuable insight into the performance of the developed prototype and its potential applications.

3.4.2 Study 2: Study Course Under Stress Conditions: Impact on Temperature Measurements With Ear-Based Sensors

In the second study, the influence of stress-induced physiological changes on temperature measurements at different locations of the ear is investigated. The study begins similarly to the first study in that the subject is given an introduction at the beginning and the explanation of the study procedure. After the subject signs the privacy statement and informed consent, a thermometer (BRAUN Thermoscan 7) is used to measure the temperature in the same ear (right) where the prototype will be placed. The prototype is attached as in Study 1. In Study 2 the attachment of the reference meter is added. A HRV chest strap (Polar H9) will provide heart rate variability as ground truth for this purpose. The chest strap is connected to the smartphone using the "EliteHRV" app and the measurement is started simultaneously with the prototype. The app is used in such a way that the subject cannot see any HRV readings, only a time indicating the length of the current measurement. An initial 20-minute acclimatization phase, during which the sensors and the subjects adapt to the environmental conditions, is followed by a 15-minute baseline phase in a sitting position. Between the phases, the person conducting the study enters the room and presses the button of the prototype in order to be able to distinguish the individual phases in the data as well. After that, the subjects are exposed to a stress situation. At the beginning of the stress-induced phase, the subjects solve a Stroop test, then an N-Back test and finally a mathematics test. Here, the subject has the task of noting the time at which he starts the respective stress test. The time is taken from the "EliteHRV" app. The Stroop test tests the subject's attention by alternately displaying words in different colors. The subject is asked to interpret and select the correct color from a range of colors. To do this, the subject has a fixed number of words on the basis of which they must determine the color. The time in which the subject processes this number is measured. The words themselves are always color words, but the words do not always match the color in which they are displayed. When the word and the color do not match, reaction time and the number of errors increase. This creates an initial stress situation for the subject [111]. Next, an N-back test with 2 dimensions is performed. Here, the subject is told a letter via a voice output and shown a position in a tic-tac-toe box. The subject must now recall N steps and indicate whether the letter or position has already been named or shown in the last N iterations. This test is performed with $N = 1, 2, 3$

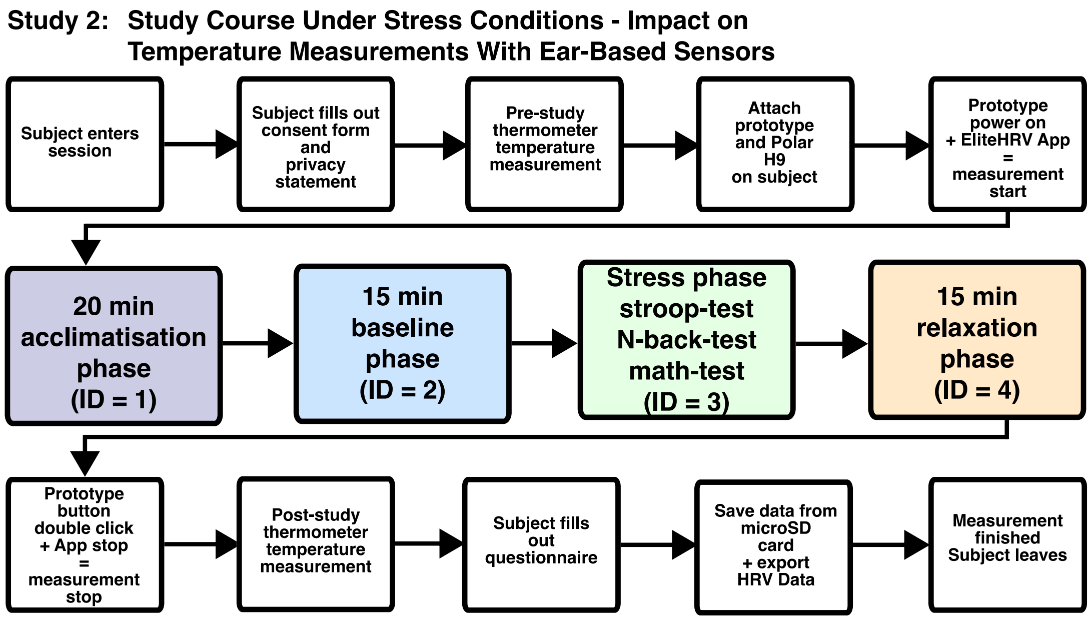

Figure 3.6: Figure outlining Study 2, which measures temperature changes under stress. The procedure includes a 20-minute acclimatization, 15 minutes of sitting, three stress tests, and a 15-minute relaxation phase. Ground truth is obtained using a BRAUN Thermoscan 7 thermometer before and after the study.

and is designed to elicit strain and stress [70]. Last, the subject is presented with a mathematical test. This involves several mathematical tasks in which 4 answer options are always available. Here, the subject has 8 minutes to solve as many tasks as possible. This is also designed to trigger a stress situation [26].

All three tests are designed to trigger stressful situations and challenge the subject in a different way each time. For the Stroop test, there is no visual timer, but the number of words is limited. There is a high score for the test, which is intended to motivate the subject to perform as well as possible. In the N-Back test, the time is strictly predetermined, and the subject has the opportunity to answer within three seconds. Here, the subject is at risk of becoming frustrated if he or she fails to complete one or more sub-steps. The mathematical test has a time limit of 8 minutes, in which the subject must solve as many tasks as possible. Again, the subject is put under pressure in a different way that is intended to trigger stressful situations. This scenario is chosen because a large study is not possible due to time constraints. The scientific standard for induction in standardized stress induction tests is the Trier Social Stress Test (TSST). However, the chosen test covers the requirements and should allow to induce stress in the subjects. To check the stress level of the subjects, heart rate variability (HRV) is measured in addition to the temperature data. These markers provide a solid scientific basis for evaluating stress induction and its effects on the measured temperature values. Here, the HRV values provide the ground truth in stress classification. The stress induction phase is followed by a further 15-minute measurement phase in a seated position, during which the subjects are not exposed to any other stressful situations. This serves to record the recovery processes and their effects on the measured parameters. The procedure is visually depicted in Figure 3.6. The study is used to analyze several hypotheses, which have already been described in section 1.4. Hypothesis 1 states that temperature will increase under stress. By recording the baseline in Phase 2 and the stress-induced phase in Phase 3, this can be solidly tested. Hypothesis 2 deals with the different temperature differences between the stress tests. Since a total of three stress tests are performed, this can also be tested.

In Study 2, the effect of different stress-inducing tests - the Stroop test, the N-back test and a timed mathematical test - on ear temperature measurement is investigated. At the same time, heart rate will be measured as an additional physiological marker of stress. The study includes an initial acclimation phase, a pre-stress baseline measurement phase, a stress induction phase, and a post-stress relaxation measurement phase to comprehensively assess changes in ear temperature under stress conditions.

4. Implementation

This chapter describes the details of the implementation of the prototype and the analysis of the data collected during the studies. To implement the prototype, Arduino software was developed to measure temperature sensor values and IMU data and store them on a microSD card with a timestamp. Implementation details for evaluating and analyzing the collected data are described afterwards.

4.1 Prototype

The prototype is controlled by OpenEarable, which was programmed to be controlled via Arduino code. An Arduino Nano33 BLE is built into the OpenEarable, which facilitates customization. The main task of the prototype is to collect data from the temperature sensors and an IMU, and store it in a CSV file on the SD card, which has its own slot in the OpenEarable. Similar to traditional Arduino code, the prototype code consists of a `setup()` and a `loop()` method. A general overview of the code can be visually seen in Figure 4.1.

In the `setup()` method, all the required components are initialized. These include the sensors, the IMU, the SD card logger and the key interrupt. The latter is used to ensure that a measurement is terminated, if the key is pressed twice within two seconds. If the key is pressed once, the phase is changed. When the sensors are initialized, a `Wire` connection is made and the multiplexer is triggered. The multiplexer is crucial when reading out the sensors, because each sensor is addressed with the same address. All temperature sensors are connected to the multiplexer and are addressed one after the other to read out the temperature value. This is possible because the multiplexer always switches through one output and thus all sensors can have the same address.

In addition to the regular operations in the `loop()` method, the code contains functions for handling keystrokes. A key press is detected using an interrupt. As soon as the key is pressed, a function is started that checks whether the key has already been pressed within the last two seconds. If this is the case, the data acquisition of sensor data and IMU data is stopped and the SD card with the collected data is written.

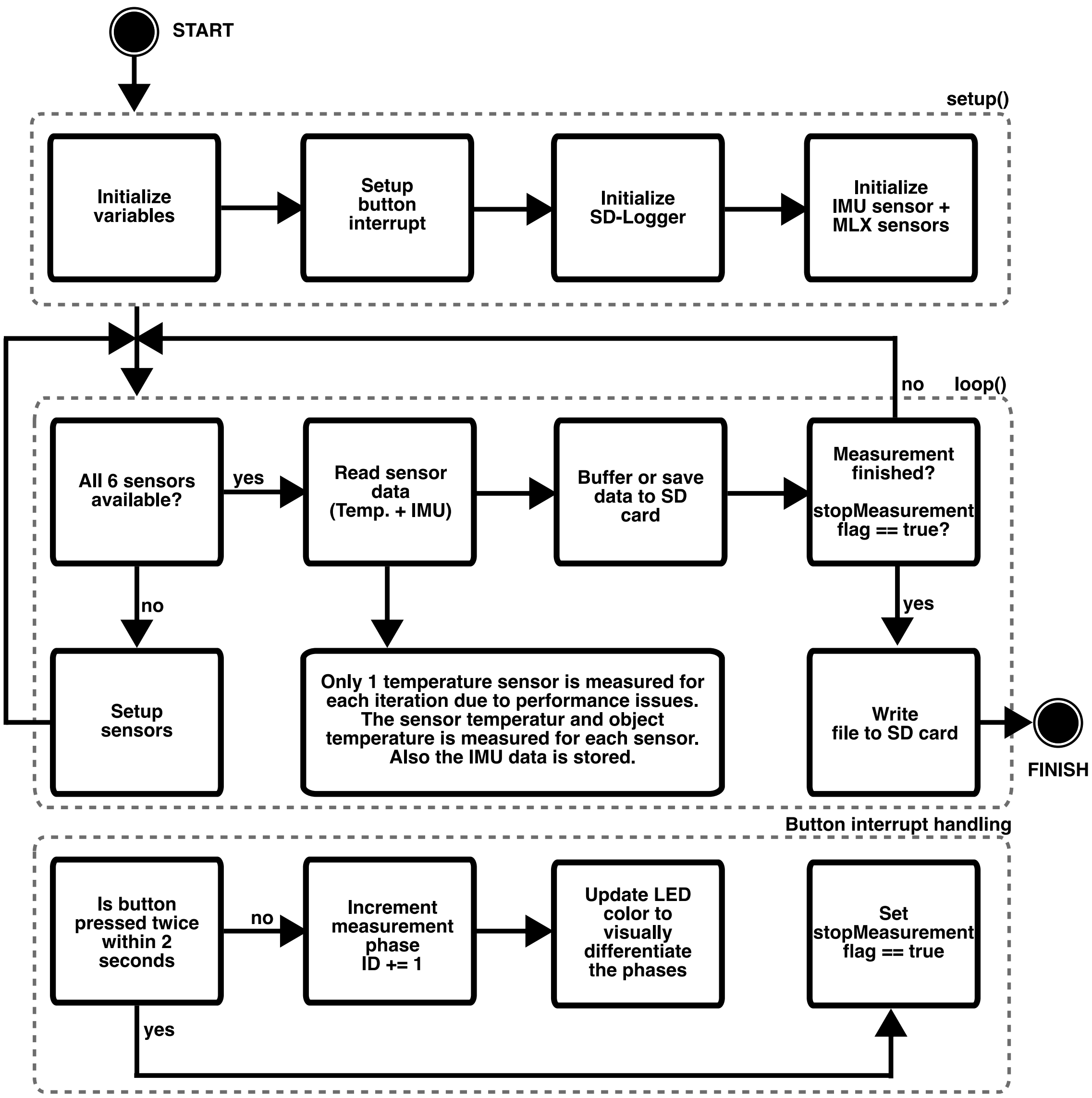

Figure 4.1: Sequence of the behavior of the prototype. Using the ArduinoIDE, the code is written in $c++$ and flashed to the OpenEarable. The code includes the usual "setup()" and "loop()" functions and their behavior to create the dataset for the two studies. This results in a csv file that contains all the information.

One of the main tasks is to read data from the MLX90632 sensors and the IMU sensor. For this, the multiplexer is always switched to the respective sensor and the value is read and persisted via the modified library "Protocentral_MLX90632". The library was strongly modified to enable a faster measurement. This is necessary because additional motion data should be recorded. The IMU sensor, built directly into the OpenEarable, provides accelerometer, gyroscope and magnetometer data.

The collected data from one iteration of the `loop()` function is then written to the SD card. Each line represents one pass of the `loop()` function and contains one of the 6 temperature sensor values and the 9 IMU data as well as a time value and an ID. Thus the 6 temperature sensor values are distributed in 6 lines.

Furthermore the library "Protocentral_MLX90632" was adapted. In the original library, the `getObjectTemp()` function waits for the temperature value to become

	ID	TIMESTAMP	TympanicMembrane	Concha	EarCanal	Out_Bottom	Out_Top	Out_Middle	ACC_X	ACC_Y	ACC_Z	GYRO_X	GYRO_Y	GYRO_Z	MAG_X	MAG_Y	MAG_Z
1	1	857	3499	0	0	0	0	0	-2673	97808	-12297	1219	12500	-4115	987000	-2325000	1083000
2	1	874	0	3403	0	0	0	0	-2775	98125	-12004	1829	13262	-4268	915000	-2373000	1107000
3	1	891	0	0	3320	0	0	0	-3056	97987	-12555	1753	15091	-4344	771000	-2421000	1095000
4	1	909	0	0	0	3386	0	0	-3235	98292	-12686	2820	15244	-5106	963000	-2397000	1083000
5	1	926	0	0	0	0	3234	0	-3786	98322	-13260	3353	15929	-6097	819000	-2277000	1083000
6	1	944	0	0	0	0	0	3142	-4007	97933	-13027	3429	14176	-7317	915000	-2205000	1089000
7	1	961	3499	0	0	0	0	0	-4521	97820	-13338	3811	13262	-6021	891000	-2373000	1083000
8	1	978	0	3403	0	0	0	0	-5365	98268	-14241	3734	11966	-4954	915000	-2325000	1071000
9	1	996	0	0	3320	0	0	0	-5664	98448	-14253	3277	9832	-5335	843000	-2397000	1089000
10	1	1013	0	0	0	3386	0	0	-5640	98382	-14301	3429	7164	-6631	843000	-2469000	1107000
11	1	1031	0	0	0	0	3234	0	-5359	97969	-14678	3277	6097	-6936	843000	-2205000	1083000
12	1	1048	0	0	0	0	0	3146	-5329	97886	-14768	2896	4954	-6402	939000	-2181000	1107000
13	1	1066	3507	0	0	0	0	0	-5120	98125	-14863	1981	4115	-4801	939000	-2253000	1077000
14	1	1083	0	3400	0	0	0	0	-4605	98538	-14211	838	3125	-3887	891000	-2205000	1083000
15	1	1100	0	0	3328	0	0	0	-4539	98472	-14702	533	3506	-4192	915000	-2397000	1071000
16	1	1118	0	0	0	3386	0	0	-4294	98185	-14008	152	3277	-3811	915000	-2205000	1101000
17	1	1135	0	0	0	0	3209	0	-3660	97844	-13852	-609	4573	-3658	723000	-2205000	1077000
18	1	1153	0	0	0	0	0	3146	-4157	97377	-14259	304	5411	-4420	915000	-2301000	1083000
19	1	1170	3507	0	0	0	0	0	-4569	97838	-14175	1219	7012	-4192	987000	-2397000	1083000
20	1	1188	0	3400	0	0	0	0	-4964	98053	-14606	1295	6859	-4268	987000	-2229000	1089000
21	1	1205	0	0	3328	0	0	0	-4809	98149	-14702	533	5106	-5792	891000	-2301000	1083000
22	1	1222	0	0	0	3386	0	0	-4719	98352	-14660	914	4878	-7012	915000	-2277000	1089000
23	1	1286	0	0	0	0	3209	0	-4408	97993	-14582	914	5868	-9679	267000	-2277000	1011000
24	1	1303	0	0	0	0	0	3146	-4910	97365	-14498	1295	6631	-9603	771000	-2373000	1101000
25	1	1321	3507	0	0	0	0	0	-4689	97515	-14170	1219	7012	-8841	939000	-2205000	1095000
26	1	1338	0	3400	0	0	0	0	-5251	97401	-14947	914	7622	-7850	1011000	-2181000	1095000
27	1	1356	0	0	3328	0	0	0	-4492	98173	-13691	990	7545	-6097	891000	-2277000	1095000
28	1	1373	0	0	0	3386	0	0	-5167	97479	-15342	2134	12728	-9222	915000	-2301000	1083000
29	1	1391	0	0	0	0	3209	0	-5837	97407	-15246	1829	11280	-8841	1011000	-2205000	1095000
30	1	1408	0	0	0	0	0	3146	-6113	96827	-14941	2134	12804	-7164	963000	-2205000	1095000

Figure 4.2: Snippet of the resulting csv-file from study 1 of subject 10. The temperature values were multiplied by 100 to store the values as integer and to have two decimal places. The IMU data were each multiplied by 10000 to retain the information over three decimal places. The timestamp is given in milliseconds, the "ID" defines the current phase the measurement is into.

available by waiting in a `while` loop for a register value to be set indicating newly available data. This resulted in an unacceptably long waiting time because the update rate per sensor is 2 Hz. During this time, no IMU data signal can be read due to the `while` loop present in the library, as the Arduino Nano33 BLE does not allow parallelism. To fix this problem, the check to see if new data is available is ignored. Instead, the temperature value is read in each loop iteration. As a result, the temperature value may not have updated yet. However, the sampling rate is so high that this does not affect the final result. The IMU data needs a sampling rate of at least 50Hz to make significant statements about the motion. To achieve this, only one sensor value per iteration was read out to achieve the performance. Additionally, the code had to be optimized several times for performance reasons, ranging from removing `for` loops to storing data in strings, instead of arrays. Finally, a sampling rate of $50Hz$ of IMU data and a sampling rate of $8.3Hz$ of sensor values has been achieved. Since the temperature sensors have an update rate of $2Hz$, some consecutive sensor values are the same, but no measured sensor value is lost. A snippet of the final result of the csv file can be taken from Figure 4.2. Please note that the temperature of the sensor itself is also stored, but is not shown here due to space limitations.

4.2 Sensor Calibration Implementation in Arduino

The calibration was implemented using the Arduino platform, modifying the library for the MLX90632 sensors to introduce an emission factor of 0.98 according to the sensor datasheet. This value is optimized to measure the temperature of the human body and was also used for the metal plate during calibration. This emission factor allows the system to account for the natural variability of thermal radiation between different materials and provide a standardized reading that is consistent across environments.

4.3 Study Analysis

A pipeline was created for each of the analyses of Study 1 and Study 2. The code of the two studies is located in the Git directory in the folder "codingStuff/study-Analysis", respectively in the folders "study1" and "study2". The pipeline first reads all the recorded data into a Pandas data frame and generates the results for the different hypotheses. For each hypothesis, a file: "hypothesisX.py" exists, where the "X" stands for the number of the hypothesis. This is called in the pipeline and all results, either output or plots, are saved in the "target" folder or printed to the console.

4.3.1 Analysis of Study 1

The analysis of the first study is stored in the file "study1_pipeline.py". Running this file starts a pipeline to evaluate all hypotheses. At the beginning of the pipeline is the `AnalysisPipeline` class, which specifies the data folders and destination folders as class attributes. This serves as a representation of the pipeline and manages the complete pipeline. In addition, the class holds the ground truth temperature measured by all subjects in the class attribute `ground_truth_temps`. Then, the function `process_directory` is called, which stores all the records of each subject's study in the class attribute `all_temp_data`. For this purpose, an object of class `TemperatureData` is created for each individual record. This file is stored in the "src" folder, as are all other files. Among other things, this object stores the raw data of the sensor values, as well as the ground truth value, which was previously stored in `ground_truth_temps` of all subjects. Since the temperature values were stored as `Integer` and multiplied by 100 in the csv file, the temperature values were also divided by 100 when persisted. Since only one temperature sensor value is stored per measurement and the other 5 sensor values are set to 0, they are also set to "NaN", which greatly simplifies the subsequent recording of the data. The "ID" represents the separation of the phases. In addition, the timestamp, which is stored in milliseconds in the csv file, was converted to minutes. The `TemperatureData` class also contains the function to smoothen the data, which averages and smoothes the data within 120 data points. This corresponds to smoothing the data from a window of about 2.4 seconds, which was chosen to be very small over a total study length of 80 minutes. In addition, the class includes a function to plot the smoothed raw data (`plot_raw_data`). After executing the constructor of the class `AnalysisPipeline`, followed by reading in all collected study data, the procedure to analyze the hypothesis can be continued. For each one there is now a separate class `HypothesisXAnalyzer`, where the "X" stands for the number of the hyothesis. The individual hypotheses are now analyzed and further supported by a significance test (paired t-tests) to prove or disprove the hypotheses.

Hypothesis 1

Hypothesis 1 compares the sensors behind the ear with those on the tympanic membrane, ear canal, and concha. For this, the method `analyze_mean_error(phases)` is called, respectively for the phases $[2]$ and $[2, 3, 4]$. This method calculates the mean temperature and the mean absolute error of the sensors behind the ear (top, middle, bottom), as well as of the sensors inside the ear (tympanic membrane, ear canal, concha). In addition, a t-test is calculated for the results using

```
scipy.stats.ttest_ind(behind_ear_means, in_ear_means)
```

and using

```
scipy.stats.ttest_ind(behind_ear_errors, in_ear_errors)
```

to further support the hypothesis. The results of the method are then printed to the console for further interpretation. In addition, a boxplot is created for each phase, which should represent the accuracy of the sensors. For this, the ground truth is subtracted from each temperature sensor value per subject in order to compare the sensors across subjects. The resulting boxplot is stored in the "target" folder.

Hypothesis 2

Hypothesis 2 involves a method that calculates the mean variance per sensor across all subjects. Here, the results of Phase 2 and Phase 3 are compared, as this represents the indoor and outdoor phases. To get a better sense, the mean distance to ground truth measured in the two phases is also calculated. The results are displayed in the console. Since multiple comparisons were made for different sensors, a Bonferroni correction was applied to control for the family-specific error rate. The Bonferroni corrected threshold with

$$\alpha = 0.05,$$
$$\text{bonferroni\_alpha} = \frac{\alpha}{k},$$

was used to determine the statistical significance of the results. Here, k is the amount of sensors, which is 6. For each sensor

```
stats.ttest_ind(indoor_var, outdoor_var),
```

is calculated and if the p-value is less than "bonferroni_alpha", the null hypothesis was rejected. The null hypothesis in this context serves as a statistical model that assumes that the observed differences in the sensor data are purely random. The results are also output to the console.

Hypothesis 3

Three methods exist for Hypothesis 3. To begin, there is a `analyze()` method, which calculates the mean correlation from Phase 2 and 3 (indoor, outdoor) over all subjects and stores them globally and additionally outputs them in the console. Here, all 6 rows were concatenated, as they represent a complete measurement of the temperature sensors. The timestamp here was averaged over the 6 individual measurements. A Spearman correlation matrix was then created from this data set. This was chosen because it not only detects linear correlations and also handles outliers well. The correlations range is from -1 to 1, with the value -1 representing a perfect negative correlation and the value 1 representing a high correlation. These mean correlations were then used in the second function `generate_heatmap()` to create a heatmap. The heatmap is then saved in the "target" folder for each of the two phases. The third method is `analyze_mad()`, which calculates the mean absolute deviation, respectively for the indoor and outdoor phases. Therefore, also a t-test is calculated with

```
stats.ttest_rel(phase2_values, phase3_values),
```

to know if the difference is significant. The results are also printed to the console.

Hypothesis 4

Hypothesis 4 is to show that the temperature measured at the tympanic membrane is the most stable. For this purpose, the mean standard deviation is calculated, which should show the stability of the sensors. By means of

```
numpy.std(phase_data[sensor]),
```

the standard deviation is calculated per sensor and per subject, which is then averaged over all subjects. This is done for the indoor and outdoor phase and displayed in the console. Furthermore, a t-test is used with

```
stats.ttest_rel(phase2_values, phase3_values),
```

to show if the data difference is significant.

Hypothesis 5

Hypothesis 5 states that motions lead to absolute relative temperature changes. Motion is determined using the IMU data for each subject. Initially, the data is filtered so that only Phases 2,3 and 4 are considered. Subsequently, by means of

```
temp_data[sensor].diff().abs().rolling(window=250).mean(),
```

the relative changes per sensor per subject are calculated, which is then averaged per sensor. The amount of relative change is considered, as otherwise the changes between subjects, should they be negative and positive respectively, could neutralize each other. In addition to the absolute relative change of the individual temperature sensors, the absolute average movement of all subjects is also calculated. For this the movement is calculated by means of

```
pd.concat(all_aggregated_imu_data, axis=1).mean(axis=1).reset_index(),
```

where `all_aggregated_imu_data` stores the IMU data of all subjects. Then, a plot is generated, which is vertically arranged shows the absolute relative temperature sensor changes and finally the absolute relative movements. The plot is stored in the ”target” folder.

4.3.2 Analysis of Study 2

The second study is structured very similarly to the first study. The pipeline `Study2Pipeline` can be found in the file ”study2_pipeline.py”. This holds the ground truth values of the five subjects. In addition, the HRV data are also included. For this purpose, all relevant timestamps are stored in the global attribute `hrv_timestamps` per subject, including the start of the measurement, as well as the time of the individual stress tests. These were noted manually per subject and are set manually here. The collected data of the study are stored and read in the folder ”data”, in which a subfolder is created per proband. Two files are stored per subject, a csv file which stores the temperature and IMU information, the same as known from Study 1. In addition, the measurements of the Polar H9 are stored in a txt file, which contains the RR intervals of the HRV measurement.

The pipeline starts as in Study 1 with the temperature data persisted into the global attribute `all_temp_data`. In addition, the HRV data are stored in the attribute `all_hrv_data`. For this purpose, an object of the class `HRVData` is created per subject, which contains the timestamps from `hrv_timestamps`, as well as the information of the txt file in a data frame. The attribute `kubios_data` is also stored per subject, which persists important findings from the analysis with the ”KubiosHRV Standard” software. These were calculated using the txt file per subject and read manually. The class `HRVData` has the method `print_statistics()`, which prints all the information about the ground truth and HRV measurement to the console, including the RMSSD, SDNN and LF/HF ratio during the different phases. To plot the raw data, the class `RawDataPlotter` is created. This plots the raw data and persists the plot to the ”target” folder. Now all the necessary steps have been done to prepare the data so that each hypothesis can be considered.

Hypothesis 1

Hypothesis 1 considers the temperature change and states that the temperature increases under stress. For this purpose, the mean temperature of the individual sensors per subject is calculated for the baseline phase, stress-induced phase and relaxation phase. The difference between the mean temperature values of the individual phases was now calculated per subject and were output directly to the console as a latex table. Additionally by means of

```
ttest_rel(data1, data2, nan_policy='omit'),
```

a t-test was performed, ignoring ”NaN” values. ”data1” and ”data2” are the two data sets on which the significance test was performed. This was done on the 3 relevant phases at the adjacent phases for each sensor. These results were also displayed in the console.

Hypothesis 2

Hypothesis 2 states that the individual stress tests have different temperature changes. For this purpose, the data set was restricted to the phase of the stress tests. This was implemented by using the time value of the HRV data to determine the intervals of each stress test. Subsequently, the difference of the mean temperture measurements of both stress tests was calculated and output as a final latex table on the console. A significance test was performed to statistically validate the results. This was done as for Hypothesis 1, but with the individual partial stress phases instead of the coarser phases. The result was output to the console.

5. Evaluation

This chapter aims to validate the hypotheses formulated for two distinct studies described in Chapter 3. Each study focuses on specific aspects of ear-based temperature measurement and aims to explore the capabilities and limitations of the developed wearable prototype. For each study, a set of hypotheses was established in Section 1.4, and the data collected in the studies are used to evaluate these hypotheses.

5.1 Results and Discussion of Study 1

Study 1 focuses on exploring the potential and limitations of the developed ear-based temperature measurement system and examines its accuracy, reliability, and robustness under various conditions. A more detailed discussion of the design and objectives of Study 1 is described in Chapter 3.4.1. Additionally, a visual representation of the procedure of Study 1 can be seen in Figure 3.5.

Figure 5.1 shows a sample measurement from Participant 7. The progression of slightly smoothed raw data across phases that can be seen is very similar to that of the other subjects. The background color represents the phase the measurement is in. At the beginning in the acclimation phase (ID=1), the sensor adapts to the body. Subsequently, in the baseline phase (ID=2), the sensor readings show little change under controlled conditions. In Phase 3, where the subjects were walking outside, the measured temperature drops for all subjects. In the relaxation phase (ID=4), the subject is back in the controlled environment and the signal settles back toward the values measured in Phase 2.

The study was conducted with a total of 12 subjects, of which 7 were male and 5 were female. After the study was conducted, a questionnaire was completed by each subject. This included the conditions and perceptions of the study. The study was conducted at a mean indoor temperature of $25.4°C$ and humidity of 47.55g/m^3. The outdoor temperature was a mean of $19.375°C$. The external conditions were mostly sunny and cloudy, but two subjects also experienced light rain. Subjects averaged 26 years of age (24-29) and were healthy. All test persons arrived in such a way that they had a short journey and had not previously done any activities that could significantly influence the temperature. After the study, all subjects were very positive about the prototype and rated it 8.1 on a scale of 0-10.

To verify the findings collected in this study, several hypotheses were formulated and tested. The hypotheses were formulated in Section 1.4. These hypotheses aim to answer specific questions related to the performance and reliability of ear-based temperature measurements. The results and their implications are discussed in the following sections, where each hypothesis is evaluated in detail based on the data collected.

To prove that the hypothesis is true or false, t-tests are used. These are only used to support a hypothesis, they do not prove the study. The t-test is a fundamental concept in statistical hypothesis testing and shows whether two sets of data are significantly different from each other. It is particularly useful when small sample sizes are involved and the standard deviation of the population is unknown. The underlying principle of the t-test is to compare the means of two groups and evaluate how likely it is that the observed differences are due to chance. The formula for the t-statistic in an independent t-test is as follows.

$$t = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}},$$

where $\bar{x}_1$ and $\bar{x}_2$ are the sample means, s_1^2 and s_2^2 are the sample variances, and n_1 and n_2 are the sample sizes for the two groups. The calculated t-statistic is then compared to a critical value determined by the degrees of freedom and the chosen significance level, commonly denoted by α.

The p-value, another important metric, quantifies the probability of obtaining the observed results if the null hypothesis were true. The null hypothesis (H_0) states that the data are not significantly different when the hypothesis states that data are significantly different. Thus, H_0 contradicts the hypothesis itself. Rejecting H_0 further supports the hypothesis proper. A low p-value ($p < \alpha$) indicates strong evidence against H_0, so it is rejected in favor of the alternative hypothesis. Conversely, a high p-value indicates that the observed data are consistent with the null hypothesis. The choice of significance level α, often set at 0.05, is critical because it controls the rate of type I errors that occur when a true null hypothesis is falsely rejected.

5.1.1 Hypothesis 1: Lower Temperature Measured on Sensors Behind the Ear

The first hypothesis is to show that a lower temperature is measured behind the ear than in the ear. For this purpose, the analysis was considered from two points of view. First, only the data points where the subject was sitting were recorded (baseline phase), and second, all data of all subjects except for the acclimatization phase (Phase 1) were considered. In both views, a distinction was made between the two two sensor groups behind the ear (Outer Ear Top, Outer Ear Middle, Outer Ear Bottom) and in the ear (Tympanic Membrane, Ear Canal, Concha).

In the first perspective, only the baseline phase (phase 2) was considered. Here, for all subjects, the mean temperature behind the ear was 36.30°C, while the mean

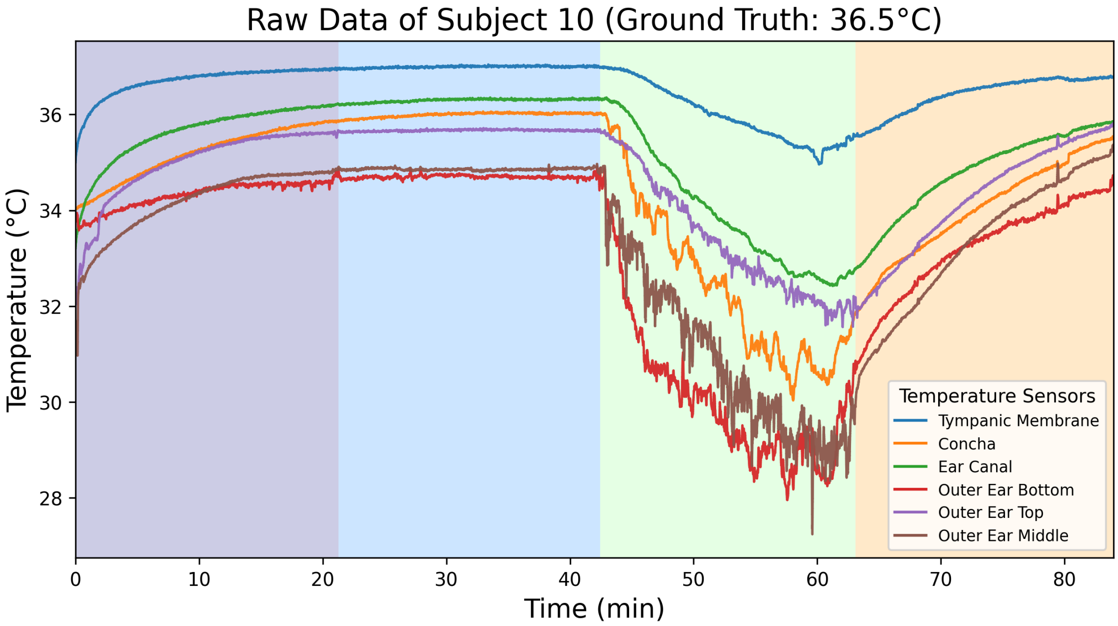

Figure 5.1: Raw data of a measurement in Study 1 of Subject 10. The subject had a body temperature of 36.5°C at the beginning. Phases 1-4 are shown, distinguished by the background color of the plot. In Phase 1, the sensor has adjusted and acclimated to the temperature of the subject. After the sensor settled in, Phase 2 measured the temperature while sitting in a room (baseline phase). In Phase 3, the subject went for a walk outside (outdoor phase). In Phase 4, he went back into the room to see how the sensors settled back to the calmer environmental conditions (acclimatization phase). During the measurement, the subject was sitting on a chair in a room with closed windows, except the outdoor phase. The ground truth is measured before and after the whole measurement in the same ear (right) where the prototype is placed. Also the room temperature, humidity and outdoor temperature was noted manually to complete the dataset.

temperature inside the ear was 36.74°C. To demonstrate a statistically significant difference between the two means, a t-test can be used. This tests the probability of the null hypothesis. The t-test yielded a p-value of 0.0424, which is less than the alpha value of 0.05. Thus, the null hypothesis, which states that the data are not significantly different, is true at less than 5%, confirming significance. The mean error between the ground truth and the temperature measured behind the ear was 0.50°C, and that for the temperature in the ear was 0.18°C. The p-value for the comparison of these errors was 0.0115, again indicating a statistically significant difference. Thus, it is clear that temperature is measured significantly lower behind the ear than in the ear while sitting.

The second perspective now also looks at other phases of the study. Now, in addition to the baseline phase (Phase 2), the outdoor phase (Phase 3) and the relaxation phase (Phase 4) were also considered. The mean temperature behind the ear was 35.33°C and in the ear it was 36.02°C. The p-value of the t-test was 0.0158, which again is statistically significant. The mean error behind the ear was 1.45°C and in the ear it was 0.77°C. The p-value for the comparison of these errors was 0.0042, which is also statistically significant. Thus, both perspectives support the hypothesis, both in the baseline phase only and during all activities except the acclimatization phase.

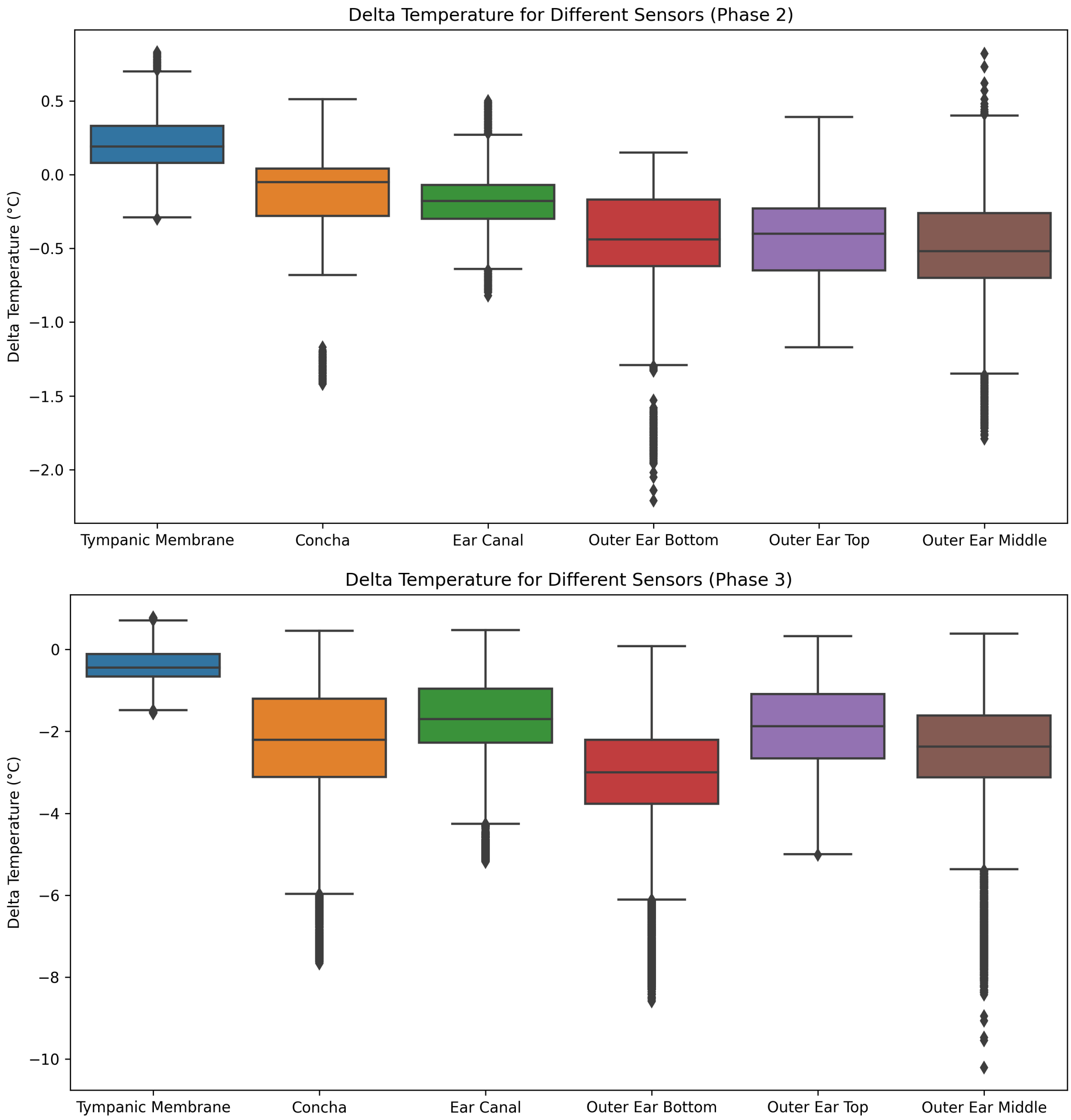

Figure 5.2: Boxplots to visually illustrate the distribution of readings from different sensor positions during Phase 2 (sitting indoors) and Phase 3 (walking outdoors). Central tendencies and their dispersion for the analysis of the sensors under different environments can be seen. Temperature values were subtracted from actual thermometer readings (ground truth) to compare all user data. These visualizations are an essential part of the evaluation of Hypotheses 1 and 2, as they highlight differences in mean temperature and variance, and highlight potential outliers.

This can also be seen in Figure 5.2. The two boxplot images show the baseline and outdoor phases (Phase 2 and 3), always zeroed to the temperature measured by the thermometer before the measurement. During sitting in the baseline phase (Phase 2), the temperature measured at the tympanic membrane is very close to the temperature measured by the thermometer (±0.5°C). The sensors in the ear canal and concha also show high accuracy. For the sensors behind the ear, although the median is sometimes very close to the sensors in the ear, the outliers are strongly

Sensor	MAD (in °C)		Mean Variance (in °C^2)		Mean Diff. from Ground Truth (in °C)	
	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor
Tympanic Membrane	0.025	0.258	0.00097	0.107	0.224	-0.391
Concha	0.042	0.820	0.00307	1.134	-0.164	-2.344
EarCanal	0.030	0.624	0.00155	0.646	-0.177	-1.742
O.E. Bottom	0.095	0.800	0.01890	1.110	-0.527	-3.094
O.E. Top	0.062	0.663	0.00694	0.650	-0.389	-1.903
O.E. Middle	0.101	0.831	0.01980	1.098	-0.529	-2.548

Table 5.1: Mean absolute deviation (MAD), mean variance, and mean distance from ground truth for different sensors (O.E. = Outer Ear). Phases 2 (indoor) and 3 (outdoor) were considered. All values were calculated for each sensor and averaged over all subjects.

represented here, which questions the reliability of the signals. When comparing the sensors behind the ear, the sensor placed at the top behind the ear provides the best results. This is due to the position behind the ear: the further below the ear, the more external influences are felt, such as a gust of wind, even if only with slight movements. This can be seen more clearly in the boxplot for Phase 3, while the test subjects were out walking. While here also the sensor pointing to the tympanic membrane shows the best results, all other sensors have outliers. There is also a significant difference between the sensor in the ear canal and the auricle. The sensor in the ear canal is further in the ear and thus somewhat more protected from external conditions, which is also evident here. The findings of the boxplot from Phase 2 are also confirmed for the sensors behind the ear.

The second perspective, which uses Phase 2,3 and 4 also confirms the hypothesis that the temperature measured behind the ear is statistically significantly lower than that measured in the ear. However, the sensors behind the ear also show a statistically significant higher error compared to the ground truth, especially when the subject is involved in activities such as walking. These findings have important implications for the use of ear-based temperature sensors in various applications.

5.1.2 Hypothesis 2: Indoor vs Outdoor Variance

The second hypothesis is to show that the variance in temperature readings from ear-based sensors is lower indoors than outdoors. This expectation is derived from the fact that the external influences in an indoor environment with closed windows are significantly less than the external influences outside during walking. To test this hypothesis empirically, the data set of several ear-based temperature sensors at different positions was considered, both indoors and outdoors. The different situations within the studies were divided into phases. Phase 2 represents an indoor measurement and Phase 3 represents an outdoor measurement during walking. Phase 2 used to be referred to as the base phase, but for indoor/outdoor comparisons it is also referred to as the indoor phase. Here, the temperature values in different areas of the ear were looked at closely. To prove the hypothesis, the variances per temperature sensor were now calculated for phases 2 and 3 respectively. The results show a clear pattern. The mean variance for the tympanic membrane sensor is 0.00097

Sensor	p-value
Tympanic Membrane	0.0005438
Concha	0.0005870
Ear Canal	0.0005009
Outer Ear Bottom	4.71×10^{-6}
Outer Ear Top	7.04×10^{-7}
Outer Ear Middle	0.0002436

Table 5.2: P-values from the Bonferroni-corrected t-tests of the different sensors using the indoor and outdoor variances.

indoors and 0.1074 outdoors. This pattern was consistently observed for other sensor locations, such as the concha with a mean variance of 0.00307 indoors and 1.134 outdoors. A detailed listing of the results can be seen in Table 5.1.

To test this hypothesis, the variances of each sensor's temperature readings were calculated for both the indoor (Phase 2) and outdoor (Phase 3) situations. A two-sample t-test was then applied to statistically compare these variances for each sensor. Because multiple comparisons were made for different sensors, a Bonferroni correction was applied to control for the family-specific error rate. The Bonferroni corrected threshold was used to determine the statistical significance of the results. For example, the p-value for the tympanic membrane sensor was significantly lower than the Bonferroni-corrected threshold, allowing us to reject the null hypothesis. This pattern was consistently observed for other sensors (see Table 5.2), providing strong empirical support for the hypothesis. In summary, the data confirm that temperature readings from ear-based sensors have significantly lower variances when measured indoors compared to outdoors.

5.1.3 Hypothesis 3: Interrelated Temperature Changes

The third hypothesis examines the correlation between the relative changes in temperature readings from different sensor locations in Phases 2 and 3. This is used to understand the consistency between the different sensor readings, especially in relation to changing weather conditions. The mean absolute deviation (MAD) is used for analysis to better understand the consistency between the different temperature sensor readings. Table 5.1 shows the MAD value for each sensor location in Phase 2 (indoor) and 3 (outdoor). In order to distinguish the values significantly, a paired t-test was performed. This compares the MAD values of the sensors per subject and thus produces a p-value, which is on a subject-by-subject basis. The results of this can be seen in Figure 5.3. It can be seen that the MAD of all sensors is significantly different with $p < 0.05$.

Initial trends can be seen in the mean distance to ground truth. For example, in the outdoor phase, the temperature drops significantly compared to the indoor phase. While the sensor measurement in Phase 2 at the tympanic membrane deviates 0.2°C from ground truth, the other sensor locations have a mean change up to −0.53°C from ground truth. This is seen even more strongly in the outdoor area. While here the measurement at the tympanic membrane deviates by −0.391°C from the ground truth, the other sensor locations have a mean change up to −3.094°C. This is mainly due to the fact that external influences such as wind, rain or sunlight may play a

Sensor	p-value
Tympanic Membrane	1.44×10^{-5}
Concha	9.80×10^{-6}
Ear Canal	5.35×10^{-6}
Outer Ear Bottom	2.89×10^{-7}
Outer Ear Top	8.52×10^{-8}
Outer Ear Middle	3.57×10^{-6}

Table 5.3: P-values from the paired t tests of the different MAD's for each sensor between phase 2 and phase 3.

large role here. When the test persons went for a walk, these influences occurred more often, which explains the deviations here. In addition, the outdoor temperature at the end of September when recorded at about 20°C was significantly lower than the indoor temperature of about $25 - 27$°C. This shows that these sensor positions are not as stable to external environmental influences as the sensor directed at the tympanic membrane. This is exactly what is shown in the mean absolute deviation.

Mean absolute deviation (MAD) serves as a robust metric to quantify the stability of different sensor locations under varying environmental conditions. As shown in Table 5.1, the MAD values for indoor and outdoor environments differ significantly. For example, the tympanic sensor has a low MAD value of 0.025°C for indoor measurements, indicating that it provides very consistent readings in controlled environments. However, this value increases to 0.258°C in the outdoor phase, indicating increased susceptibility to environmental factors such as wind and temperature variations. This is consistent with the observed mean deviation from ground truth, further confirming the relevance of MAD as an assessment metric. Other sensors, particularly those positioned outdoors such as Outer Ear Bottom and Outer Ear Middle, also show a significant increase in MAD values as they transition from an indoor to an outdoor environment. This is consistent with their increased mean differences from ground truth and highlights their volatility in response to external influences. Thus, the MAD values illustrate the central message of this hypothesis: sensors vary in their stability in response to external environmental influences, and this variation is quantifiable.

This can also be seen in the heatmap in Figure 5.3. Correlations between pairs of sensors are calculated using Spearman's rank correlation, which is more robust to outliers and non-linear relationships. Phase 3 (outdoors) shows uniformly high correlations, often above 0.9, across all sensor pairs. This suggests that the sensors behave more coherently when subjects are outdoors, possibly due to a common response to environmental factors such as wind and sunlight. It is noteworthy that the tympanic membrane sensor, which showed aberrant behavior indoors, closely matched the other sensors outdoors. However, it is clearly seen here in the raw data from Figure 5.1 that temperature measurements in the ear drop less than temperature measurements behind the ear. This is confirmed by the MAD and mean deviations to ground truth. Thus, the heat map not only supports the primary hypothesis, but also reveals subtleties about how each sensor responds to different conditions. Additionally, together with the MAD and mean deviation to ground truth, it provides confirmation of the hypothesis.

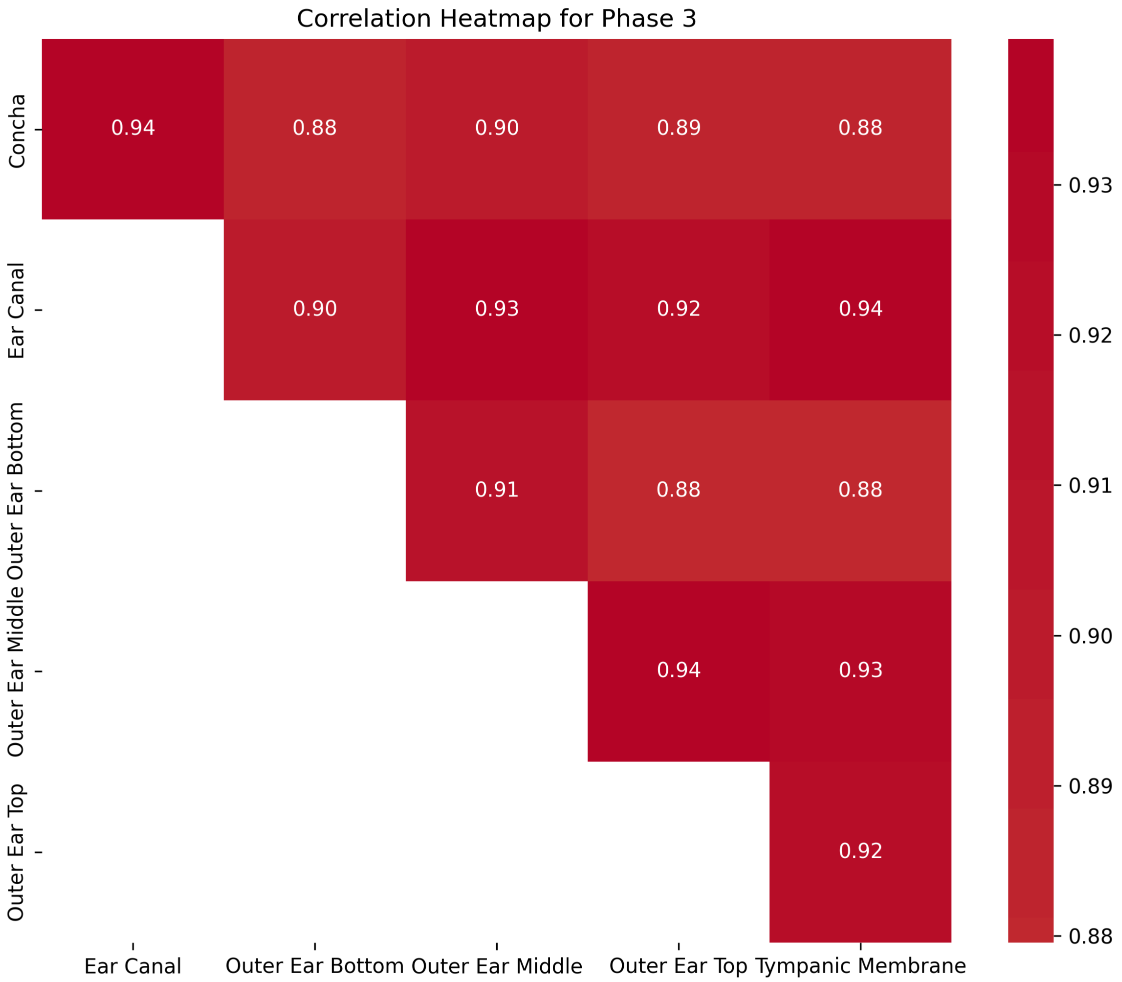

Figure 5.3: Heat maps showing the Spearman correlation matrices of temperature readings from different ear-based sensors during Phase 3 (outdoor). The Spearman correlation values range from -1 to 1, where -1 indicates a perfect inverse relationship, 1 indicates a perfect direct relationship, and 0 suggests no correlation. The color-coded matrices offer a nuanced visual representation of these correlations: darker shades signify stronger positive correlations while lighter shades indicate weaker or negative correlations. These matrices not only assess the consistency between sensor measurements but also reflect their sensitivity to external environmental changes, thus providing empirical evidence for Hypothesis 3.

In summary, the heat map supports the hypothesis by showing that indoor sensor readings fluctuate widely, while outdoor conditions tend to synchronize readings, albeit with higher volatility. This hypothesis is supported by the analysis of the mean absolute deviation. Furthermore, it can be seen that the sensors at the different positions are differently stable to external environmental influences, especially when the subjects are outdoors.

5.1.4 Hypothesis 4: Temperature at the Tympanic Membrane Is Most Stable

The fourth hypothesis considers the stability of temperature sensor readings at the tympanic membrane compared to other positions during phases 2 (indoor) and 3

Sensor	Mean Standard Deviation Phase 2 (indoor)	Mean Standard Deviation Phase 3 (outdoor)
Tympanic Membrane	0.0308	0.3048
Concha	0.0535	0.9882
Ear Canal	0.0378	0.7496
Outer Ear Bottom	0.1138	1.0156
Outer Ear Top	0.0730	0.7836
Outer Ear Middle	0.1176	0.9875

(a) Mean Standard deviations of temperature readings for different sensors during phases 2 and 3, averaged over all subjects. Lower values indicate higher stability.

Sensor	p-value
Tympanic Membrane	1.25×10^{-5}
Concha	9.39×10^{-6}
Ear Canal	5.96×10^{-6}
Outer Ear Bottom	2.09×10^{-7}
Outer Ear Top	6.59×10^{-8}
Outer Ear Middle	2.71×10^{-6}

(b) P-values from the paired t-tests of the different sensors between Phase 2 and Phase 3.

Figure 5.4: Mean standard deviations and the p-values of the paired t-test comparing the indoor and outdoor values for each sensor to detect significant differences. Phases 2 and 3 are used for the indoor and outdoor phases.

(outdoor). The metric used here is the standard deviation. The standard deviation results can be found in Table 5.4a. In Phase 2, the standard deviation is still relatively similar for all measurements, with only the position behind the ear in the middle yielding a worse value of 0.1154. The standard deviation from the tympanic membrane nevertheless sets itself apart from those of the others with 0.0288 compared to $0.05 - 0.07$. In Phase 3, however, it is clear that the measurement of temperature at the tympanic membrane shows the most stability. At 0.1971, the deviation is significantly smaller than for the rest $0.65 - 0.92$. Additionally, it can be seen from Figure 5.2 that measurements at the tympanic membrane show the least quantile differences and are closest to the thermometer values. From the calculated standard deviations, it appears that the tympanic membrane has the lowest values in both phases, indicating higher stability. In contrast, the other sensors show higher standard deviations, more specifically the sensors outside the ear. This makes them more susceptible to external conditions, such as environmental changes. Thus, this confirms the hypothesis that the tympanic membrane measurement provides the most stable temperature readings.

5.1.5 Hypothesis 5: Movement Leads to Changes in the Temperature Readings

Hypothesis 5 addresses the evaluation of the effect of participant movement on the variability of temperature measurements at different ear-based sensor locations. This analysis was conducted with calibration data that included both temperature and IMU data. Temperature data were collected from six strategically placed sensors:

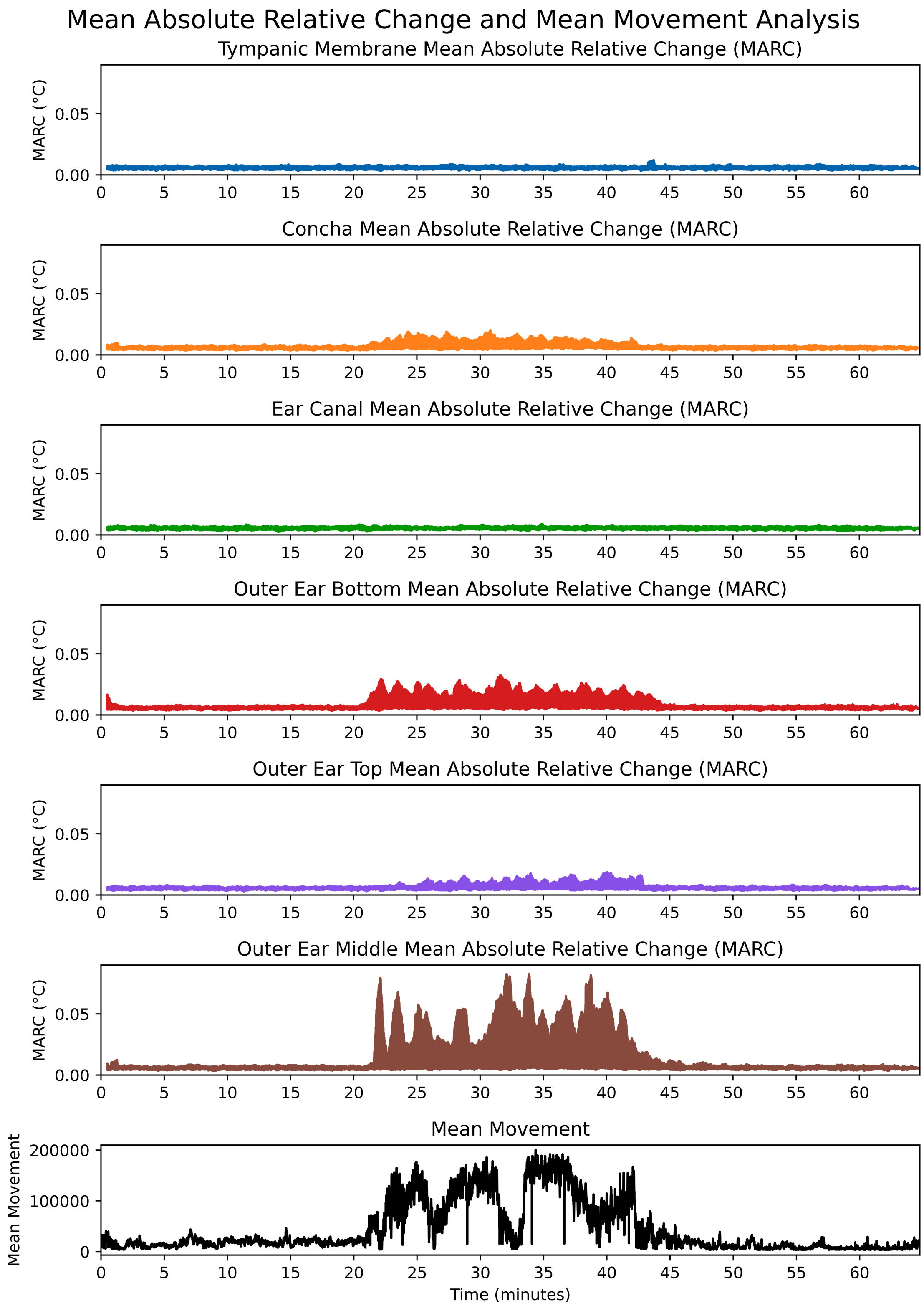

Figure 5.5: Analysis of mean absolute relative change (MARC) for ear-based temperature readings and mean absolute motion. The MARC for six different sensor positions in the ear is plotted for phases 2, 3, and 4 of the study. The last subgraph shows the mean motion calculated from the IMU data during the same phases.

Tympanic Membrane, Concha, Auditory Canal, Outer Ear Bottom, Outer Ear Top and Outer Ear Center. A 9-axis IMU sensor was used to measure mean inertial motion. The analysis was limited to phases 2, 3 and 4 of the calibration procedure because Phase 1 is used to acclimate the sensors. The mean absolute relative temperature change (MARC) was calculated for each sensor position and plotted versus time. For this purpose, the formula:

$$\text{relative change} = \left|T_{\text{current}} - T_{\text{previous}}\right|,$$

was used, where T_{current} and T_{previous} are the current and previous temperature values, respectively.

Figure 5.5 shows the mean relative absolute changes (MARC) per sensor, averaged across all subjects. These MARC plots per temperature sensor were combined with the mean motion data in a time series plot. This approach effectively captures the total motion intensity at each time point by considering all available IMU sensors. The motion data were averaged across all sensors and subjects to capture motion in all directions. The result shows a noticeable correlation between changes in temperature readings and subject motion, a consistency observed across different sensor positions. The temperature sensor aimed at the tympanic membrane shows the least change with movement, followed by the sensor in the ear canal. Somewhat surprisingly, the sensor behind the concha appears to show less change than the sensor inside the concha. However, the other two sensors behind the ear in the middle and bottom show much stronger relative changes. This is likely due in part to the fact that the sensors behind the ear, which are located slightly lower and are less protected by the hair, are more sensitive to environmental influences. The concha is also much more exposed to environmental influences from the front, which also explains the increase in this sensor. In general, relative changes can be seen for the individual temperature sensors in the three phases, but this may be due to different conditions. In Phase 3, the temperature generally decreased significantly when the subjects left the room and went outside. This is exacerbated by exercise during the outdoor phase. Thus, it cannot be clearly stated whether this is due to the outdoor temperature drop, the exercise itself or both. This evaluation provides the basis for future research on optimal sensor positioning and data fusion techniques for ear-based temperature sensing, especially during movement, but needs to be verified by further studies.

5.2 Results and Discussion of Study 2

Having checked the validity of the temperature measurements, a second study will now observe how the measured temperature behaves when the subject is placed under stress. A more detailed introduction to the design and objectives of Study 2 is described in Chapter 3.4.2. Additionally, a visual representation of the procedure of Study 2 can be seen in Figure 3.6.

After the study was conducted, a questionnaire was completed by each subject. This included the conditions and perceptions of the study. The study was conducted at a mean indoor temperature of 23.16°C and humidity of 53.56g/m^3. The outdoor temperature averaged 20.6°C. The external conditions were mostly sunny and cloudy. Subjects averaged 26 years of age (24-29) and were healthy. All test persons arrived in such a way that they had a short journey and had not previously done any activities that could significantly influence the temperature. After the study, all subjects were very positive about the prototype and rated it a 7.8 on a scale of 0-10. In comparison to the questionnaire from the first study, a NASA-TLX questionnaire was also attached, which should make the stress of the stress-induced phase more tangible. The scale here ranges from 0-10. Here, the mental demand was rated on average at 7.1, as well as the physical demand at 0.4. Since the stress tests (stroop test, N-back test, math test) each have mental demands and do not require physical demands, this reflects the expectation. Since the study was also expected to elicit time stress, the time requirement was also expected to be high. This was confirmed with a score of 7.3. Since the tasks were designed to not all be solvable in time, subjects were also asked about their personal performance. This was answered very differently, as some subjects were very satisfied with their performance, but others were not at all. This resulted in the mean value of 5.3. The effort of the subjects was on average 6.5 and the frustration was 4.6.

In order to fundamentally assess stress for the first time, an HRV measurement with the Polar H9 is performed in parallel. The raw data of the study measurement on Subject 4 can be seen in Figure 5.6. This will first test whether the subjects actually experienced stress during the study in Phase 3 by looking at the HRV signal and classifying the stress. Hypotheses are then tested and proven or disproven.

5.2.1 Stress Detection

At the outset, we examine whether the study actually produced stress in the subjects. This is necessary because the stress detection procedures used, although scientifically accepted, do not produce good results in every subject. A much better stress test would be the Trier Social Stress Test (TSST), but the time effort for such a huge study was not possible for this master thesis. To verify the stress score, HRV (heart rate variability) values were recorded using the Polar H9. These are saved in the form of a txt file, in which the RR intervals (resting rate) were persisted. With this information all values needed for the classification of stress can be calculated. These include SDNN (Standard Deviation of NN intervals), RMSSD (Root Mean Square of Successive Differences) and LF/HF (Low Frequency/High Frequency). The SDNN represents the variability in the time between successive heartbeats (NN intervals). Higher SDNN often indicates better autonomic flexibility, although it may increase or decrease under stress depending on individual variability. The RMSSD is another HRV metric for the classification of short-term variations in heart rate. In general, higher RMSSD values represent a healthier heart and lower stress. However, this can vary from person to person. The LF/HF ratio is a widely used analysis method to describe the balance between parasympathetic and sympathetic activities. Higher values often describe the dominance of sympathetic activity, i.e. stress. Lower values rather describe the dominance of the parasympathetic activity, i.e. relaxation. In addition, other measures were considered using the "KubiusHRV Standard" software. The software provides the parameters SNS index (Sympathetic Nervous System), PNS index (Parasympathetic Nervous System) and a stress index, which should confirm the findings from SDNN, RMSSD and LF/HF ratio. The SNS index describes the activities of the sympathetic nervous system. Higher positive values induce stress or fight-or-flight responses. The PNS index de-

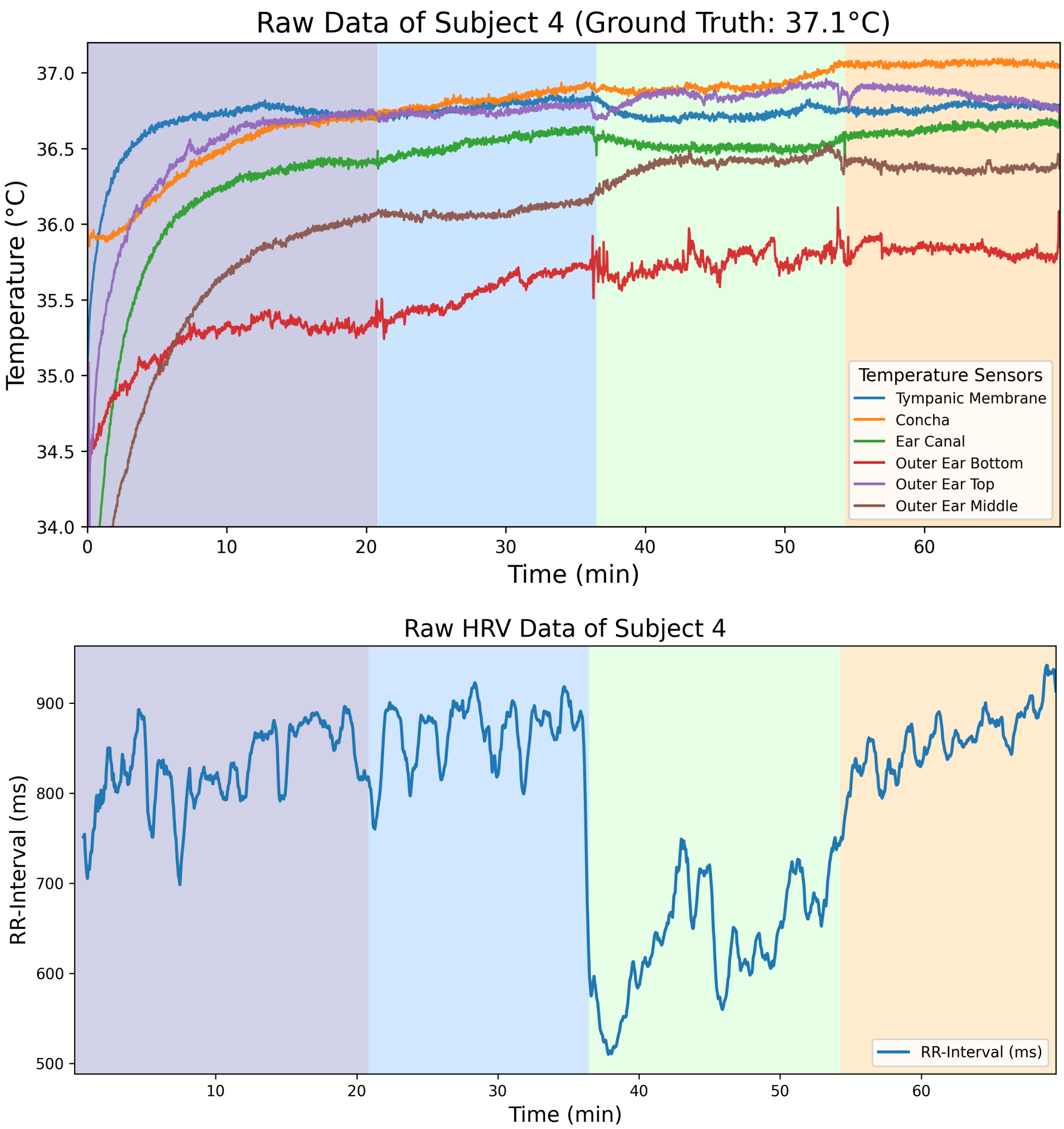

Figure 5.6: Raw data from Subject 4 during the complete measurement. In the first phase (acclimatization phase), the sensors get used to the new environment. In Phase 2 the baseline was measured, in Phase 3 the test person was put under stress. Phase 4 represents the relaxation phase.

scribes the activities of the parasympathetic nervous system. Higher positive values indicate relaxation. The results are shown in Figure 5.7.

Here it can be seen that for Subject 1, the SDNN and RMSSD value decreased during the stress-induced phase, which is an indication of stress. However, for Subject 1 there is also a decrease in LF/HF ratio, which is contrary to a normal stress-induced phase. The two SNS and PNS indices are helpful here, as values indicate stress, as the stress index does, which increases from 7 to 11. For Test Person 2, a slight increase in the values can be seen in the stress-induced phase, which is contrary to the expectation of recognizing stress. The stress index also remains stable at the value 8, which confirms the values. The PNS and SNS indices show slight increases, which could indicate stress, but the increases are not sufficient to detect a stronger

Subj.	SDNN (ms)		RMSSD (ms)		LF/HF		Stress-Index		PNS Index		SNS Index	
	Base	Stress	Base	Stress	Base	Stress	Base	Stress	Base	Stress	Base	Stress
1	65.89	47.25	29.66	21.99	12.08	9.80	7	11	-1.6	-1.85	1.96	2.73
2	70.93	71.62	42.05	44.76	2.75	3.49	8	8	-0.92	-0.98	0.87	1.02
3	150.45	163.09	99.82	79.58	0.68	1.22	5	6	2.21	0.92	-1.33	-0.51
4	101.44	71.71	35.86	19.37	2.08	4.40	9	14	-0.51	-2.01	0.33	2.73
5	225.16	202.75	268.12	235.46	0.29	0.34	2	2	7.26	6.44	-2.28	-2.24

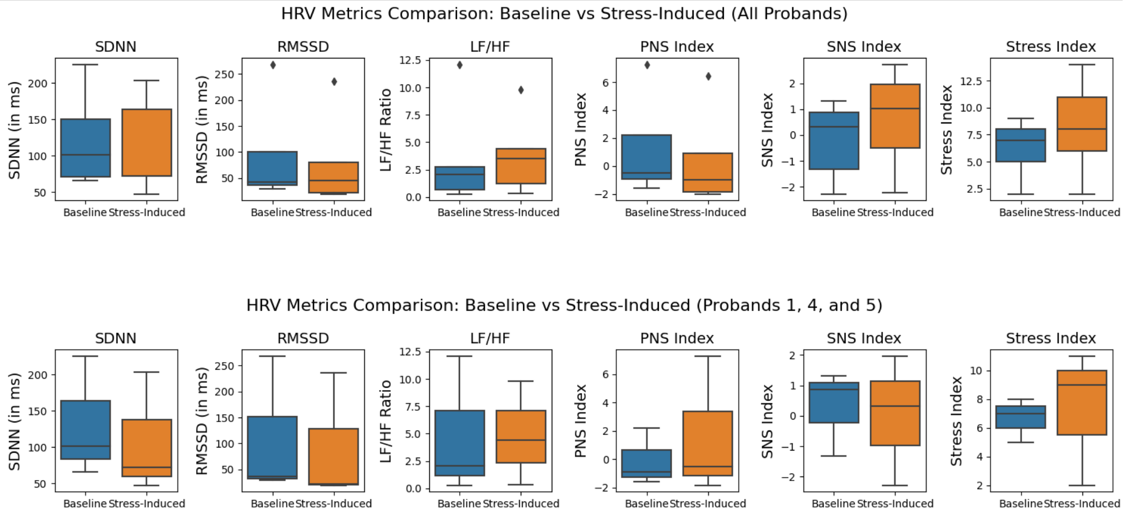

Figure 5.7: Comparison of heart rate variability (HRV) between baseline and stress induced phase in five subjects. SDNN, RMSSD, and LF/HF are HRV metrics, while stress index, PNS index, and SNS index are derived from analysis using "KubiosHRV Standard" software. All metrics are presented as pairs, with the baseline value appearing first, followed by the value under stress-induced conditions. Additionally, the values are presented as a boxplot across all subjects. The PNS is the regeneration index and indicates the recovery ability. The lower the value, the higher the regeneration phase and the more stressed the person is. The normal value is 0. The SNS is the stress index. The higher this value is, the higher the stress and accordingly the more stressed the person is. Here, too, the normal value is 0.

tendency here. Test Person 3, no stress can be detected on the basis of the SDNN and RMSSD values either, as an increase in the SDNN and a decrease in the RMSSD values can be seen here. However, the LF/HF ratio increases, which indicates stress, as the slight decrease in the PNS index and slight increase in the stress index to 14. However, the decrease in the SNS index is an atypical sign of stress, which is why stress cannot be accurately attributed to Subject 3 either. Proband 4 delivers the best values. Here a significant decrease of the SDNN and RMSSD values during the stress-induced phase, a dramatic increase of the LF/HF ratio, a strongly increasing stress index to 14. Furthermored, changes of PNS and SNS indices can be seen, which are all clear indications for stress. Subject 4 here provides exactly the expected responses to stress. Subject 5, on the other hand, shows a decrease in SDNN and RMSSD during the stress-induced phase. This indicates stress, which is confirmed by the slight increase in the LF/HF ratio. However, the stress index remained stable for Subject 5, and the PNS and SNS index increased slightly, which is additionally indicative of stress, even though the increases are very small.

Subject	Tympanic Membrane (in °C)	Concha (in °C)	EarCanal (in °C)	Outer Ear Bottom (in °C)	Outer Ear Top (in °C)	Outer Ear Middle (in °C)
1	-0.04	-0.0	-0.08	0.25	0.11	0.19
2	-0.01	0.2	0.16	0.14	0.1	0.27
3	0.0	0.21	0.17	0.15	0.12	0.02
4	-0.05	0.1	-0.02	0.2	0.11	0.32
5	-0.04	0.0	-0.04	0.05	0.03	0.11

(a) Temperature difference from baseline to stress-induced for each participant.

Subject	Tympanic Membrane (in °C)	Concha (in °C)	EarCanal (in °C)	Outer Ear Bottom (in °C)	Outer Ear Top (in °C)	Outer Ear Middle (in °C)
1	-0.02	-0.08	-0.07	-0.15	-0.04	-0.04
2	0.0	0.14	0.16	0.07	0.04	0.14
3	-0.03	0.1	0.11	0.28	0.02	0.11
4	0.04	0.14	0.12	0.08	0.0	-0.02
5	-0.15	-0.12	-0.13	-0.11	-0.06	-0.07

(b) Temperature difference from stress-induced to relaxation for each participant.

Figure 5.8: Evaluation of Hypotheses 1: Mean temperature changes during baseline, stress-induced, and relaxation phases. The tables represent the temperature changes between the phases. A negative value implies a temperature fall between the two comparing phases, and a positive value implies a temperature rise, respectively.

In summary, the study showed mixed efficacy in eliciting stress in the subjects, with Subject 4 showing the most consistent and significant signs of stress across all measurements. Interestingly, the male subjects (1, 4, and 5) generally showed more significant signs of stress compared to the female subjects (2 and 3) who showed ambiguous or inconsistent signs. This suggests that gender plays a role in these physiological responses, although further studies would be needed to confirm this hypothesis. However, this statement should be taken with extreme caution, as such conclusions are very difficult to make with such a small number of subjects. However, there is a tendency which can be further investigated by further studies.

5.2.2 Hypothesis 1: Stress-Induced Temperature Rise

To evaluate hypothesis 1, the analysis focuses on the average temperature changes measured by different ear-based sensors during three different phases: baseline, stress-induced, and relaxation. The first phase, which serves to acclimate the temperature sensors, is disregarded here for analysis. To ensure a fair comparison, the mean temperatures were subtracted with the ground truth for each participant.

To evaluate the hypothesis, the mean temperature per sensor per subject is calculated. From this, the temperature differences of the different phases are calculated, which can be seen in Figure 5.8. Here, table 5.8a shows the mean temperature difference between the baseline and stress-induced phases, and table 5.8b between the stress-induced and relaxation phases. A significant increase of up to $0.6°C$ can be expected [113, 93, 75]. The largest increase in temperature to the stress-induced phase is observed behind the ear in the middle with $0.27°C$, however, these results are not consistent enough. Most importantly, they are not consistent with the additional assumption that the temperature of the tympanic membrane provides the most accurate measurement results. This records a temperature drop of $-0.04°C$. In summary, the data do not provide clear evidence for the hypothesis. While there are minor variations, they are not consistently in the direction of a temperature increase during the stress-induced phase, making it difficult to definitively confirm the hypothesis. It is important to note at this point that the conduct of the study is also a critical factor. Since the study was conducted in a short time frame that did not allow for a social stress test (TSST) to be conducted, and also only five subjects were used in the study, a re-study with a larger sample is recommended to reach a more conclusive conclusion.

5.2.3 Hypothesis 2: Stress Test Temperature Variability

Hypothesis 2 states that the temperature changes between the different stress tests. This can happen because stress is triggered by the sympathetic nervous system when the body goes into fight-or-flight mode. This may be addressed differently during the different stress tests, which is then reflected in the body temperature. To evaluate hypothesis 2, the mean temperature change between each stress test per subject is calculated. The results are shown in Figure 5.9. Here, Table 5.9a shows the mean temperature differences between the Stroop test and the N-back test, Table 5.9b between the N-back test and the math test. The results show that there is no measurable temperature difference between the tests. Since previous studies have already shown that the signal at the tympanic membrane is the most accurate, no pattern is apparent with this small sample size. In both comparisons of the two tables, the maximum temperature change is $0.16\ °C$, which is definitely not due to a stress-induced temperature increase.

In summary, hypothesis 2 assumed that temperature changes between different stress tests would be detectable due to different sympathetic nervous system responses. However, the analysis as detailed in Figure 5.9 does not support this hypothesis. In particular, the tympanic membrane, previously identified as the most reliable sensor, showed negligible temperature changes during the stress tests. With a maximum temperature shift of $0.16°C$, the observed variations are statistically insignificant and cannot be attributed to stress-induced temperature changes. This limitation may be due in part to the small sample size, suggesting that more comprehensive studies are needed for a conclusive evaluation. In addition, a Trier Social Stress Test (TSST) could induce a stronger stress condition.

5.2.4 Further Discussion

For Study 2, there are additional hypotheses that can be considered. First, the correlation between heart rate variability (HRV) and ear temperature can be considered. In addition, it can be considered whether the ear temperature returns to the "normal level" after the stress-induced phase. It can also be considered that the regeneration of the body after the stress test differs from subject to subject and takes different amounts of time to return to baseline temperature. In addition, the thesis can be considered that stress has different characteristics between male and female subjects and whether this is also reflected in the temperature. For this, however,

Subject	**Tympanic Membrane (in °C)**	**Concha (in °C)**	**EarCanal (in °C)**	**Outer Ear Bottom (in °C)**	**Outer Ear Top (in °C)**	**Outer Ear Middle (in °C)**
1	0.0	0.03	-0.02	0.05	0.03	0.02
2	-0.01	0.06	-0.03	0.07	-0.01	0.11
3	-0.01	0.05	0.02	0.04	0.09	0.05
4	-0.08	-0.01	-0.06	0.04	0.11	0.16
5	-0.02	0.03	-0.02	0.09	0.05	0.06

(a) Temperature differences between Stroop and N-Back for each participant.

Subject	**Tympanic Membrane (in °C)**	**Concha (in °C)**	**EarCanal (in °C)**	**Outer Ear Bottom (in °C)**	**Outer Ear Top (in °C)**	**Outer Ear Middle (in °C)**
1	-0.06	-0.01	-0.05	0.03	0.02	0.05
2	-0.03	0.09	0.1	0.0	0.05	0.11
3	0.03	0.12	0.11	0.1	0.13	0.13
4	0.02	0.03	-0.01	0.06	0.01	0.02
5	-0.03	-0.04	-0.07	0.07	-0.01	0.02

(b) Temperature differences between N-Back and Math for each participant.

Figure 5.9: Summary of Hypothesis 2 Evaluation. The tables show mean temperature differences in °C for subjects participating in Stroop, N-Back, and Math stress tests between the different stress tests. A negative value implies a temperature fall between the two comparing phases, and a positive value implies a temperature rise, respectively.

the number of subjects must be significantly higher. However, it can already be seen in Table 5.8 that the temperature hardly changes between the stress-induced phase and the phases around it. Because of this, the analyses are not continued here, as a new study with an increased number of subjects is needed. In addition, the selected stress tests (as already mentioned in Section 3.4.1) do not elicit sufficient stress in every subject. A Trier social stress test (TSST) is also a clearly scientifically recognized stress test, which should be considered for this purpose in the future. In summary, Study 2 has provided very helpful information and some approaches for future work, but no meaningful conclusions can be confirmed.

6. Conclusion and Future Work

6.1 Conclusion

In this master's thesis, the field of ear-based temperature sensing was studied in depth, with a focus on sensor placement and evaluation for wearable applications.

The research began with the design and development of a prototype equipped with temperature sensors at various locations on the ear. The development of this prototype was a critical step because it enabled the collection of temperature data with high accuracy, which served as the basis for subsequent analysis. The prototype demonstrated the feasibility of ear-based temperature monitoring and its potential applications in healthcare and beyond.

The initial study, which focused on local temperature measurement at the ear, provided valuable insight into the intricacies of ear-based temperature sensing. It highlighted that sensors require an acclimation period to adapt to individual physiological conditions. It was also clearly seen that the temperature sensors always took different lengths of time to adapt to the new conditions. In addition, the study confirmed the reliability and stability of temperature readings at different locations on the ear. The results showed that the sensors were quite stable after the acclimation period, confirming the usefulness of the prototype for long-term temperature monitoring. While people sit in a room, the temperature of each sensor hardly changes, but it is constantly different between sensors. This is due to the different positions, as each has different temperatures. While the subjects went outside for a walk after the 20 minute sitting period, there was a noticeable drop in temperatures. The further the sensor was in the ear, the less the temperature changed. Here, it was clearly seen that the sensors were exposed to external conditions, such as the temperature drop (approximately 5°C outdoor temperature), wind, sunlight, and other conditions. After the subjects arrived back in the room, the temperature settled back to the value measured earlier in the second phase. In general, it was also shown that the variance in the outdoor phase was significantly higher than in the indoor phase (Phase 2). In addition, the sensors behind the ear were shown to have lower temperatures than the sensors in the ear and at the concha. Since motion data was recorded in addition to temperature, it was shown that the subjects exhibited increased relative absolute changes in the different temperature measurement points during the outdoor phase. The most stable measurement was obtained with the sensor pointing to the tympanic membrane. Here, the measurement was very close to the ground truth and had the least environmental effects to show.

The second study focused on investigating the effects of stress on ear temperature. The study was designed with three different stress-inducing tests to provide a holistic view of the effects of stress. Due to limited capacity, a Trier social stress test (TSST) was not used, which is currently considered the best scientific option to induce stress. In the study, five subjects were used for recording, in which initial tendencies were shown. Only one subject had clear rashes of stress during the stress phase, the other subjects showed mild to no signs of stress. It was recognizable that slight to strong signs were seen in male subjects and no signs of stress in female subjects. However, this cannot be generalized directly because the number of subjects was too small (5, 3 male, 2 female). When looking at temperature, no significant temperature increases were detected during stressful periods. However, this is also not an indication that the temperature does not increase during stress, since on the one hand the number of subjects was much too small for this and on the other hand the optimal stress test was not selected due to time constraints. Further studies are needed to provide clarity here.

Overall, the results of this research have implications not only for stress detection, but also for a broader range of applications such as health monitoring and potentially early disease detection. The thesis successfully bridged the gap between theoretical concepts and practical implementation and provides a foundation for future work in this promising area.

6.2 Future Work

This chapter presents possible future work that can be built upon the foundation of this thesis. This thesis focused on building a prototype, looking at its measured values in a first study and also collecting first findings on temperature changes under stress in a small scale. Based on this, there are numerous areas which can be investigated with the new prototype.

Detection of Circadian Rhythm

One of the most interesting avenues for future work is the study of circadian rhythm patterns through ear-based temperature measurements. By using the prototype, continuous temperature monitoring can provide data that can give insight into a person's biological clock and help diagnose and treat sleep disorders, among other things. Here, across the different sensor positions, it is possible to test which sensor can be used to detect such patterns. This could have far-reaching consequences should a sensor other than the sensor pointing to the tympanic membrane also detect such patterns. This is because it would then be possible to integrate such a sensor into a conventional in-ear headphone and monitor the body's temperature for a longer period of time.

Early Detection of Disease

The prototype can also make a significant contribution to the detection of diseases, since, among other reactions of the body, the core body temperature also increases due to a defensive reaction to viruses and bacteria. Here, core body temperature is an early indicator of disease. It could be checked whether this can also be detected by the various sensors of the prototype.

Cycle Tracking for Women

Another promising application is tracking women's menstrual cycles. Body temperature is known to change slightly during the menstrual cycle. Continuous monitoring via the ear could provide a non-intrusive method of tracking these changes. This could aid in fertility planning or in detecting irregularities that might require medical attention.

TSST for Stress Detection with Increased Sample Size

To further validate stress detection skills, administration of the Trier Social Stress Test (TSST) could be beneficial in future studies. The TSST is a standardized procedure for inducing psychological stress and could provide a more comprehensive assessment of the prototype's stress detection abilities. This test would extend the second study conducted in this thesis. This would again test the expected temperature increases, which were not detected in the setup used in this master thesis Notably, the second study was conducted with a limited number of subjects. Future work could include a larger, more diverse population to statistically validate the results.

Real-World Applications

Future work could include field studies in which participants perform everyday activities while wearing the device. This would test the robustness and applicability of the device in real-world conditions and potentially reveal unforeseen challenges or opportunities. However, battery life would need to be optimized for this. Activity classification would also need to be accurate.

Approaches to Machine Learning

The rich dataset generated by the prototype could be used to train machine learning models for automatic detection of different physiological states or conditions to create a smarter, more adaptive system.

By pursuing these avenues for future research, this work can be expanded and refined and contribute to the growing body of knowledge in wearable health technologies. The optimal position for detecting as many symptoms as possible, coupled with a position that fits into an everyday object such as in-ear headphones, provides tremendous scientific potential. It also provides very important health values for the user, which he currently cannot obtain through any other alternatives.

7. Appendix

The appendix contains the schematic of the two boards that were created for the prototype.

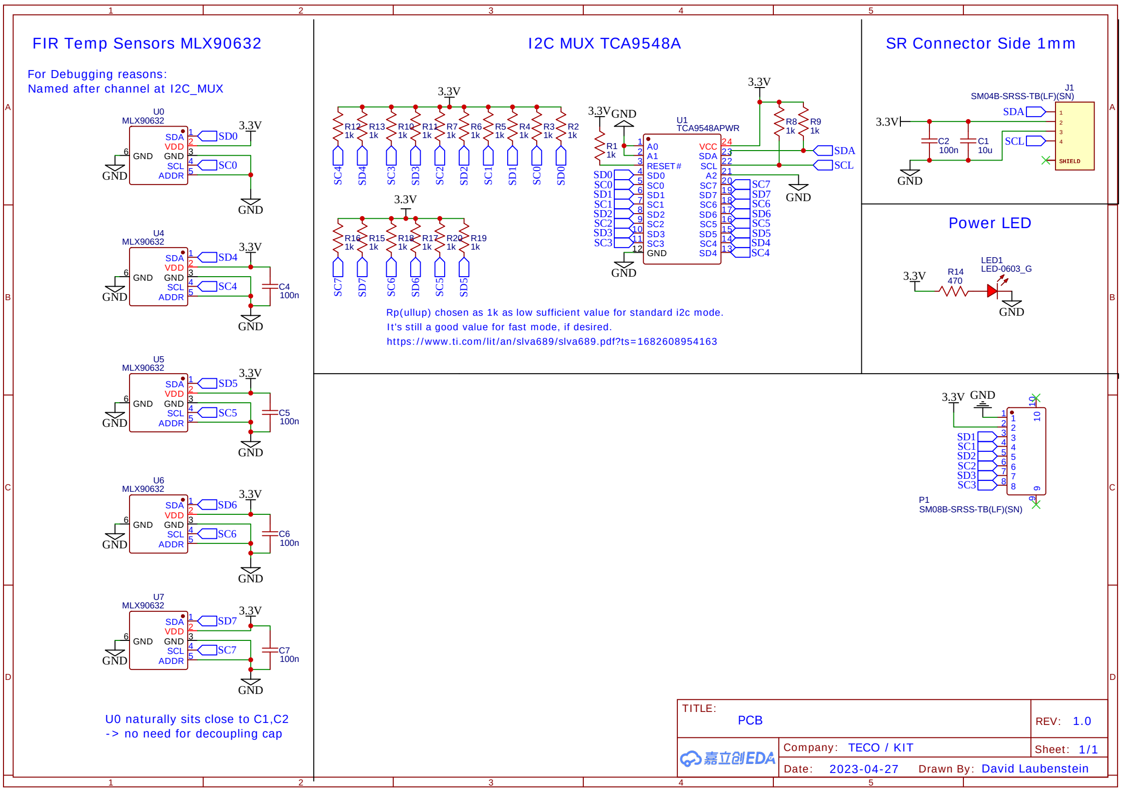

Figure 7.1: Schematic of the PCB which is placed behind the ear.

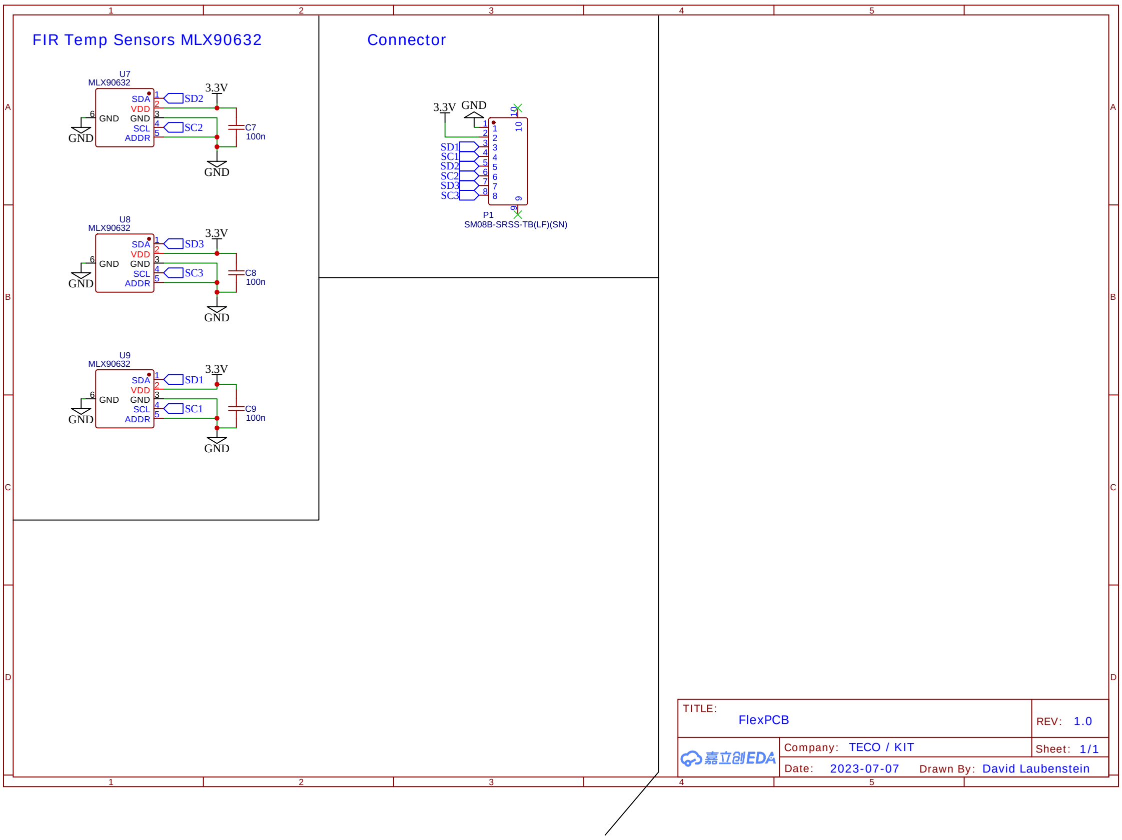

Figure 7.2: Schematic of the FlexPCB which is placed in the prototype in the ear.

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