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The Comfstat – Automatically sensing thermal comfort for smart heating

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Abstract

Current smart thermostats use a simple strategy when aiming to increase the efficiency of heating and cooling systems, they adjust the temperature whenever the conditioned zone becomes empty. However, while targeting energy savings, these systems often neglect inhabitants' thermal comfort. We propose to increase thermal comfort by automatically monitoring the inhabitants' satisfaction with the thermal environment using different hardware components. To this end, we designed the Comfstat infrastructure, capable of collecting essential parameters for thermal comfort prediction. We then use our system to collect detailed temperature and heart-rate data of five users and show that thermal comfort can be inferred automatically from a combination of sensor data within 0.5 points on the ASHRAE scale.

Zusammenfassung

Aktuelle intelligente Thermostate verwenden für die Effizienzerhöhung von Heiz- und Kühlsystemen eine einfache Strategie: sie regulieren die Temperatur, wenn sich keine Personen in der klimatisierten Zone befinden. Da dabei der Fokus auf der Energieeinsparung liegt, vernachlässigen diese Systeme oft die thermische Behaglichkeit der Bewohner. Wir schlagen vor, die thermische Behaglichkeit zu erhöhen, indem wir die Zufriedenheit der Bewohner mit der thermischen Umgebung mit verschiedenen Hardware-Komponenten überwachen. Zu diesem Zweck haben wir die Comfstat-Infrastruktur entwickelt, die die wesentlichen Parameter für die Vorhersage thermischer Behaglichkeit sammelt. Im Anschluss verwenden wir unser System um detaillierte Temperatur- und Herzfrequenzdaten von 5 Anwendern zu sammeln und zeigen, dass die thermische Behaglichkeit automatisch aus einer Kombination von Sensorendaten innerhalb von 0,5 Punkten auf der ASHRAE-Skala abgeleitet werden kann.

Dedicated to my parents

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1 Introduction

A number of studies on climate change have heightened the need for reducing greenhouse gas emissions [40, 53]. In particular, on the 13th December 2015, 195 countries agreed to keep the global temperature to $1.5°C$ above pre-industrial levels [55]. According to the International Energy Agency (IEA), in 2010 energy consumption represented by far the largest CO_2 source of global greenhouse gas emissions. In 2013, 82% of energy consumed came from fossil fuel sources. Continued energy demand plays an important role in the increasing trends on CO_2 emissions [16]. Hence, finding ways to decrease energy consumption is crucial. Current building automation systems seek to reduce energy consumption of heating ventilation and air conditioning (HVAC) units. To this end, numerous projects in research [33, 38, 52] and industry [39, 54] have shown the feasibility of developing systems and algorithms to autonomously regulate temperature in buildings.

Smart thermostats integrated into building systems attempt to reduce energy waste. However, user acceptance for such smart thermostats is still quite low [31, 45, 56]. Non-technical challenges like sensor placement, uncertainty about the choices made by the system and doubts regarding achievable savings are some of the causes for low acceptance of these devices. Even if they show how energy consumption can be reduced, they often struggle with providing *thermal comfort* for the occupants. In fact, to save the maximum amount of energy, one could simply switch off the HVAC system altogether [44].

Most modern HVAC systems use a simple strategy, they define a single comfort temperature. The building is then kept at this temperature throughout the day whenever it is occupied. Even though the chosen temperature may have been obtained from experiments, the fact that it is fixed makes no allowances for the individual occupants' thermal preferences, which can translate into user discomfort. In this thesis, we target this problem by evaluating techniques to automatically sense thermal comfort from the occupants' heart rates as well as ubiquitous temperature and humidity sensors.

The American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) defines thermal comfort as "that condition of mind that expresses satisfaction with the thermal environment" [4]. As such it is expressed by a combination of environmental as well as personal factors—including the clothing, health and mental state of the occupants. Since Ole Fanger first examined these factors in 1970 [10], further research has established various standards such as ASHRAE 55 [4] and ISO 7730 [24].

Recently, there has been growing interest to build systems to sense comfort automatically [9, 13, 14, 32], following Fanger's observations. These systems combine sensory input (e.g., infrared temperature sensors) with user participation (i.e., through voting on the current comfort level) to enhance the accuracy of their models due to the complexity posed when trying to obtain some of the parameters which influence thermal comfort (e.g., air speed and mean radiant temperature) in real-world settings. While some of these systems include the metabolic rate in their calculations, in no case did they use available sensors to sense the heart rate as a proxy for the metabolic rate.

The significance of the metabolic rate for thermal comfort has recently been re-affirmed by Luo *et al.* [34]. The authors have shown that an increase in the metabolic rate is often a sign for discomfort. We build upon this work and the fact that the heart and the metabolic rate are closely related [22] to design our system–The Comfstat.

The Comfstat architecture allows for the collection of heart rate data from both Android Wear smart watches and compatible Bluetooth chest straps. By using a machine learning approach and combining the heart rate with temperature and humidity data, we present a system that predicts thermal comfort automatically from the raw sensor data.

Besides showing that our approach can deduce thermal comfort with a mean error between 0.10 and 0.36 on the 7-point ASHRAE scale, we make the following contributions:

- An *infrastructure* to collect sensory data from Android Wear watches, compatible BLE heart rate monitors, temperature and humidity sensors; as well as an application for registering ground truth thermal comfort through voting on both Android and Android Wear devices.
- A thermal comfort *dataset*[1] comprised of five participants, and including three different experiments.
- A comparison between heart rate data collected on current *smart watches* and *dedicated chest straps*.
- An overview of the feature space and a detailed analysis of the performance of two approaches to predict thermal comfort.
- A comparison of the accuracy of PMV calculation using three different methods to estimate metabolic rate.

[1] `https://github.com/LilianaB/ComfstatDataSet`

Our work comprised three significant stages: (i) system design and implementation, (ii) data collection and (iii) machine learning. Each of them was executed sequentially.

The rest of this document is organized as follows. Chapter 2 explains fundamental notions for the understanding of this thesis. Chapter 3 introduces the most significant standards with regards to thermal comfort and our research, and relevant related work. Chapter 4 describes the system's design, specifically, it shows Comfstat's use case specification, user interface design and architectural design. Chapter 5 explains in detail how we used different technologies to collect all data needed for predicting thermal comfort. At this point of the thesis we documented all work related to stage (i) of our project. Chapter 6 shows how we executed the data collection stage through different empirical studies. Chapter 7 and 8 detail the machine learning stage, where our model and different regressions techniques are shown. Lastly, we draw the conclusions of our work in Chapter 9.

2 Fundamentals

This chapter describes fundamental notions related to this thesis. The chapter is composed of three sections. The first section defines basic concepts that are addressed in this thesis. Section two describes the importance of Fanger in thermal comfort research. Lastly, section three explains how human thermo-regulation works.

2.1 Definitions

Air speed: Ashrae Standard 2010 defines air speed as “the rate of air movement at a point, without regard to direction” [4].

Air temperature: as quoted by Parsons, air temperature can be defined as:

> The temperature of the air surrounding the human body which is representative of that aspect of the surroundings which determines heat flow between the human body and the air [42].

Clothing insulation: Ashrae Standard 2010 defines clothing insulation as “the resistance to sensible heat transfer provided by a clothing ensemble” [4]

Heart rate: Binder *et al.* define heart rate as “the number of contractions of the ventricles per unit of time, typically expressed as beats per minute (bpm)” [36].

Mean radiant temperature: Ashrae Standard 2010 defines mean radiant temperature as:

> The uniform surface temperature of an imaginary black enclosure in which an occupant would exchange the same amount of radiant heat as in the actual nonuniform space [4].

Metabolic rate: Ashrae Standard 2010 defines metabolic rate as:

> The rate of transformation of chemical energy into heat and mechanical work by metabolic activities within an organism, usually expressed in terms of unit area of the total body surface [4].

Predicted mean vote (PMV): Ashrae Standard 2010 defines PMV as "the index that predicts the mean value of the votes of a large group of persons on the seven-point thermal sensation scale" [4].

Predicted percentage of dissatisfied (PPD): Ashrae Standard 2010 defines PPD as "the index that establishes a quantitative prediction of the percentage of thermally dissatisfied people determined from PMV" [4].

Relative humidity: Ashrae Standard 2010 defines relative humidity as:

> The ratio of the partial pressure (or density) of the water vapor in the air to the saturation pressure (or density) of water vapor at the same temperature and the same total pressure [4].

Thermal comfort: Ashrae Standard 2010 defines thermal comfort as "that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation" [4].

Thermal neutrality: Ashrae Standard 2010 defines thermal neutrality as "the indoor thermal index value corresponding with a mean vote of neutral on the thermal sensation scale" [4].

Thermal sensation: Ashrae Standard 2010 defines thermal sensation as:

> A conscious feeling commonly graded using the categories cold, cool, slightly cool, neutral, slightly warm, warm, and hot; it requires subjective evaluation [4].

2.2 Human thermo-regulation

Human body heat is produced in the cells of our bodies. Our body produces metabolic heat to maintain an internal body temperature of around 37 °C, known as *set point* temperature. The body has different mechanisms to attempt preserving or losing sufficient heat to the environment to try to maintain that temperature. Hence, estimating metabolic heat production is fundamental to the assessment of human thermal environments [42].

One of the most powerful forms of human thermo-regulation is behavioral; putting on or taking off clothes, changing posture, moving, taking shelter, etc [42]. Additionally, the human body has a physiological system of thermo-regulation, its goal is to ensure human survival and comfort.

Figure 2.1 describes a simplified model of physiological thermo-regulation. Most models that describe physical thermo-regulation agree on the body responses. They all recognize that when the body becomes hot it loses heat by vaso-dilation, and sweating if necessary. When the body becomes cold, the heat is preserved by means of vaso-constriction, and shivering. Details of how our body senses and how information is processed by the controller (hypothalamus) are not known yet. In particular, how is the so-called *set point* established and how it changes with certain factors such as time and exercise [42].

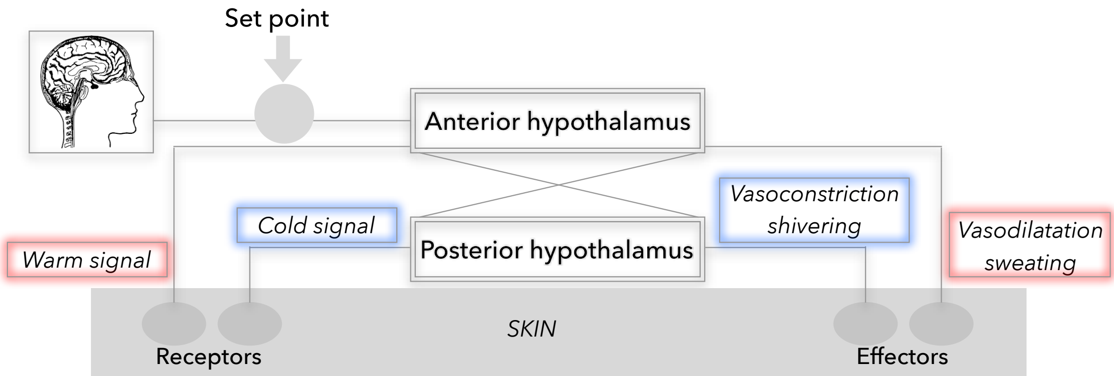


Figure 2.1: Simplified diagram of the human thermo-regulatory system. "Displacement of brain temperature above the *set point* results in vaso-dilation and sweating; while displacement below set point produces vaso-constriction and shivering". (Modified from Parsons 2014 [42].)

2.2.1 Effects of Temperature

Heat exposure: If the temperature of the body is increased, the rate of chemical reactions (in cells) increases by around 13% for each 1 °C rise in temperature. Muscle stiffness is reduced and blood and synovial fluid becomes less viscous, enabling faster rates of body activity. In hot environments people may adapt by slowing down to maintain comfort or avoid heat strain even in what appear to be paced tasks. *Metabolic rate* may be increased by adaptive mechanisms such as opening windows or moving from areas of discomfort. In cold environments there is a good incentive to move around and increase metabolic heat [42].

Cold exposure: When the body cools, for a resting person there is a lower critical temperature below which metabolic heat production starts to increase by non-shivering thermo-genesis or shivering. Shivering can increase metabolic rate by up to 4-5 times that of the non-shivering subject [42].

2.3 Bluetooth Low Energy (BLE)

Bluetooth is a wireless personal area network technology with low energy requirements. This makes it suitable for running long periods on power sources such as coin cell batteries. Two roles are defined in a BLE connection: central and peripheral. The central role scans, looking for service advertisement, while the device in the peripheral role makes the advertisement, to let other devices know that it is available.

2.3.1 GATT

GATT is an acronym for Generic Attribute Profile, it defines the way two BLE devices transfer data between each other. GATT is built on top of the Attribute Protocol (ATT). This is also referred to as GATT/ATT. ATT is optimized to run on BLE devices, by using as few bytes as possible. Each attribute is uniquely identified by a Universally Unique Identifier (UUID), which is a standardized 128-bit format for a string ID used to uniquely identify information. The attributes transported by ATT are formatted as characteristics and services.[1]

GATT defines two roles: Server and Client. The GATT server responds to GATT client requests, also it sends indications and notifications asynchronously to the GATT client when specified events occur on the GATT server.

GATT transactions in BLE are based on a hierarchical data structure containing nested objects called Profile, Service and Characteristics. The structure is exposed to connected BLE devices. Figure 2.2 shows GATT data structure.

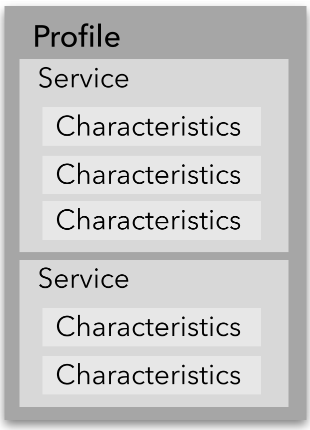


Figure 2.2: GATT hierarchical data structure.

[1]Google Developers. Bluetooth Low Energy. Retrieved from `https://developer.android.com/guide/topics/connectivity/bluetooth-le.html` (accessed April 10, 2016).

Profile

The GATT Profile is the top level of the hierarchy, it specifies the structure in which profile data is exchanged. This structure defines basic elements such as services and characteristics used in a profile. A profile is composed of one or more services necessary to fulfill a use case.[2] These services can be already defined as a bluetooth adopted standard or they can be defined during implementation.

Service

A service is a collection of data. They are used to break data up into logic entities, and contain specific chunks of data called characteristics. A service can have one or more characteristics, and each service is uniquely identified with a numeric ID called a UUID, which can be either 16-bit (for officially adopted BLE services) or 128-bit (for custom services).[3]

Characteristic

Encapsulates a single data point. As services, characteristics are distinguished via pre-defined 16-bits or 128-bits UUID. Characteristics are important because they are the main point of interaction with BLE peripheral devices.

[2] Bluetooth. GATT. Retrieved from `https://developer.bluetooth.org/TechnologyOverview/Pages/GATT.aspx` (accessed April 10, 2016).

[3] Adafruit. Bluetooth Low Energy. Retrieved from `https://learn.adafruit.com/introduction-to-bluetooth-low-energy/gatt` (accessed April 10, 2016).

3 Related Work

3.1 Fanger (1970)

Povl Ole Fanger was a Danish expert in the field of thermal comfort. His book *Thermal Comfort* is the most significant landmark in thermal comfort, it defines the conditions necessary for thermal comfort as well as methods and principles for assessing thermal environments with respect to thermal comfort [42]. Fanger's methods are the most influential and widely used around the world. The main reason for his success is considering the "user's requirements" [42]. He recognized that the combined effect of six factors, four physical variables (air temperature, air velocity, mean radiant temperature, and relative humidity), and two personal variables (clothing insulation and activity level) were crucial to determine the average thermal comfort level of a group of people, this is what is known as Fanger's equation for predicted mean vote (PMV) of a large group of persons. PMV's equation provides the thermal comfort sensation on a seven-point scale, refer to table 3.1 for detail.

3.2 ASHRAE Standards

The American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) published two important documents concerning human response to thermal environment: a standard called *Thermal Environmental Conditions for Human Occupancy* which is the ANSI/ASHRAE Standard 55, and *Thermal Comfort* [42].

ASHRAE 55 defines conditions for acceptable thermal environments for a majority of occupants in a building. The standard is based on Fanger's findings that human

Table 3.1: Seven-point thermal sensation scale.

Thermal sensation	**Score**
Hot	+3
Warm	+2
Slightly warm	+1
Neutral	0
Slightly cool	−1
Cool	−2
Cold	−3

thermal comfort level is influenced by a combination of four physical variables and two personal variables. ASHRAE 55 identifies six primary factors (metabolic rate, clothing level, air temperature, mean radiant temperature[1], air speed and humidity) that influence the occupants' satisfaction with the thermal environment. Based on climate chamber experiments, the standard provides equations to compute thermal comfort from these factors [42].

3.3 ISO Standards

The International Organization for Standardization (ISO) has established international standards around the world "as practical methods for assessing heat stress, cold stress and thermal comfort in indoors as well as outdoors environments" [42]. These standards are developed by a panel of international experts and are agreed through a voting system by member countries. Member countries consider both scientific content and validity as well as practical consequences of the use of the standards when voting [42]. ISO has defined numerous standards concerning ergonomics of the thermal environment, these standards can be used as assessment methodologies [17–28]. This thesis is based on the ISO 7730 and ISO 8996 standards.

3.3.1 ISO 7730: Ergonomics of the Thermal Environment – Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria

Ashrae [3] defined thermal comfort as "that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation". Whole body discomfort assessment is based on Fanger's indices predicted mean vote (PMV) and predicted percentage of dissatisfaction (PPD) [42]. ISO 7730 provides an analytical method for assessing moderate environments based on the PMV and PPD indices. More specifically, the standard provides equations to determine these indices, and also explains how to interpret them.

3.3.2 ISO 8996: Ergonomics of the Thermal Environment – Determination of Metabolic Rate

The standard provides different methods for estimating metabolic heat production of humans. It serves as support to other ISO standards. One key parameter of the PMV is the metabolic rate. Therefore, ISO 8996 [22] establishes different methods for the determination of metabolic rate in the context of climatic working environment. The standard states that in most types of industrial work the muscular work is so small

[1]The average temperature of surfaces like the floor and the walls.

that it is assumed to be negligible and set to zero. In consequence, the total energy consumption while working can be assumed equal to the heat production. Similarly, in ISO 8996, the metabolic rate is assumed to be equal to the heat production rate.

ISO 8996 presents different approaches for determining metabolic rate. Four levels of accuracy are specified, the accuracy of the results and costs of the study increases from level one to level four. Meaning that the most accurate results are achieved by using level four. Table 3.2 depicts the four different levels with their respective accuracy.

Level	**Method**	**Accuracy**
1. Screening	1A: Classification according to occupation	Rough information
	1B: Classification according to activity	Very great risks of error
2. Observation	2A: Group assessment tables	High error risk
	2B: Tables for specific activities	Accuracy:±20%
3. Analysis	Heart rate measured under defined conditions	Accuracy:±10%
4. Expertise	4A: Measurement of oxygen consumption	Errors within the limits of the accuracy of the measurement or of the time and motion study
	4B: Doubly labeled water method	
	4C: Direct calorimetry	Accuracy:±5%

Table 3.2: Levels for the determination of the metabolic rate. (Adapted from ISO 8996 [22].)

Relation between heart rate and metabolic rate

The ISO standard established a linear relationship between heart rate and metabolic rate in the range from a lower limit of 120 bmp up to 20 bpm below the maximum heart rate of the person. In this range the relationship between both variables can be written as:

$$HR = HR_0 + RM \times (M - M_0) \tag{3.1}$$

where M corresponds to the metabolic rate, in watts per minute; M_0 corresponds to metabolic rate at rest, in watts per square meter; RM is the increased heart rate per unit of metabolic rate and HR_0 is the heart rate, under neutral thermal conditions. The standard states that when (1) is derived from HR and M measurements during an experiment, its precision is estimated at ±10%.

From (1) we can then derivate M as:

$$M = \frac{1}{RM} HR - HR_0 + M_0 \tag{3.2}$$

The standard also provides a set of equations based on subjects characteristics such as age (A years), weight (P kilogram) to estimated different parameters of (1). Using the estimates implicates further loss in the accuracy. However, the standard does not specify how much accuracy is lost. Expression (1) can be derived from the following estimates.

Metabolic rate at rest as:

$$M_0 = 55Wm^{-2} \tag{3.3}$$

Increase in heart rate per unit of metabolic rate as:

$$RM = \frac{(HR_{max} - HR_0)}{MWC - M_0} \tag{3.4}$$

Maximum working capacity MWC

$$Men : MWC = (41,7 - 0,22A)P^{0,666}Wm^{-2} \tag{3.5}$$

$$Women : MWC = (35,7 - 0,22A)P^{0,666}Wm^{-2} \tag{3.6}$$

Maximum heart rate HR_{max} estimated by:

$$HR_{max} = 205 - 0,62A \tag{3.7}$$

Additionally, the standard provides direct estimations of the $HR - M$ relationship for men and women with ages between 20 and 60 years and weights from $50kg$ to $90kg$.

3.4 Limitations of current thermostats

Peffer *et al.* found out that nearly half of the users with programmable thermostats do not use the programming features, mainly due to difficulties understanding the thermostat's interface. Particularly, users noted "smart" thermostat complexity, small size of buttons and text, confusing terms and symbols, and the number of steps needed to program the device. [43]. Similarly, Karjalainenam *et al.* found that even when local control for thermostats is available for occupants, they are rarely used, even when occupants are in thermal discomfort. Again, poor interface design restrained users from interacting with the controls [51].

Other researches have focused their work on analyzing how people use smart thermostats, and have shown that there is still low acceptance towards these smart devices. Yang *et al.* reported lessons learned for intelligent systems for the home, they based their research on the Nest[2] thermostat, and found out that some intelligent features of the nest were not perceived to be as intelligent or intuitive as expected, in particular due to the system's inability to understand user's intent or behavior [56].

[2]Nest thermostat: smart thermostat for heating and cooling systems with learning capabilities such as automatic scheduling. Retrieved from `https://nest.com/thermostat/meet-nest-thermostat/` (accessed July 8, 2016).

3.5 Systems for sensing thermal comfort

Many researchers have realized the importance of Fanger's findings regarding "user's requirements" to accurately predict thermal comfort. In this section we show existing approaches that have their foundations on Fanger's work.

3.5.1 Enhancing PMV and PPD

As both PMV and PPD do not explicitly track individual occupants' thermal comfort levels, Gao *et al.* introduced the "Predicted Personal Vote" model which extends the PMV for individual occupants [13, 14]. The model allows to achieve different micro-climates using personal heating and cooling appliances. Gao *et al.* measure the temperature near the surface of the occupants' clothing using an infrared thermometer directed by a Microsoft Kinect camera. However, for the metabolic rate they depend on pre-computed tables.

Other work examines how occupants can dynamically vote on their current thermal comfort. In [9], Erickson *et al.* allow occupants to use their iPhone to vote on the 7-point ASHRAE scale, periodically. In [32], Lam *et al.* provide a mobile application for occupants to express their thermal satisfaction.

Metabolic rate estimation

There are conflicting opinions with regards to metabolic rate calculations for PMV. Past studies have treated metabolic rate as constant depending on the activity level of the person [13,14,29,35]. However, this is thought to be inaccurate as people tend to engage in different activity levels through the day rather than performing the same activity nonstop. Moreover, there are other factors that can affect metabolic rate, for example, thermal conditions. Luo *et al.* in their research [34], measure the impact of thermal conditions on occupants' metabolic rate. They used climate chambers for the experiments, together with both physiological measurement and subjective questionnaires. They concluded that metabolic rate can be significantly affected by thermal conditions such as environment temperature and cloth insulation level.

Havenitha *et al.* in their work show that the methods provided by ISO 8996 for determining metabolic rate do not offer sufficient accuracy to determinate comfort (expressed in PMV) in sufficient precision to classify buildings to within 0.3 PMV units. ISO 8996 states that there is a linear relation between metabolic heat production for heart rates above 120 bpm. However, to this statement, the researches argue that a heart rate of 120 bmp implies work level beyond office work [15]. Alternatively, Freedson *et al.* propose using motion sensors and heart rate monitors to estimate activity levels, they recommend using heart rate simultaneously with motion to achieve better accuracy as neither of these sensors separately can be described as perfect markers of physical activity [11]. Other studies, independent from thermal comfort, have successfully estimated energy expenditure (EE) by means of heart rate monitoring [6, 49].

Only, few systems currently attempt to measure the metabolic rate to assess thermal comfort. Ciabattoni *et al.* propose a system utilizing a Raspberry Pi to measure environmental parameters like the temperature and CO_2 levels [7]. In addition they use a smart watch to measure the heart rate and skin temperature. The authors depend on fixed equations from ISO 8996 to deduce metabolic rate from the raw measurements [22].

Revel *et al.* propose an environmental monitoring system to monitor the PMV in an environment. However, while they discuss the importance of using the correct metabolic rate during the calculation they require the user to input their clothing level and metabolic rates manually through an Android device [46].

4 Design

This chapter describes Comfstat's infrastructure and user interface design, paying special attention to Comfstat's most significant characteristic, its ability to retrieve data to predict thermal comfort with minimal user interaction. In section 4.1, we introduce Comfstat's use cases, these allowed us to define all possible interaction between users and our system. Following, section 4.2 shows the high fidelity prototype developed while designing Comfstat's user interface. Finally, section 4.3 defines Comfstat's architecture.

During Comfstat's preliminary work, we used scenario-based development techniques to elaborate our system's concept, for further details on Comfstat's vision and resulting use case scenarios refer to appendix A.

4.1 Use case

Comfstat includes functionality from user account management to user's heart rate retrieval. We did several iterations over the use case specification, figure 4.1 depicts Comfstat's final use case diagram. Use cases highlighted in blue represent Comfstat's core functionality to retrieve data needed for thermal comfort prediction. The rest of the use cases serve as support features. For a detailed use case specification refer to appendix B.

4.2 User interface

Following the use case specification, we executed an iterative process to design Comfstat's user interface considering existing hardware and software limitations. Figure 4.2 shows the most relevant interfaces of the smart phone application, these include:

- Comfstat's main menu (cf., Figure 4.2a).
- Interface to provide thermal comfort feedback (cf., Figure 4.2b), there, each option has a color that represents the comfort level.
- Request user's current heart rate (cf., Figure 4.2c).
- Overview of last summited thermal comfort feedbacks (cf., Figure 4.2d).
- Review current environment state (cf., Figure 4.2e).
- Finally, figures 4.2f to 4.2h display Comfstat's settings interface.

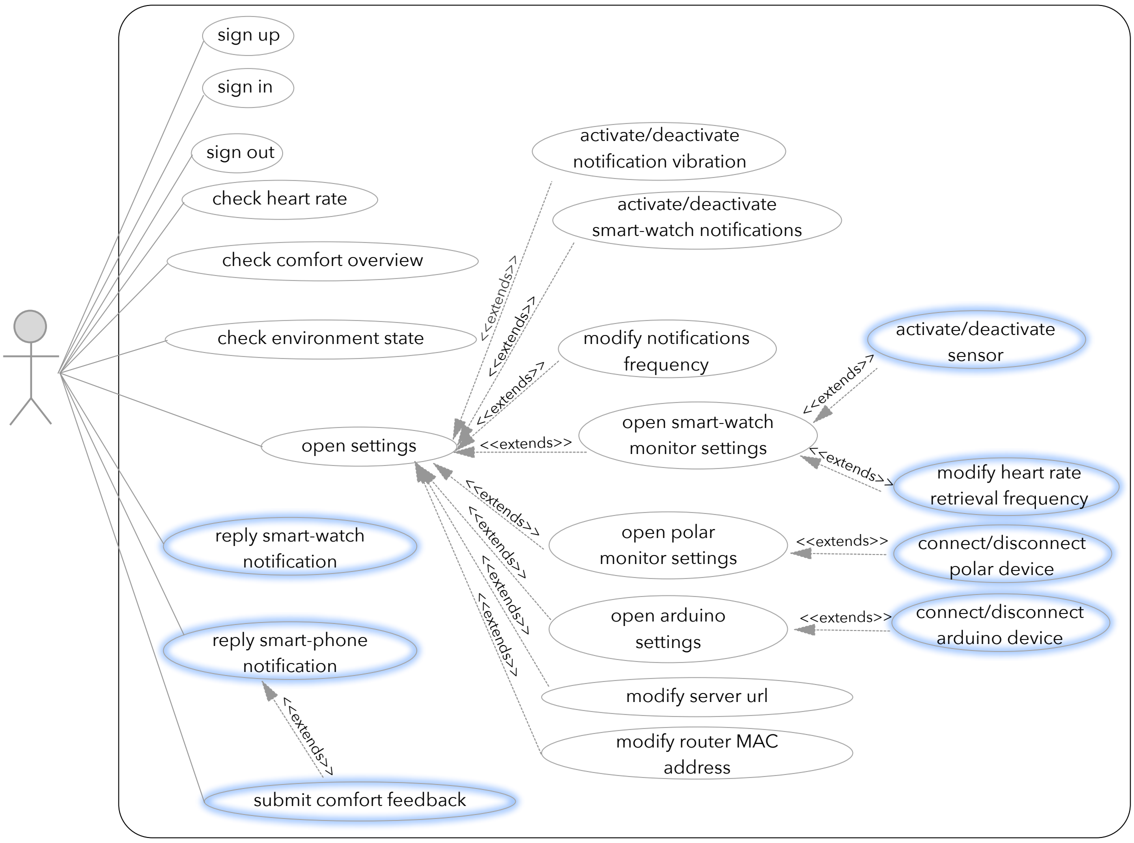


Figure 4.1: Comfstat's use case diagram.

We also created a high fidelity prototype for the smart watch application. Figure 4.3 depicts its main screens. We intended to use the same color coding and icons as in the smart watch application design for the thermal comfort level options. However, manipulating the representation for notifications is currently limited. For instance, it is possible to set predefined responses—this was used to provide thermal comfort level—but it is not possible to change the background color or icons of the options. Moreover, is not possible to set a default reply option. When replying to a notification, the first option to be displayed is the option that is on top of the list. Ideally, the default option would be *neutral*, and for fairness, the distance from *neutral* to any other option would be the same. For Comfstat's complete user interface design refer to appendix C.

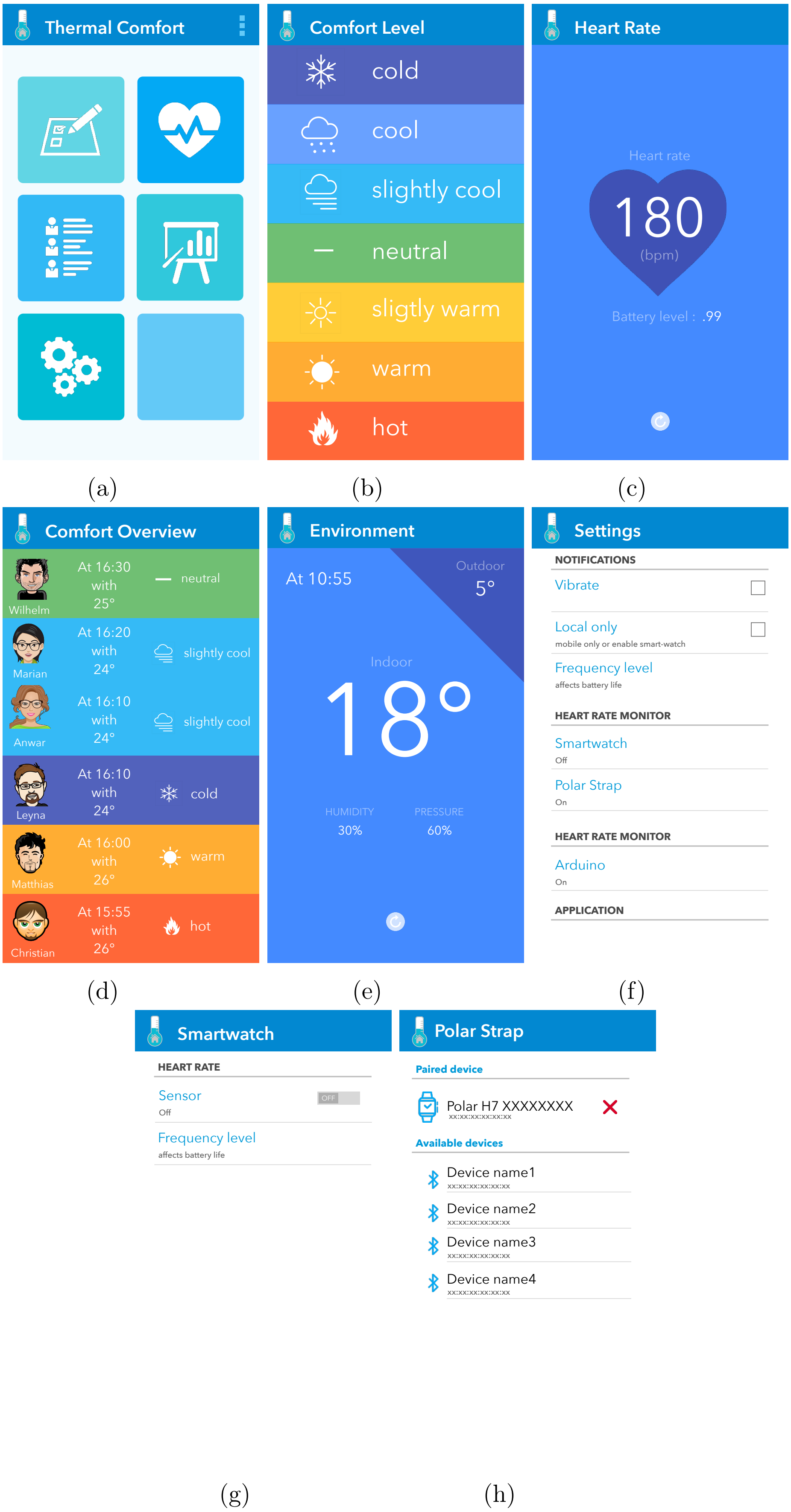


Figure 4.2: Smart phone application – high fidelity prototype.

(a) (b) (c) (d) (e)

Figure 4.3: Smart watch application – high fidelity prototype.

4.3 Architecture

The goal of Comfstat is to unobtrusively sense users' thermal comfort levels. We envision Comfstat to be installed as part of smart heating and cooling systems to better regulate *set point*[1] temperatures. To achieve this, Comfstat is built around a mobile phone application supported by different sensors: temperature, humidity and heart rate. Figure 4.4 shows the three key components of our architecture. The *sensors*, the *smart phone* as a hub and the *server* to collect and analyze the data. Following, we will explain the design decisions behind each component.

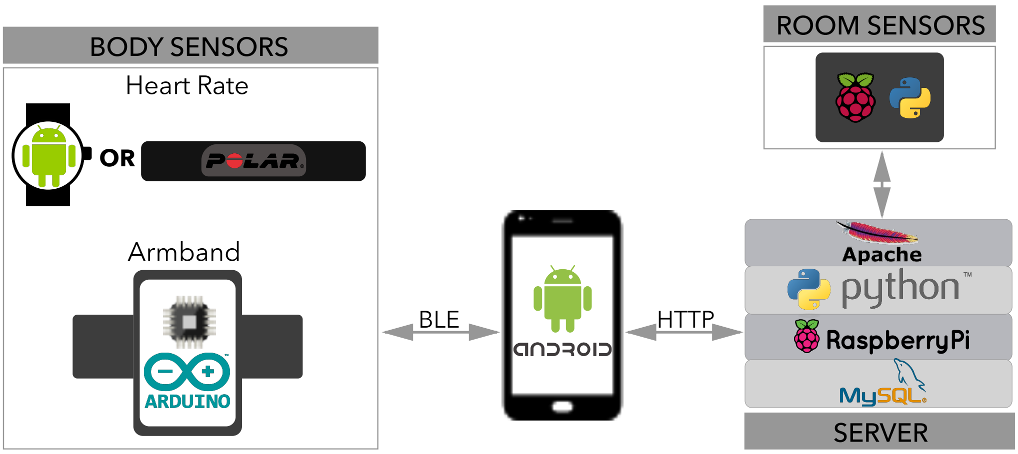


Figure 4.4: Overview of the main components of the Comfstat sensing infrastructure.

4.3.1 Server

As sensing and recording users' metabolic rates, key parameter for calculating thermal comfort, can be considered an intrusion into users' privacy, one requirement of our system is to work standalone inside users' home. However, in order to sense comfort, environmental parameters (e.g., air temperature) as well as personal factors

[1] Set point temperature refers to the target or desired temperature of a HVAC.

(e.g., heart rate and thermal comfort votes) have to be combined. We thus aggregate the data on a local server. To this end we designed a Web application that allows for the storage and analysis to run on a low-cost single board system such as the Raspberry Pi.

4.3.2 Mobile application

The mobile application serves as the central hub for gathering personal sensory data. It connects via Bluetooth Low Energy (BLE) to an Android Wear smart watch and a chest-worn strap to collect heart rate data. It also obtains humidity and temperature values from sensors worn by the participants. Sensory values are quickly accessible to the user through the application.

The mobile application is realized on a Nexus 5 smart phone running the Android operating system. It synchronizes its data with the in-home server every five minutes. To preserve privacy and battery life, data is only collected and synchronized when the smart phone is situated within the home. This is achieved by validating that the user is connected to her home Wi-Fi.

In addition to the raw sensor values, the application allows us to collect ground truth thermal comfort data on the 7-point ASHRAE scale. A companion application on the smart watch also allows for quick voting (cf., Figure 4.3). The data can be collected at frequencies between 5 and 15 minutes. Note that the collection of this "ground truth" data is only necessary for training the system. Once trained, the system should sense comfort automatically using the sensors introduced in the next section.

4.3.3 Sensors

As mentioned before, sensors are one of Comfstat's key components. Comfstat sensors can be divided into three different categories heart rate sensor, room temperature sensor and armband sensor.

Heart rate

Heart rate (HR) measurements are a proxy for the metabolic rate. The metabolic rate is closely linked to thermal comfort as it determines how much thermal energy leaves the body [22]. Comfstat offers two modalities to reliably collect heart rate data—a smart watch application or a BLE heart rate monitor—figure 4.5 depicts both sensors we considered.

Smart watch: application for the Android Wear operating system (running on an LG Watch R W110), which obtains heart rate values directly from an optical

(a) (b) (c)

Figure 4.5: Heart rate sensors: (a) LG Watch R W110 front, (b) LG Watch back – optical sensor, (c) Polar H7 heart rate BLE monitor.

HR sensor built into the watch. The data are then transferred via the smart phone application to the server.

BLE monitor: heart rate can be collected directly through a dedicated sensor which implements the Bluetooth profile for heart rate advertisement. We use an off-the-shelf Polar H7 heart rate monitor. As the Polar H7 uses a chest strap to measure the heart rate, it's measurements are more accurate than those of the smart watch.

Room temperature sensor

In order to collect the temperature in the conditioned area we use a DS18B20 temperature sensor connected to a Raspberry Pi. The temperature is retrieved every five minutes and forwarded to the in-home server.

Armband sensors

Normally, the air temperature varies slightly throughout the conditioned area (e.g., it will be slightly warmer near the windows due to the solar radiation). Therefore, we provided users with an armband carrying an additional DHT22 temperature and humidity sensor (cf., Figure 4.6). Note that the close proximity of the sensor to the body of the participant also means that its reading is likely to be influenced by the participant's body temperature. We will discuss this further in Section 7 when we elaborate on the features used to automatically deduce thermal comfort.

The sensor is sampled by an Adafruit Feather 32u4 Bluefruit LE board. The board is powered by a Lithium Ion Polymer Battery with 2500 mAh, which allows for approximately five days of uninterrupted sensing.

(a) (b) (c)

Figure 4.6: Armband sensor: (a) Adafruit Feather 32u4 Bluefruit LE board connected to Lithium Ion Polymer Battery. (b) DHT22 temperature and humidity sensor attached to armband. (c) User wearing armband.

5 Implementation

This chapter describes Comfstat's implementation details. The content is structured into four sections. The first three sections show implementation details of Comfstat's key components—server, mobile application and sensors. Following, section 5.4 describes Comfstat's initial platform test.

5.1 Server

Comfstat features a pull server. All data requests are originated by the client, and then are responded to by the server. It is implemented with python and runs on a RaspberryPi, it has two main responsibilities: exposing Comfstat API and holding Comfstat's database.

5.1.1 API

Comfstat API enables communication between the mobile application and the server. Our API definition is shown from table 5.1 to table 5.9.

Description	User authentication
URL	`/login`
Method	`GET HTTP_AUTHORIZATION`
Requires	base64 encoded `username` and `password`
Success	`200 OK`
Failure	`401 (unauthorized), 500 (internal server error)`

Table 5.1: GET – User.

Description	Creates user profile record
URL	`/login`
Method	`POST`
Requires	`application/json: username, sex, weight, height, password, birthday`
Success	`200 OK`
Failure	`500 (internal server error) , 409 (conflict)`

Table 5.2: POST – User.

Description	Get last 10 submitted thermal comfort feedbacks
URL	`/vote`
Method	`GET`
Returns	array of json objects with `user id, comfort level, username, temperature, creation date`
Success	`200 OK`
Failure	`500 (internal server error)`

Table 5.3: GET – Vote.

Description	creates thermal comfort feedback record
URL	`/vote`
Method	`POST`
Requires	`application/json: user id, comfort level, creation date`
Success	`200 OK`
Failure	`500 (internal server error)`

Table 5.4: POST – Vote.

Description	creates polar heart rate record
URL	`/polar`
Method	`POST`
Requires	array of json objects with `user id, heart rate, rr_interval, creation date`
Success	`200 OK`
Failure	`500 (internal server error)`

Table 5.5: POST – Polar.

Description	creates arduino temperature record
URL	`/temperature`
Method	`POST`
Requires	array of json objects with `user id, temperature, creation date`
Success	`200 OK`
Failure	`500 (internal server error)`

Table 5.6: POST – Arduino temperature.

Description	creates arduino humidity record
URL	`/humidity`
Method	`POST`
Requires	array of json objects with `user id, humidity, creation date`
Success	`200 OK`
Failure	`500 (internal server error)`

Table 5.7: POST – Arduino humidity.

Description	Get current environment temperature
URL	`/environment`
Method	`GET`
Returns	`application/json: temperature`
Success	200 OK
Failure	`500 (internal server error)`

Table 5.8: GET – Environment.

Description	Creates smartwatch record
URL	`/smartwatch`
Method	`POST`
Requires	`application/json heart rate, time, battery, user id, elapsed time, accuracy`
Success	`200 OK`
Failure	`500 (internal server error)`

Table 5.9: POST – Smartwatch.

5.1.2 Database

Comfstat's data is stored in a MySQL database, which is handled on the server through a Python object-relational mapping (ORM) library called *peewee*. Figure 5.1 depicts Comfstat's database scheme.

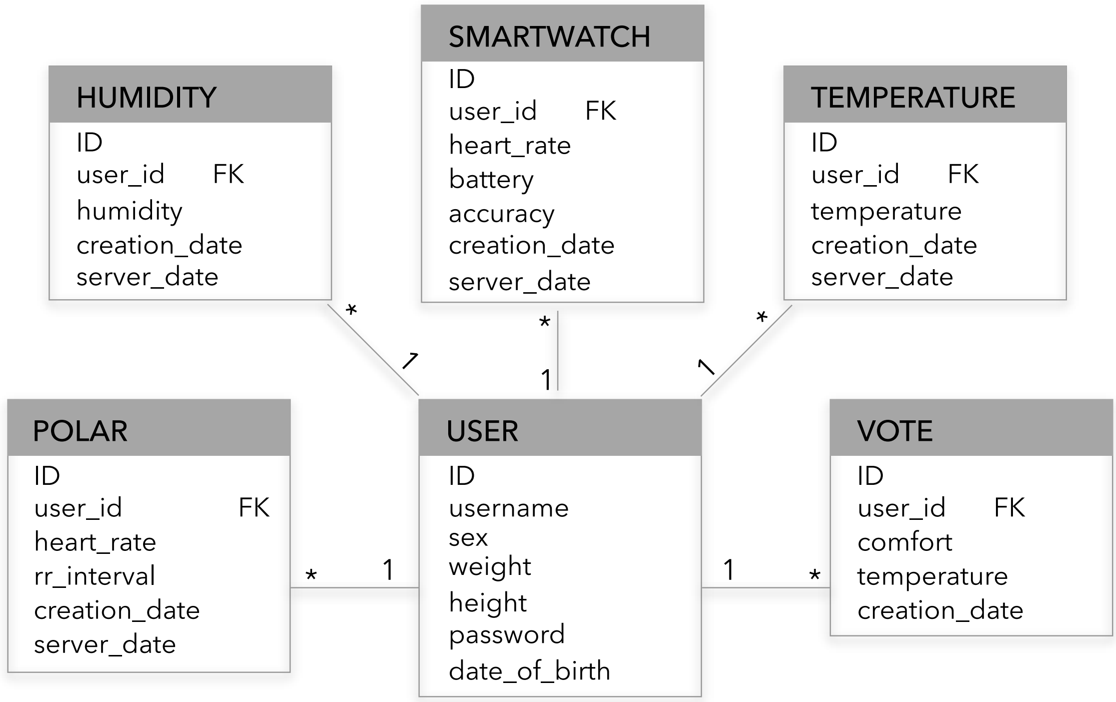


Figure 5.1: Database Schema.

5.2 Mobile application

As mentioned before, Comfstat's smart phone serves as a sensing hub, it helps us collect data needed to predict thermal comfort. Moreover, it is in charge of sending data to the server, where it is stored persistently. To achieve Comfstat's goals of sensing platform, three Android application components were essential. These are alarms, services and notifications.

This section is organized as follows. First, we briefly explain how we implemented alarms, services and notifications. Next, we show four subsections where we explain in detail Comfstat's smart phone key features, these include querying users for thermal comfort, retrieving heart rate data, and retrieving data from the armband sensors. Additionally, we present a subsection with all the other support functions provided by Comfstat's smart phone.

Alarms are used to schedule different services. Alarms allow to perform time-based operations outside Comfstat's lifetime. Moreover, alarms can be triggered in set intervals, which allows Comfstat to start services periodically depending on frequency level set in the application settings (e.g., high, medium, low).

Google Cloud Messaging (GCM) in conjunction with sync adapters offers a similar functionality to the *AlarmManager* for scheduling services. Nevertheless, it would require user data to be sent to an external server. Hence, for security reasons we decided to implement scheduling through the *AlarmManager*. Alarms, however, have a trade-off. When using repeating alarms, if not designed well, they could caused battery drain or significant load on servers. We addressed this trade-off with three strategies. First, by allowing alarms to be triggered at imprecise times. Second, by not having high frequency alarms. Third, by using Android's elapsed real time clock, which uses the "time since system boot" as reference, instead of using "real time clock". Elapsed real time is suited to setting alarms based on the passage of time (e.g., an alarm that fires every 15 minutes or even 30 seconds) since it is not affected by timezone. "The real time clock type is better suited for alarms that are dependent on current locale"[1].

Services we used services to implement notifications, heart rate retrieval and data synchronization with the server. Comfstat's services extend the *IntentService* class, which allows to run background services without requiring an Android activity (user interface). *IntentService* is a base class for Android *Service*, it handles requests (expressed as Intents) asynchronously. Comfstat starts its services as needed using alarms. Each service request is handled by a working thread, and stops itself when it runs out of work.

The *IntentService* class exists to simplify the "work queue processor" pattern, commonly used to offload tasks from an application's main thread. All requests are handled on a single thread – "they may take as long as necessary (and will not block the application's main loop), but only one request will be processed at a time"[2]. Handling requests sequentially does not present a problem for Comfstat, because services are not designed to run synchronously, but rather to run sequentially and periodically. For example every five, fifteen or thirty minutes depending on user's preferences.

5.2.1 Heart rate retrieval

This subsection describes implementation details for both heart rate retrieval modalities available in Comfstat—smart watch application or a BLE heart rate monitor.

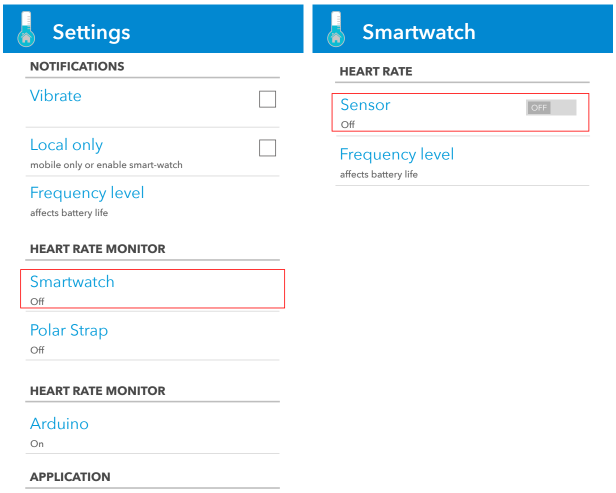
[1] Google Developers (2015). Scheduling Repeating Alarms. Retrieved from `http://developer.android.com/training/scheduling/alarms.html#type` (accessed March 25, 2016).

[2] Google Developers (2015). IntentService. Retrieved from `http://developer.android.com/reference/android/app/IntentService.html` (accessed March 25, 2016).

Smart watch

The implementation has two main components. First, a user interface for activating the functionality. Second, a service that handles the communication with the smart watch and sends the data to the server.

Interface: when a user desires to use the smart watch as a heart rate monitor, she must select the option "Smartwatch" on Comfstat's settings (cf., Figure 5.2a). A screen will show the smart watch settings available (cf., Figure 5.2b). There, she can activate the sensor by using the highlighted switch. Additionally, she can set the retrieval frequency.



(a) (b)

Figure 5.2: Steps to activate smart watch heart rate measurement retrieval.

Heart rate service: is in charge of retrieving heart rate measurements from the smart watch, and sending data to the server to make it persistent.

We use Google's MessageApi to manage communication between smart phone and smart watch. Messages are a one-way communication mechanism that is good for remote procedure calls (RPC), such as sending a message to the wearable to start an activity[3]. We send messages in both directions to request applications to perform specific actions.

An alarm is used to schedule heart rate retrieval. The service is triggered periodically depending on a frequency set in the user's preferences (e.g., high, medium or

[3]Google Developers (2015). Sending and Receiving Messages. Retrieved from `http://developer.android.com/training/wearables/data-layer/messages.html` (accessed March 25, 2016).

low). Assuming that the smart watch service for heart rate retrieval is active, when the alarm is triggered the following sequence diagram (cf., Figure 5.3) outlines how the communication happens between the different system components. On it we can appreciate that the user does not play a role, in this case all services are triggered as background services. This process is repeated every time the alarm is triggered.

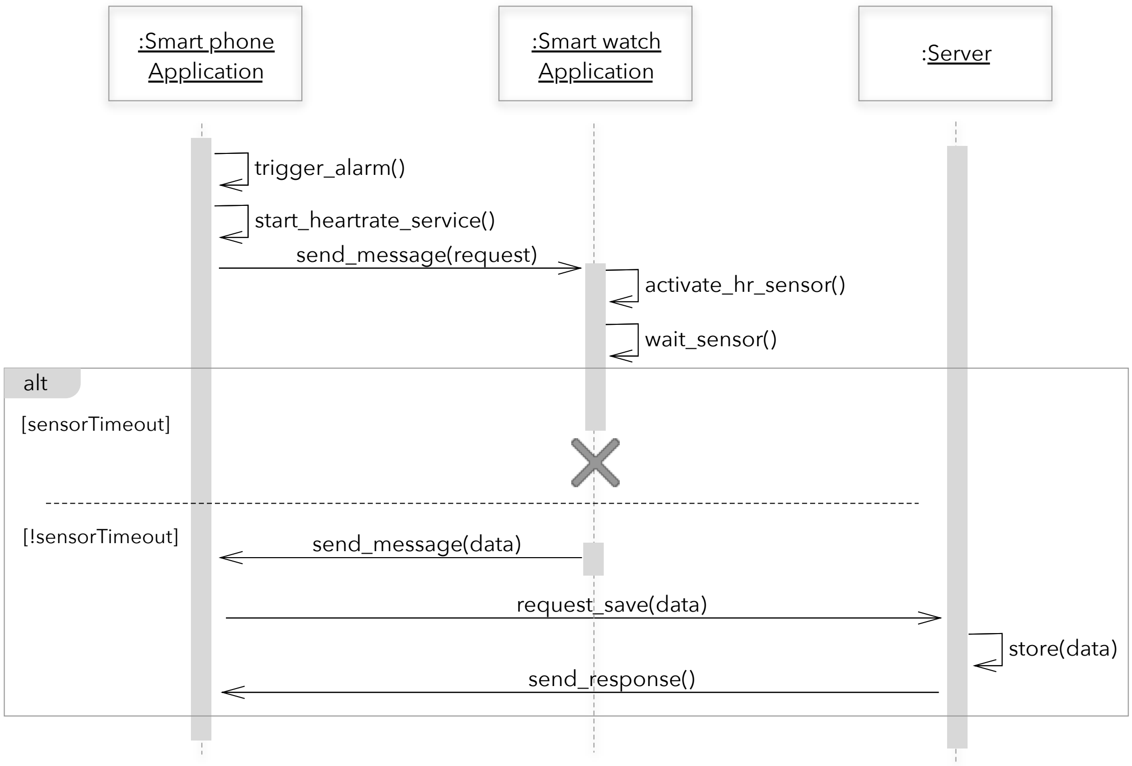
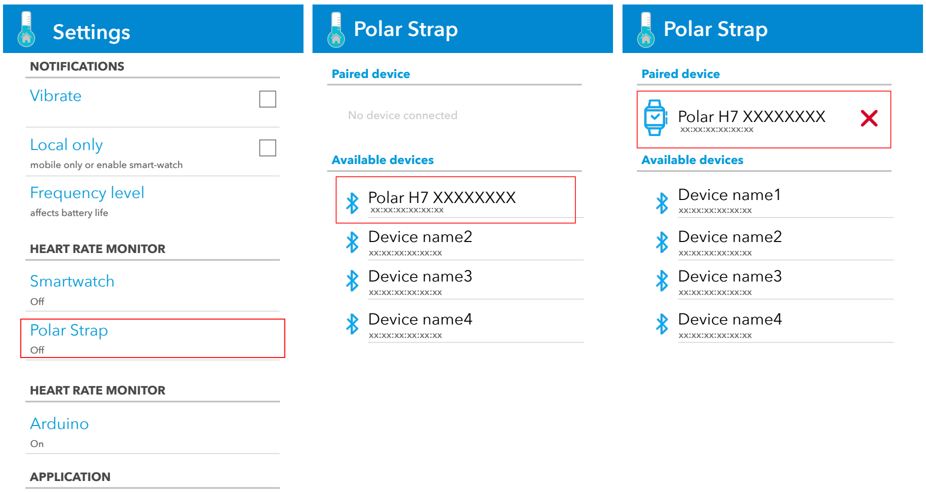


Figure 5.3: Heart rate retrieval service with smart watch – sequence diagram

BLE device

Comfstat's implementation for the heart rate retrieval using a BLE device has three components. First, a user interface for selecting the desired BLE device. Second, a service that handles the connection to the BLE device and stores data temporarily on the smart phone. Finally, a service in charged of sending the data to the server.

Interface: When a user desires to use a BLE device to retrieve heart rate measurements, she must open Comfstat's settings and select the option "Polar Strap" (cf., Figure 5.4a). A screen will show all available BLE devices. There, she can select the device she wants to use (cf., Figure 5.4b). This screen is handled with Android fragments. Fragments allow to manipulate portions of a user interface. We use a fragment on the top of the screen to indicate details of the connected device, or to simply indicate that no device is connected. If a user selected a BLE device that advertises the GATT service for heart rate with its respective Heart Rate Measurement characteristic, Comfstat's background service will automatically subscribe to the characteristic and will wait for data notifications. Meanwhile, a fragment with the selected device will be shown on the screen (cf., Figure 5.4c).



(a) (b) (c)

Figure 5.4: Steps to activate BLE heart rate measurement retrieval.

BLE service: Comfstat's smart phone application is programmed as a GATT client, it gets data from a BLE device. Our application gets data from the GATT server, which is a BLE heart rate monitor that supports the Heart Rate Profile.

We implemented all interactions with the BLE device using the Android BLE API. When our application receives the advertised services of the selected BLE device, we first check that it advertises the heart rate service (UUID 0x180D). Additionally, we verify that the service includes the Heart Rate Measurement characteristic (UUID 0x2A37), used to represent heart rate measurement values[4].

Once the connection is established with the GATT server and our application is subscribed to the heart rate measurement characteristic, the client stays waiting for notifications. All incoming data is stored temporarily on the smart watch database. To make the system more reliable, we ensured that when our application disconnects from the BLE device unintentionally, it reconnects automatically once the device is available.

[4]Bluetooth. Heart Rate Service. Retrieved from `https://developer.bluetooth.org/gatt/services/Pages/ServiceViewer.aspx?u=org.bluetooth.service.heart_rate.xml` (accessed April 10, 2016).

Synchronization service: Data persistence is achieved once it is stored on the server. To this end, we implemented an Android service that takes non-synced data records from the smart watch database and send them to the server using the corresponding server API call. This service is triggered through an Android alarm.

Code snippet 5.1 outlines part of the implemented alarm. On it, it is possible to see that the alarm is set as inexact, and that the alarm type is `ELAPSED_REALTIME_WAKEUP`[5]. The "wakeup" version tells Android to wake up device's CPU if the screen is off. The alarm frequency is set to five minutes.

Code snippet 5.1: Polar data syncing alarm.

```
private void setAlarmHelper(Context context, long frequency) {
  mAlarmMgr = (AlarmManager)context.getSystemService(Context.ALARM_SERVICE);
        Intent intent = new Intent(context, PolarAlarmReceiver.class);
        mAlarmIntent = PendingIntent.getBroadcast(context, ALARM_ID, intent,
             PendingIntent.FLAG_CANCEL_CURRENT);

        mAlarmMgr.setInexactRepeating(AlarmManager.ELAPSED_REALTIME_WAKEUP,
          frequency, frequency, mAlarmIntent);
}
```

Figure 5.5 outlines how the communication happens betweens the different system components involve in the heart rate data retrieval when using a BLE device.

5.2.2 Armband data retrieval

Comfstat's implementation for the armband sensor data retrieval is very similar to the BLE heart rate retrieval, the difference lies in the used GATT server. The implementation has also three components: a user interface, a service to retrieve sensory data and a service to sync data with the server.

Interface: Figure 5.6 depicts the interface implemented to activate temperature and humidity data retrieval. The screen that shows all available BLE devices is handled with Android fragments, in a similar way as for heart rate BLE monitor. However, in this case we verify that the selected BLE device advertises the GATT environmental sensing service with temperature and humidity characteristics before starting any process.

BLE service: Comfstat gets data from the GATT server, which is a BLE device that supports the Environmental Sensing Profile.

We implemented all interactions with the BLE device using the Android BLE API. When our application receives the advertised services of the selected BLE device,

[5] `ELAPSED_REALTIME_WAKEUP` preferred option for alarms that do not required to be triggered at a precise time. They are suited to set an alarm based on the passage of time using the "system's time" as reference. Retrieved from `http://developer.android.com/training/scheduling/alarms.html#type` (accessed March 4, 2016).

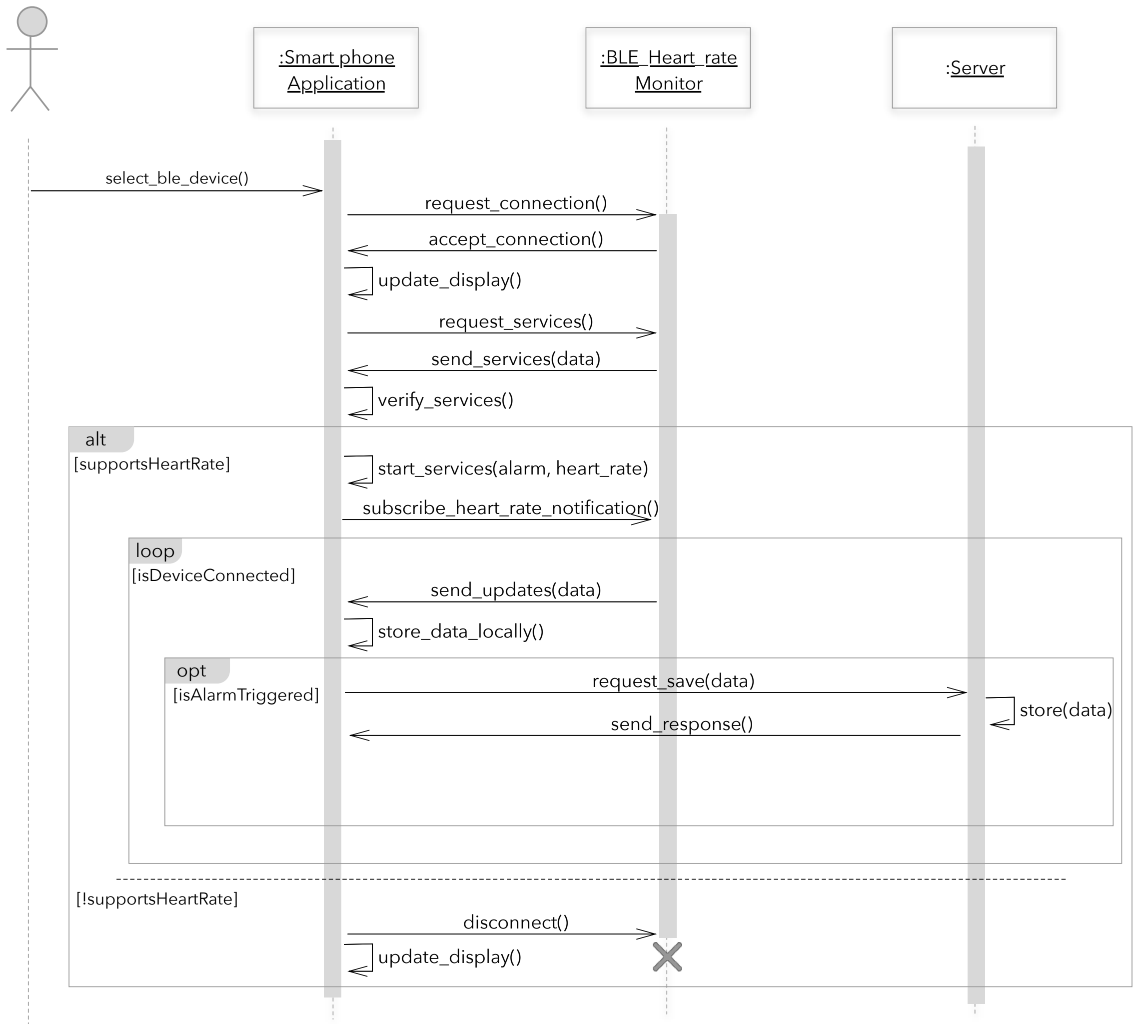
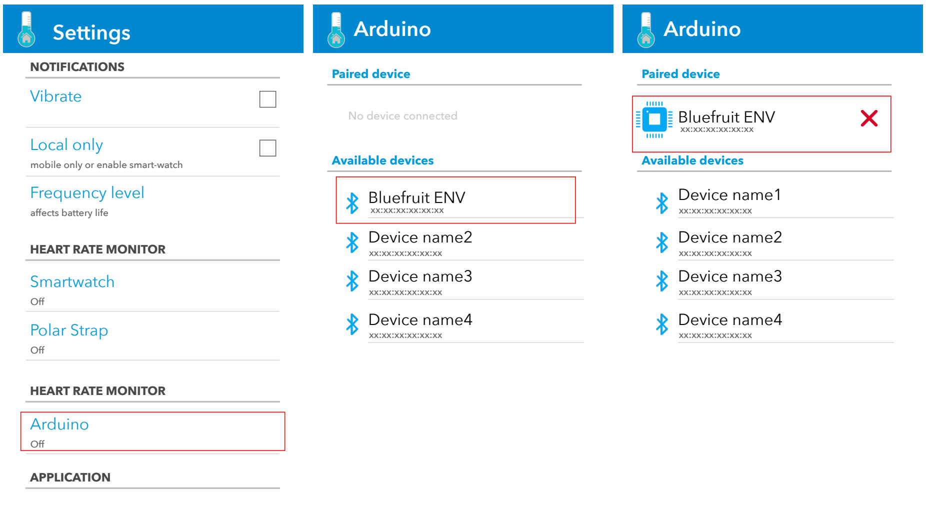


Figure 5.5: Heart rate retrieval service sequence diagram.

we first check that it advertises the environmental sensing service (UUID 0x181A). Additionally, we verify that the service includes the temperature (UUID 0x2A6E) and humidity (UUID 0x2A6F) characteristics. Moreover, our application recognizes the Battery Service (0x180F) with its Battery Level characteristic (UUID 0x2A19).

Once the connection is established with the GATT server and our application is subscribed to the characteristics (temperature, humidity and battery level), the client stays waiting for notifications. All incoming data is stored temporarily on the smart watch database.

Synchronization service: We achieve data persistence in the same way that is done for the heart rate measurements. This means, through a scheduled alarm and a background service that sends non-synced data records to the server.



(a) (b) (c)

Figure 5.6: Steps to activate BLE temperature and humidity measurement retrieval.

Figure 5.7 outlines how the communication is carried out betweens the different system components involved in the armband sensory data retrieval.

5.2.3 Thermal comfort level retrieval

Users can provide their thermal comfort level by using Comfstat's user interface (refer to section 4.2 for details). We defined an Android activity called ThermalComfortActivity that is responsible for displaying thermal comfort level options that users can tap on; in order to provide their feedback. We employed Android's list functionality to display the different comfort levels according to ASHRAE 7-point scale. Code snippet 5.2 outlines ThermalComfortActivity's most relevant methods, while figure 5.8 shows the thermal comfort submission sequence diagram.

Code snippet 5.2: ThermalComfortActivity class.

```
public class ThermalComfortActivity extends ListActivity {
  @Override
      protected void onCreate(Bundle savedInstanceState)
      @Override
      protected void onListItemClick(ListView l,
            View v, int position, long id)
 }
```

We use Android's notifications to remind users to submit their thermal comfort feedback. To avoid disturbing users, we allow them to set the frequency of notifications in Comfstat's settings. Notifications are triggered similarly to heart rate retrieval service, by using scheduled alarms. Notifications are implemented with the Android's NotificationManager. Depending on the user's settings they can be sent to the smart phone and/or smart watch. On the smart phone, when a users

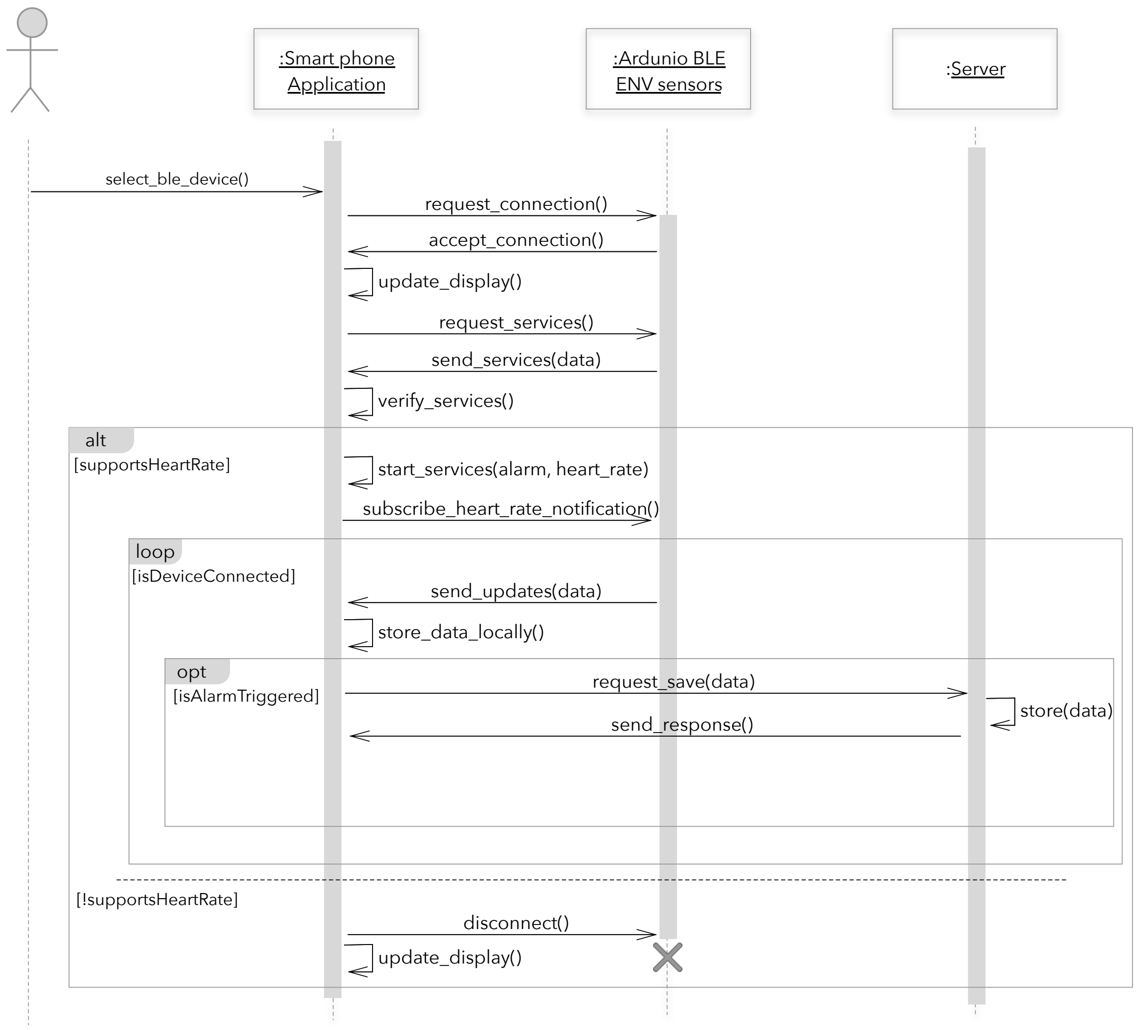


Figure 5.7: Armband data retrieval services sequence diagram.

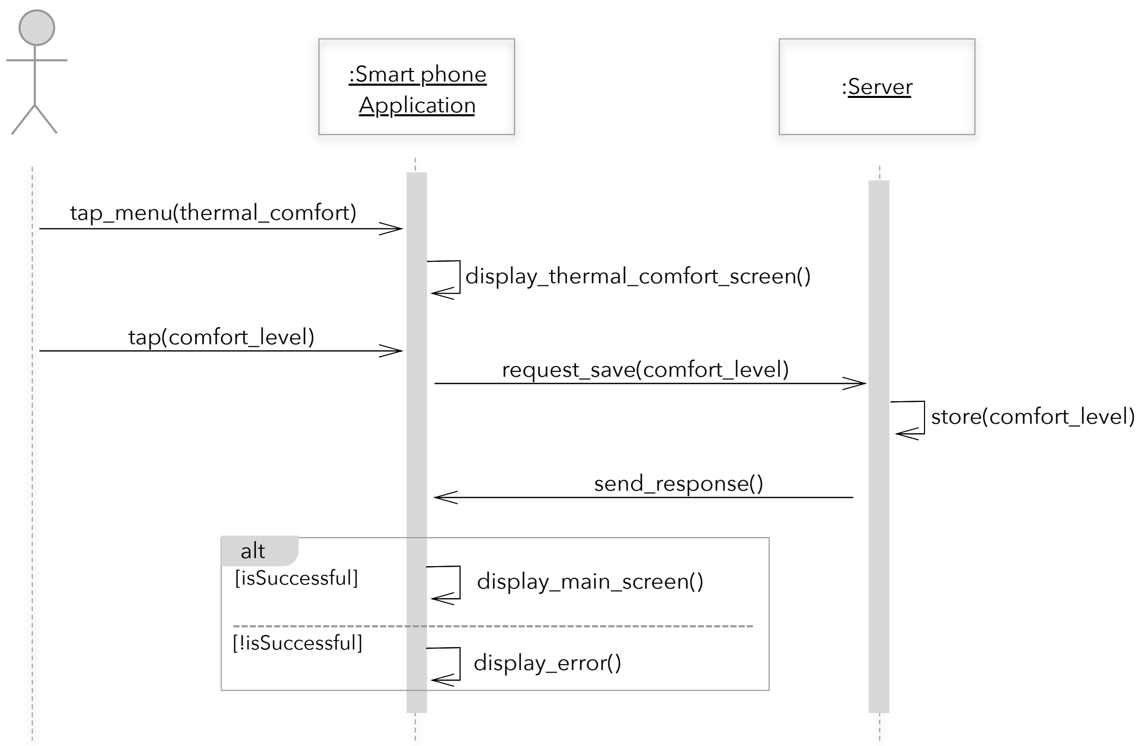


Figure 5.8: Thermal comfort submission sequence diagram.

replies to a notification, they are redirected to Comfstat's thermal comfort screen. We programmed notifications in a way that if a user never dealt with it before a new one is triggered, the old one will be replaced by the most recent notification.

5.2.4 Additional features

We also implemented several Android's Activities[6] to support Comfstat. A brief discussion of their functionality and implementation is shown below.

LoginActivity

Class responsible for displaying login screen, verifying the authenticity of users who intent to access Comfstat's core functionality and start programmed services such as notifications and sensory data retrieval. Code snippet 5.3 outlines *LoginActivity*'s main methods; the *login* method verifies locally that all required fields were provided before sending an HTTP Authorization request to the server.

[6]Google defines its Activities as "an application component that provides a screen with which users can interact in order to do something, such as dial the phone, take a photo, send an email, or view a map. Each activity is given a window in which to draw its user interface". Google Developers (2015). Activities. Retrieved from `http://developer.android.com/guide/components/activities.html` (accessed July 20, 2016).

Code snippet 5.3: ThermalComfortActivity class.

```
public class LoginActivity extends Activity {
     @Override
     protected void onCreate(Bundle savedInstanceState)
     public void startSignUpActivity(View view)
     public void login()
}
```

SignUpActivity.

Class responsible for displaying sign up screen and request user record creation on the server. Code snippet 5.4 outlines *SignUpActivity*'s most relevant methods. The *Validate* method verifies locally that all required fields were provided and that they have the right format before sending an HTTP POST request to the server.

Code snippet 5.4: SignUpActivity class

```
public class SignUpActivity extends Activity {
   @Override
   protected void onCreate(Bundle savedInstanceState)
   public void validate()
}
```

HomeActivity

Class responsible for displaying Comfstat main screen, requesting last submitted thermal comfort feedbacks, and executing logout when requested. Code snippet 5.5 outlines *HomeActivity*'s most relevant methods. The first five public methods are responsible for redirecting the user to the right screen depending on the user's selection. The *logoutHelper* method in charge of logging out the current user from the application and shutdown all scheduled services.

Code snippet 5.5: HomeActivity class.

```
public class HomeActivity extends Activity {
   @Override
   protected void onCreate(Bundle savedInstanceState)
   @Override
   protected void onResume()
   public void goToVoteActivity()
   public void goToStatsActivity()
   public void goToPreferenceFragment()
   public void goToHeartRateActivity()
   public void goToOverview()
   private void logoutHelper()
}
```

HeartRateActivity

Class in charge of retrieving user's heart rate, displaying it and storing it on the server's database. The heart rate is retrieved using an Android smart watch with heart rate sensors capabilities.

Code snippet 5.6 outlines HeartRateActivity class. On it, it is possible to see that the class implements *MessageApi.MessageListener* interface. The method *onCreate* is responsible for creating an instance of the GoogleApiClient. This instance is connected on the *onStart* method. *OnStop* is responsible for disconnecting the client. *onConnected* takes care of adding the GoogleApiClient instance as a listener for the *Wearable.MessageApi*. When a connection fails, *onConnectionFailed* removes GoogleApiClient from the listeners. Finally, *onMessageReceived* is called when the smart watch sends a message containing heart rate data. Additionally, this method takes care of executing the required server calls to make data persistent on the server.

Code snippet 5.6: HeartRateActivity class.

```
public class HeartRateActivity extends Activity implements
      MessageApi.MessageListener, GoogleApiClient.ConnectionCallbacks,
      GoogleApiClient.OnConnectionFailedListener {

   @Override
   protected void onCreate(Bundle savedInstanceState)
   @Override
   protected void onStart()
   @Override
   protected void onStop()
   @Override
   public void onConnected(Bundle connectionHint
   @Override
   public void onConnectionFailed(ConnectionResult result)
   @Override
   public void onMessageReceived(final MessageEvent messageEvent)
}
```

OverviewActivity

Class responsible for displaying an overview of the last submitted thermal comfort feedbacks. Data displayed on this screen comes from the server's database, but it is retrieved, as mentioned before, by *HomeActivity* class. A list containing the values to be displayed in the overview is passed from *HomeActivity* to *OverviewActivity* in the *intent* using a *parcelable* data object. Code snippet 5.7 outlines *OverviewActivity* class structure.

Code snippet 5.7: OverviewActivity class.

```
public class OverviewActivity extends ListActivity {
   @Override
   protected void onCreate(Bundle savedInstanceState)
}
```

EnvironmentActivity

Class in charge of displaying current room environment conditions, these values include room temperature, outside temperature, humidity and pressure. The server is responsible for providing and getting all required values. Code snippet 5.8 outlines the class structure.

Code snippet 5.8: EnvironmentActivity class.

```
public class EnvironmentActivity extends ListActivity {
   @Override
   protected void onCreate(Bundle savedInstanceState)
}
```

PreferenceFragment

Class responsible for displaying and handling Comfstat's settings. These settings allow users to modify the application's behaviors. For example, allow users to specify whether notifications are enabled or specify how often the applications retrieve heart rate values. All available settings were previously mentioned on Comfstat's use case diagram.

Comfstat's settings were implemented using Android's Preference APIs, which provides an interfaces consistent with the user experience in other Android applications (including system settings)[7].

5.3 Sensors

This section contains implementation details for Comfstat's sensors.

5.3.1 Heart rate

Comfstat has a smart watch application that allows to retrieve heart rate measurements from a heart rate sensor. This application was developed in a previous Comfstat project. Details of the implementation can be found in Appendix D.

An implementation for a BLE heart rate monitor was not required as Comfstat works with any BLE device capable of advertising the bluetooth heart rate profile. Throughout this thesis we used an off-the-shelf Polar H7 heart rate monitor.

[7]Google Developers (2015). Settings. Retrieved from `http://developer.android.com/guide/topics/ui/settings.html` (accessed July 20, 2016).

5.3.2 Armband

We expose the armband sensor data through an Arduino program. The Arduino language is merely a subset of C/C++ functions[8]. To facilitate querying data from the DHT22 temperature and humidity sensor, we followed the Bluetooth standard and implemented adopted[9] services. Specifically, we used the Environmental Sensing service, whose UUID is 0x181A, together with its characteristics temperature (UUID 0x2A6E) and humidity (UUID 0x2A6F). Our implementation queries the sensor every 3 seconds as this is the maximum retrieval rate allowed.

Additionally, to monitor the performance of the used Lithium Ion Polymer Battery, we implemented the adopted bluethooth Battery service, whose UUID is 0x180F, with its respective battery level characteristic (UUID 0x2A19). This service is advertised every five minutes to avoid unnecessary battery drain.

5.3.3 Room temperature

Initially we used a Sense HAT to query environmental data (room temperature, pressure, humidity). Sense HAT is an add-on board for Rasberry Pi. However, the values were not very accurate because the sensors were influenced by the board's temperature. Therefore, in order to collect more accurate temperature measurements in the conditioned area, we use a DS18B20 temperature sensor connected to a Raspberry Pi. The temperature is retrieved every five minutes and stored in the in-home server.

5.4 Initial platform test

After implementing all components, we conducted a testing phase for four days. The goal was to verify that all components were working as expected, and that we were able to retrieve measurements in the required granularity. Two participants took part in the evaluation. Both were asked to wear Comfstat infrastructure during the whole day and to give comments regarding Comfstat's usability. During this phase we found problems with our initial server implementation. Initially, our server held a SQLite database. SQLite is a lightweight disk-based database that does not require a separate server process[10]. SQLite is not designed for multiple users accessing the same table simultaneously. However, Comfstat intents to control the HAVC systems for multiple users. Therefore, Comfstat's database must handle gracefully

[8] Arduino. FAQ. Retrieved from `https://www.arduino.cc/en/Main/FAQ` (accessed August 2, 2016).

[9] Bluetooth Special Interest Group (SIG) supervises the development of Bluetooth standards, once a standard is "well" defined it is called adopted. Adopted standards are encouraged to be used to facilitate development and interoperability.

[10] Python Software Foundation (2015). sqlite3. Retrieved from `https://docs.python.org/2/library/sqlite3.html` (accessed July 10, 2016).

simultaneous requests on the same file. Hence, we decided to run Comfstat in an Apache server with a MySQL database.

Another issue we found is that the Adafruit Feather 32u4 Bluefruit LE board performs unexpectedly a factory reset. After the factory reset is done, the board stops collecting sensory data. This issue was reported to the Adafruit developers[11]. To this day, they have not been able to find a solution to the problem, as it is not easy to replicate and sometimes takes more than 8 hours until it happens. Our solution was to send an email each time an unexpected exception occurs in order to fix the problem as soon as possible and avoid data losses.

[11]Forum discussion with Adafruit about unexpected factory request. URL: `https://forums.adafruit.com/viewtopic.php?f=53&t=86236&start=30` (accessed August 1, 2016).

6 Empirical Study

We conducted a series of empirical studies to collect data using Comfstat's infrastructure. Data collection was the second significant part of this thesis. The goal of the studies was to collect data that later would be used as input in the machine learning phase of our project.

The analysis presented in this thesis is based on sensor data collected from five participants in three controlled experiments. We refer to this data as the Comfstat data set and make it available to the research community[1]. Table 6.1 summarizes participant's profiles.

Table 6.1: Participants' profiles.

Participant	**Gender**	**Age**	**Height**	**Weight**
p_1	female	26	1.65 m	62 kg
p_2	male	28	1.80 m	66 kg
p_3	female	28	1.59 m	55 kg
p_4	female	23	1.61 m	67 kg
p_5	male	26	1.72 m	77 kg

Table 6.2 shows the recorded variables and their respective sampling interval. To achieve a higher accuracy for the HR measurements, participants were asked to use the Polar H7 heart rate monitor instead of the smart watch. This way we can more precisely analyze the feasibility of automatically sensing comfort from the users' heart rate. Section 8.5 gives an indication of the accuracy possible with current wrist-worn optical sensors.

Table 6.2: Collected variables.

Variable	**Abbrev.**	**Interv.**
Room temperature (°C)	`room_temp`	5 min
Temperature (armb.) (°C)	`ard_temp`	3 sec
Rel. humidity (armb.) (%)	`ard_hum`	3 sec
Heart rate (bpm)	`hr`	1 sec
Comfort (7-point scale)	`comfort`	1-5 min

[1]Comfstat data set. URL: `https://github.com/LilianaB/ComfstatDataSet`

Before each experiment, participants were asked to sign a consent form for volunteer subjects in an ergonomics investigation involving exposure to hot or cold temperatures. This consent form is based on the ISO 12894 standard [25]. A sample form can be found in Appendix E.

The preliminary "cold" experiment was carried out with p_1 and p_2 only. Participants p_1, p_3, p_4 and p_5 took part in the main "controlled" temperature experiment. In a third experiment ("non-sedentary") with p_1 we assessed the effects of physical exercise on thermal comfort. Table 6.3 summarizes which participants took part in which experiments.

Table 6.3: Experiment participants.

Experiment	**Participant**
Cold	p_1, p_2
Controlled	p_1, p_3, p_4, p_5
Non-sedentary	p_1

The rest of this chapter is organized into four sections. The first three sections explain each experimental setting. Finally, section 6.4 presents a preliminary analysis of the gathered data.

6.1 Cold experiment

This preliminary experiment was conducted to test the Comfstat infrastructure and to measure the participants' responses to extreme thermal conditions. Two participants, p_1 and p_2, were subjected to low temperatures between 8 °C and 14 °C while wearing light clothing (i.e., 0.49 clo – 0.76 clo). The data was collected twice from 9.30 a.m. until 4.00 p.m. on two separate days. Figure 6.1 shows the timeline of the session.

During the preparation phase, participants were situated in a comfortable environment and explained how to use Comfstat. Next, the participants were asked to enter a cold (e.g., between 8 °C and 14 °C) environment for an hour. During this time, the participants were requested to provide feedback through the mobile application every one to five minutes. After one hour, the participants returned to their offices and

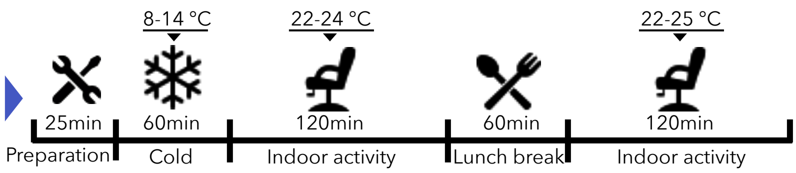


Figure 6.1: Timeline of the "cold" temperature experiment.

resumed their normal daily routines (e.g., mainly sedentary activities). The room temperatures in p_1's office varied from 22 °C to 24 °C, while p_2's office temperature was stable at 22 °C. After their respective lunch breaks, the participants resumed their sedentary activity until 4 p.m.

6.2 Controlled temperature experiment

Four participants (p_1, p_3, p_4 and p_5) took part in the main experiment. Three of the participants are female and one is male. While the previous experiment served to measure the subjects' responses to extreme conditions and to test the system, the goal of this experiment was to measure the subjects' responses in more natural settings. For this purpose, participants were exposed to three different thermal environments: (i) *warm* (27 °C to 29 °C), (ii) *neutral* (23 °C), and (iii) *cold* (17 °C to 18 °C).

The main goal of this experiment is to analyze the subjects' body responses to temperature changes. To achieve the different thermal environments, three rooms were conditioned to the *warm*, *neutral*, and *cold* settings, respectively. Figure 6.2 shows the timeline of the experiment for each participant. The participants were exposed to each temperature setting for 30 minutes. In total, each experimental session lasted for 90 minutes. During the experimental period, all participants remained seated and only engaged in sedentary activities. Environmental data as well as the participants' satisfaction with the thermal environment were collected using the Comfstat infrastructure. Each participant undertook the experimental setting twice.

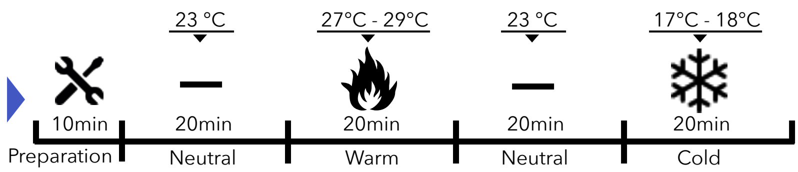


Figure 6.2: Timeline of the "controlled" temperature experiment.

6.3 Non-sedentary experiment

The previous two experiments investigated how thermal comfort varies with different thermal environments when the subjects are sedentary. In order to analyze the effect of physical activity on thermal comfort, we conducted a separate 90-minute experiment with participant p_1. During the experiment p_1 wore light clothing (i.e., 0.44 clo) [50]. During the first 30 minutes, p_1 was asked to relax during a sedentary activity to obtain a baseline. Next, she was asked to perform physical exercise for

30 minutes followed by another 30-minute phase of relaxation. Figure 6.7 shows the timeline of the experiment.

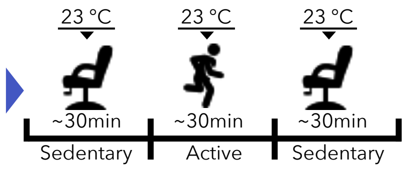


Figure 6.3: Timeline of the “non-sedentary” temperature experiment.

6.4 Preliminary observations

Before going on to explain how we compute thermal comfort from the measured sensor values, we will identify a few key observations from the data set.

6.4.1 Thermal comfort is subjective

Figure 6.4 shows how the participants' thermal satisfaction is linked to the current temperature level. For each vote obtained through the smart phone application, figure 6.4 shows the average temperature when the vote was cast. In general, participants show different thermal sensations at the same temperature levels, while females prefer higher temperatures. These results are confirmed by Karjalainen *et al.* [30], who found a significant impact of gender on thermal comfort. Our results indicate that to automatically infer thermal comfort, it may be necessary to create and train multiple models.

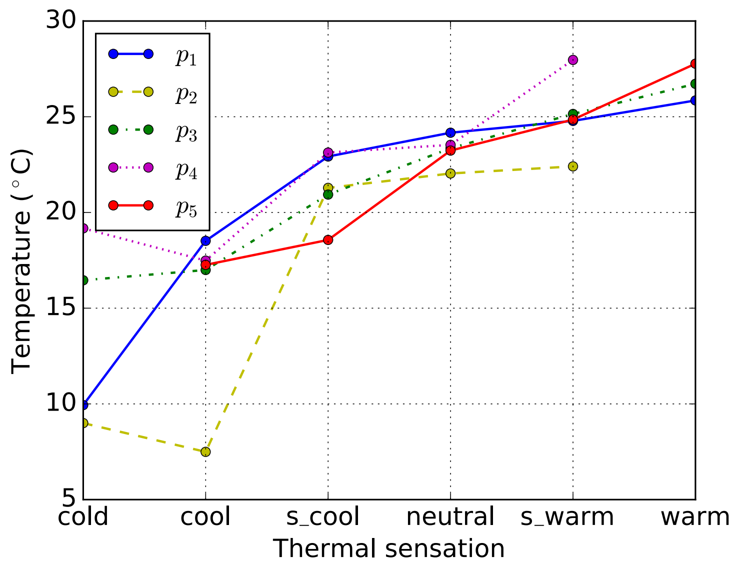


Figure 6.4: Thermal comfort preference per user.

6.4.2 Heart rate higher in extreme environments

Figure 6.5 shows the distributions of the measured heart rates per thermal comfort level for p_1. The figure shows that the median heart rate (red line) tends to increase towards both cold and hot thermal sensations. Table 6.4 summarizes these results for all participants. Our results are confirmed by Maohui Luo *et al.* [34], who found that the metabolic rate increases when the thermal sensation tends towards either end of the scale.

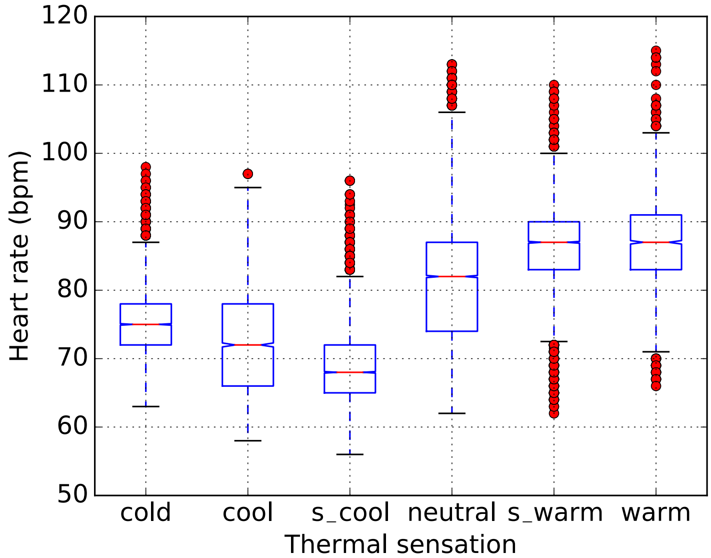


Figure 6.5: P_1 heart rate per thermal comfort level.

Table 6.4: Average heart rate per comfort level (-3: Cold, -2: Cool, -1: Slightly Cool, 0: Neutral, 1: Slightly warm, 2: Warm). Note that no data for Hot (3) is available.

	-3	**-2**	**-1**	**0**	**1**	**2**
(p_1)	75	72	69	81	86	87
(p_2)	84	84	77	93	94	-
(p_3)	74	67	72	74	70	71
(p_4)	84	80	84	85	84	-
(p_5)	-	79	76	79	81	80

6.4.3 Thermal comfort indicated by temperature

During the preliminary analysis we also observed a correlation between participants' thermal comfort and the temperature measured by both the armband and the stationary sensor. Figure 6.6 shows, exemplary for p_1, how `ard_temp`, the temperature measured on the participants' arms, the room temperature `room_temp` and thermal satisfaction `comfort` change over the course of one "controlled" session. A summary of the correlation between `ard_temp` and `comfort` for all participants is shown in Table 6.5.

In figure 6.6 we can also observe the effect of human thermo-regulation: when changing from warm to neutral environment, p_1 needs time to adapt to the new environment conditions.

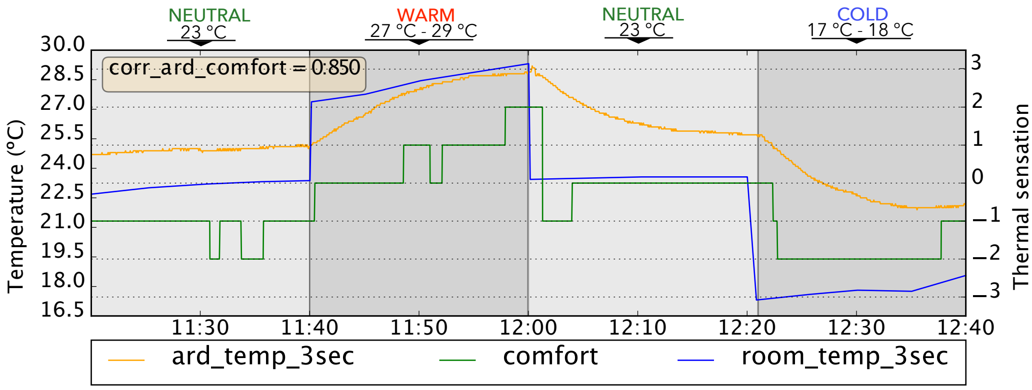


Figure 6.6: P_1 Thermal comfort and temperature correlation (session 1 – "controlled" temperature experiment).

Table 6.5: Pearson correlation between `ard_temp` and `comfort` ("controlled" temperature experiment).

	Pearson correlation			
	p_1	p_3	p_4	p_5
Session 1	0.85	0.79	0.81	0.79
Session 2	0.79	0.97	0.84	0.74

We found an exception in the correlation between participants' thermal comfort and the temperature measured by both the armband and the stationary sensor during the "non-sedentary" experiment. Figure 6.7.a shows the data while p_1 was engaging in non-sedentary activity. During this part of the experiment a possible explanation for low correlation is that while p_1 was doing physical exercise, she moved her arm quickly. Hence, the sensor perceived a higher air speed which in turns translated into a lower temperature, instead of translating into a higher temperature as a result of the raised body temperature. Following, p_1 stopped being active and engaged in sedentary activity (cf., Figure 6.7.b). In this case, while p_1's body slowly adapted to reach thermal comfort, simultaneously, the armband sensor stopped perceiving high air speed and started warming up as a result of p_1's high body temperature.

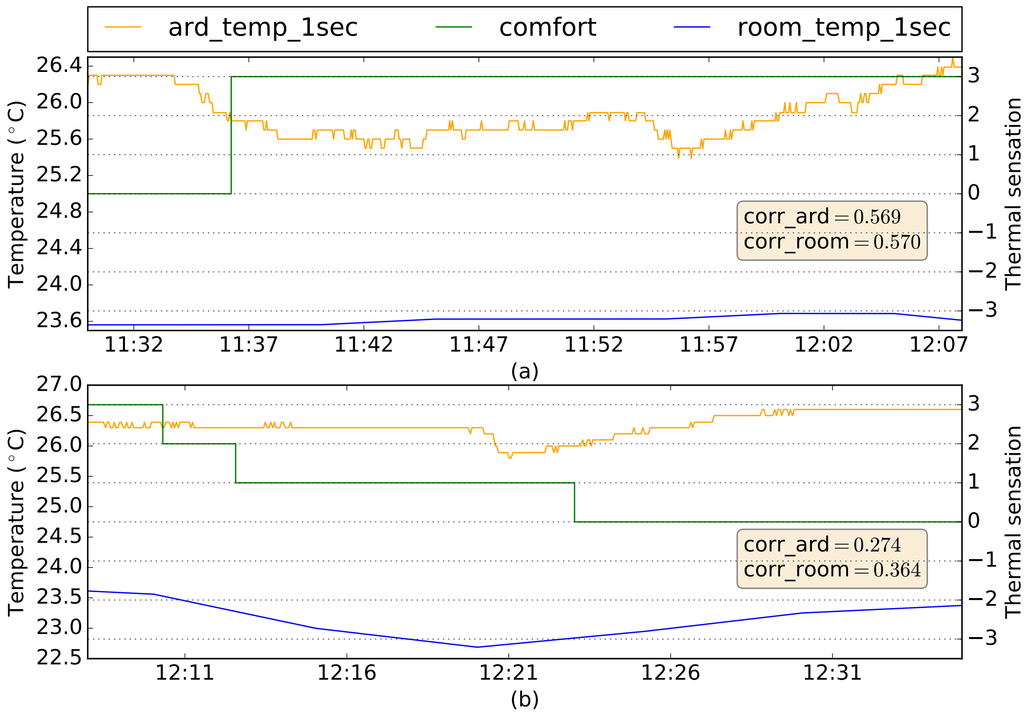


Figure 6.7: P_1 Thermal comfort and temperature correlation.("Non-sedentary" temperature experiment).

6.4.4 Heart rate variations during the day

We analyzed the "cold" experiment data, and observed that heart rate values fluctuate throughout the day. Figures 6.8 to 6.10 show histograms with the heart rate distribution per session[2] (morning, lunch and afternoon), the red line indicates the mean heart rate. During the morning participants had the lowest heart rates. The highest heart rates were recorded during lunch time. Additionally, we observed that participant's heart rate values are higher in the afternoon than in the morning. Our results are confirmed by Robert F. Schmidt's book Human Physiology [48]. There, it is stated that metabolic rate varies depending on the level of activity. This explains why participants have high heart rate in the afternoon: Normally, participants spend the morning sitting, and the afternoon engaging in non-sedentary activities for short periods of time (e.g, walking). Also, Schmidt states that metabolic rate has diurnal fluctuations and that food consumption together with digestion raises metabolic rate. This last statement explains why participants had the highest heart rate values during their lunch break. Table 6.6 summarizes the mean heart rate values recorded during each phase of the day.

[2]Using as baseline the timeline of "cold" temperature experiment. *Morning session* refers to the period after the cold session, and *afternoon session* refers to the session after the lunch break.

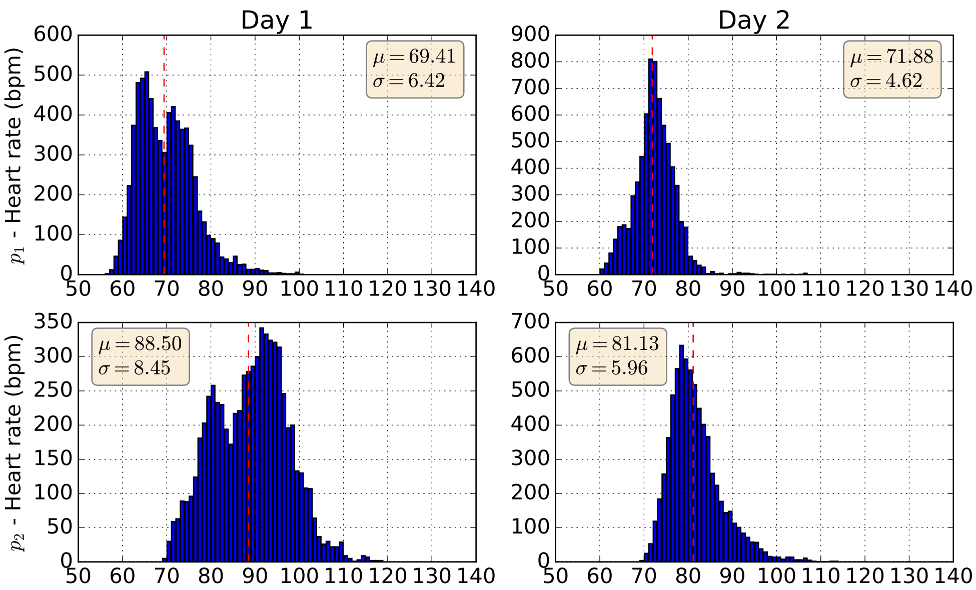


Figure 6.8: Histogram – Mean heart rate (bpm) morning session ("cold" temperature experiment).

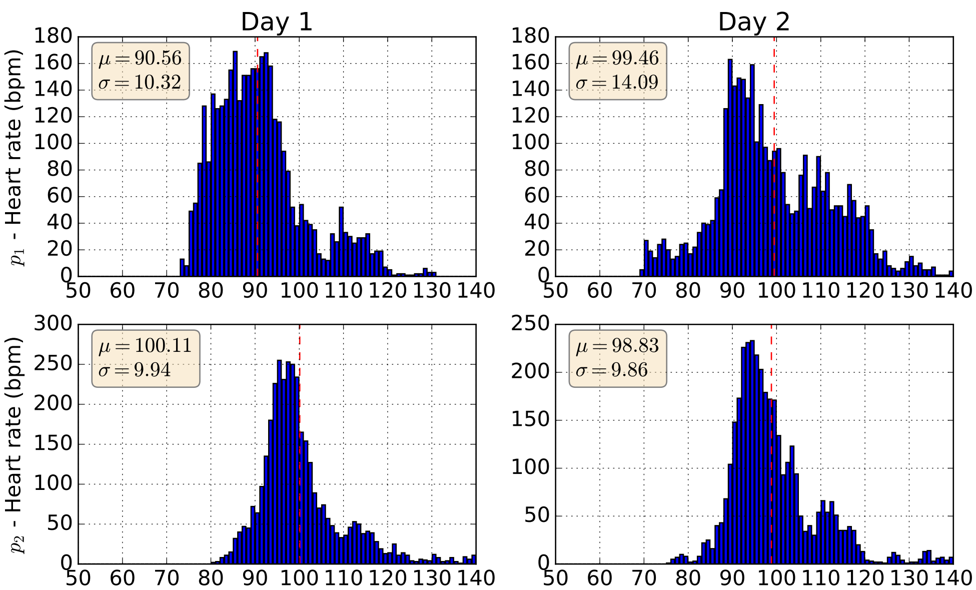


Figure 6.9: Histogram – Mean heart rate (bpm) lunch session ("cold" temperature experiment).

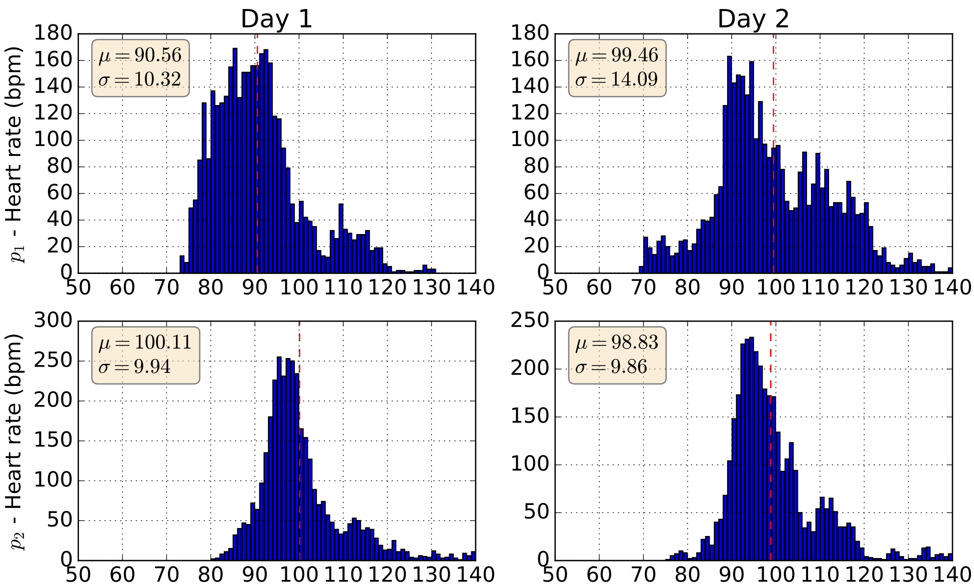


Figure 6.10: Histogram – Mean heart rate (bpm) afternoon session ("cold" temperature experiment).

Table 6.6: Mean heart rate (bpm) during difference session ("cold" temperature experiment).

	p_1		p_2	
	day_1	day_2	day_1	day_2
Morning	69	72	88	81
Lunch	91	99	100	99
Afternoon	87	87	95	99

6.4.5 Metabolic rate gender differences

Figure 6.11 shows the average minimum of the recorded heart rate measurements per participant during both days of the "cold" experiment. There, we can see that p_1 always reached a lower heart rate compared to p_2. Considering that both participants are healthy, around the same age and mainly engaged in non-sedentary activities (e.g., sitting) during the experiment, our findings could be explained by the fact that females generally have resting metabolic rates 5-10% lower than males [37, 41]. Table 6.7 summarizes the minimum heart rate values reached by both participants.

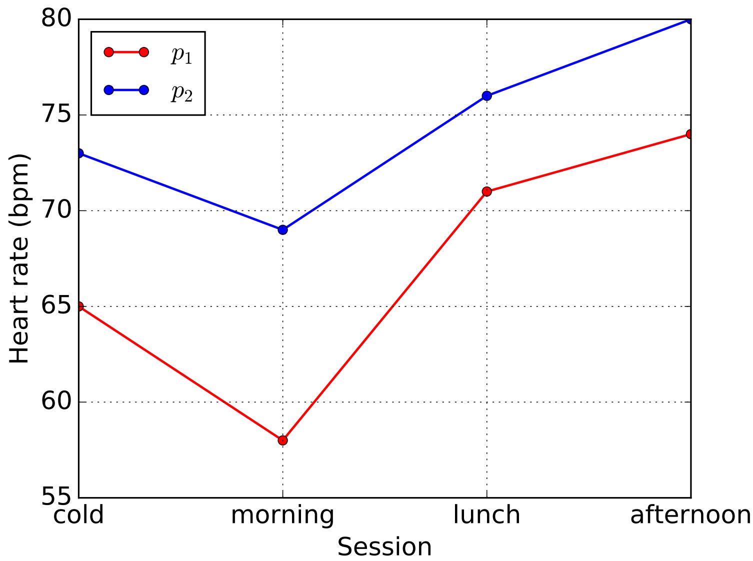


Figure 6.11: Average minimum heart rate per session ("cold" temperature experiment).

Table 6.7: Minimum heart rate (bpm) recorded during each session ("cold" temperature experiment).

	p_1		p_2	
	day_1	day_2	day_1	day_2
Cold	77	74	83	85
Morning	69	72	88	81
Lunch	91	99	100	99
Afternoon	87	87	95	99

7 Model

After the data collection, we started with the third part of our project—the machine learning part. To this end, we developed a data model. Our goal is to show how thermal comfort can be deduced automatically from the sensory input collected by the Comfstat infrastructure. According to the ASHRAE 55 standard, the satisfaction with the thermal environment can be expressed on a 7-point scale where -3 indicates *cold* and $+3$ indicates *hot*. This is also how thermal comfort is registered through Comfstat's mobile application (cf. Figure 4.2b).

Thus, thermal comfort may be considered a categorical variable. In Fanger's PMV and PPD calculations, however, fractional values are also possible. In the following we will therefore use two regression techniques—*linear regression* and *logistic regression*[1]—to model the relationship between the measured data and thermal comfort. While the former outputs values on a continuous scale, the latter uses the discrete ASHRAE scale.

7.1 Feature extraction

Before we evaluate the performance of the two regression approaches in Section 8, we show how we identified and extracted a set of features which serve as good indicators for the comfort level. The features are based on the six fundamental factors (metabolic rate, clothing level, air temperature, mean radiant temperature, air speed and humidity) which define human thermal comfort [10].

7.1.1 Environmental factors

From the environmental factors (i.e., air temperature, mean radiant temperature, air speed and humidity), we only include air temperature and humidity by means of the `ard_temp`, `ard_humidity` and `room_temp` features. The first two are based on the sensor worn on the participant's arm while the latter is situated at a fixed position in the room.

We do not model the air speed or the mean radiant temperature (i.e., the average temperature of surfaces like the floor and the walls) as both are difficult to measure outside the controlled environment of a climate chamber.

[1] Regularization parameter set to 1 and not tuned for for best possible alpha.

Table 7.1: Features computed on collected data.

#	Feature name	Description
f_1	polar	Heart rate in bpm in 1s intervals
f_2	room_temp	Room temperature interpolated to 1s intervals
f_3	ard_temp	Armband temperature sensor interpolated to 1s internals
f_4	ard_humidity	Armband humidity sensor interpolated to 1s internals
f_5	temp_delta	Difference between room temperature and armband temperature interpolated to 1s intervals
f_6	weight	Participant's weight in kilograms
f_7	height	Participant's height in meters
f_8	age	Participant's age in years
f_9	gender	Participant's gender (1: female and 0: male)
f_{10}	polar_1min_min	Minimum heart rate (bpm) value registered in the last minute (sliding window)
f_{11}	polar_1min_max	Maximum heart rate (bpm) value registered in the last minute (sliding window)
f_{12}	polar_1min_mean	Mean heart rate (bpm) value registered in the last minute (moving average)
f_{13}	room_temp_1min_min	Minimum room temperature value registered in the last minute (sliding window)
f_{14}	room_temp_1min_max	Maximum room temperature value registered in the last minute (sliding window)
f_{15}	room_temp_1min_mean	Mean room temperature value registered in the last minute (moving average)
f_{16}	ard_temp_1min_min	Minimum armband temperature value registered in the last minute (sliding window)
f_{17}	ard_temp_1min_max	Maximum armband temperature value registered in the last minute (sliding window)
f_{18}	ard_temp_1min_mean	Mean armband temperature value registered in the last minute (moving average)
f_{19}	ard_hum_1min_min	Minimum armband humidity value registered in the last minute (sliding window)
f_{20}	ard_hum_1min_max	Maximum armband humidity value registered in the last minute (sliding window)
f_{21}	ard_hum_1min_mean	Mean armband humidity value registered in the last minute (moving average)

7.1.2 Metabolic rate

From [24, 42] we know that an estimation of the metabolic heat production in the human body is essential when assessing human thermal comfort, also we know that metabolic rate can be inferred through heart rate. ISO 8996 establishes a linear relationship between the heart and metabolic rates of a person [22]. However, the calculation of the metabolic rate from the heart rate requires additional calibration to obtain parameters like the resting heart rate. To avoid this overhead, we decided to use the raw heart rate as a feature. In previous work, the heart rate has proved to be a good indicator for approximating energy expenditure [2, 6, 12, 47, 49]. We use the `polar` feature to denote the heart rate in bpm over a 1 s interval.

7.1.3 Clothing level and temperature differences

In addition to the heart rate, we model the difference `temp_delta` between the temperature measured on the body using the armband `ard_temp` and the temperature measured by the fixed sensor (i.e., `room_temp`). `temp_delta` is influenced by both, the room temperature and the participant's heat dissipation. As the armband is worn over the clothing, the weight of each temperature is influenced by the clothing level of the participant.

7.1.4 Temporal variations

Table 7.1 summarizes the selected features. All features are computed at 1-second intervals. Whenever the granularity of the raw data was less than 1 s, linear interpolation was used. In addition to the raw data from the sensors (i.e., `polar`, `room_temp`, ard_temp and ard_humidity), we introduce, for each, their respective minimum, maximum and mean over the previous 60 seconds to capture temporal variations. We denote these by adding the suffixes _1min_min, _1min_max and _1min_mean.

Using the temporal variations on the polar feature (i.e., features f_{10}, f_{11} and f_{12}), our goal is to recognize when a person's activity level has increased for a short period of time (e.g., a person just climbed the stairs to reach her office). The thus increased metabolic rate may cause thermal discomfort only for a brief moment, making an adjustment to the thermal environment unnecessary.

Features f_{13} to f_{21} capture recent changes in the environmental conditions (i.e., temperature and humidity). This is important as the human body needs time to adapt to changes in the thermal environment [42]. Figure 6.6 shows that when a participant entered a neutral from a warm environment, she needed several minutes before feeling comfortable.

7.1.5 Regression over multiple participants

Features f_6 to f_9 (e.g., weight, height, age and gender) are used specifically for evaluating the performance of the regression on different participants.

8 Evaluation

During the last phase of this thesis, we investigate whether the satisfaction with the thermal environment—expressed on the 7-point ASHRAE scale by our participants—can be determined automatically from the raw sensor data. To this end, we tested both linear regression and logistic regression on the Comfstat data set. We will use the subscripts $_{\mathrm{LIR}}$ and $_{\mathrm{LOR}}$ to denote performance figures for the linear and logistic regression, respectively.

To evaluate the approaches, we merged all available data for each participant. The data was then shuffled and split into training and testing sets using 10-fold cross validation. For each fold, the regression was tested on 1/10 of the data and trained on the remaining 9/10 (cf., Figure 8.1). To ensure that each fold contained sufficient training data, the folds were chosen to preserve the distribution of samples for each thermal comfort category.

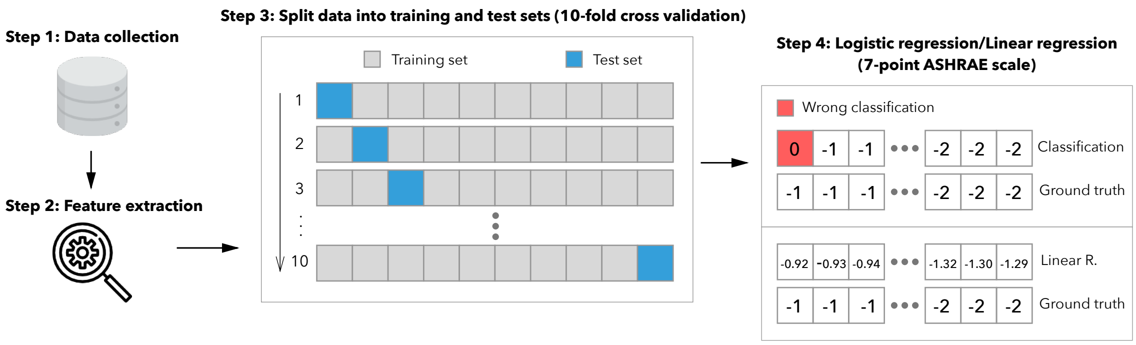


Figure 8.1: Setup of the 10-fold cross validation with merged data.

8.1 Metrics

We use four different metrics to measure the performance of the approaches. $\bar{e}$ and $\hat{e}$ denote the mean and median absolute error, respectively. These two metrics give an indication of how many points (on the ASHRAE scale) the comfort prediction is away from the actual sensation of the participants. The R^2 measure is included for reference in the figures as it is the standard means for determining the fit of a regression line.

As the median absolute error $\hat{e}$ is less useful for logistic regression—which outputs a categorical variable—we have also included the classification accuracy Acc as a metric. The accuracy gives the percentage of samples that have been classified correctly (e.g., the system correctly classified that a participant was feeling "cold" at a particular interval).

8.2 Baseline

As baseline we used three models. *Temperature only*, denoted by the subscript $_{\mathrm{TEM}}$, is the performance obtained by using linear regression on the temperature data alone (*i.e.* only f_2—`room_temp`—is used to predict comfort). The *Neutral* model (subscript $_{\mathrm{NEU}}$) always assumes that a person is feeling comfortable (i.e., the vote on the ASHRAE scale is 0). This neutral vote is in the middle of the scale and has a maximum error of 2. The *Random* model (subscript $_{\mathrm{RND}}$) assigns a uniform probability to all seven points on the ASHRAE scale and predicts a random comfort level at each interval. While the latter two approaches do not require any knowledge about the distribution of the comfort levels, they serve as lower bounds for the performance of the regression.

8.3 Regression performance

Table 8.1 shows the performance of the two regression approaches on the data from the *controlled temperature* experiment (cf. Section 6.2). Both regression approaches clearly outperform the baseline strategies. When only the temperature is used to deduce the participant's comfort levels, the mean error $\bar{e}_{\mathrm{TEM}}$ is on average 0.59 points. The Neutral strategy has a mean error $\bar{e}_{\mathrm{NEU}}$ between 0.89 and 1.17, while Acc_{NEU} is only 49% in the best case. As expected, the Random approach performs even worse with $\bar{e}_{\mathrm{RND}}$ between 1.92 and 2.05 and an average Acc_{RND} of 15%.

For the linear regression, the mean error $\bar{e}_{\mathrm{LIR}}$ varies between 0.39 and 0.53 for p_5 and p_3, respectively. This means, the prediction falls on average within 0.5 points of the actual thermal satisfaction of the participants. Similarly, the median error $\hat{e}_{\mathrm{LIR}}$ ranges from 0.32 to 0.47, meaning that 50% of the time, the actual vote is within less than 0.5 points of the prediction. Using the full feature set means the mean error incurred (i.e., $\bar{e}_{\mathrm{LIR}}$) is 0.13 points lower than the mean error incurred when only the temperature data is used (i.e., $\bar{e}_{\mathrm{TEM}}$). The effect of the additional heart rate features is strongest for p_1 and p_5 where the respective differences in $\bar{e}$ are 0.22 and 0.17.

Figure 8.2 shows the results of the linear regression for p_1 over all data points. This data has been obtained by concatenating the results from all 10 testing folds. While it fails to notice short changes in the thermal sensation, the green regression line

Table 8.1: Regression performance (controlled temperature experiment).

		p_1	p_3	p_4	p_5	**Avg.**
Linear R.	$\bar{e}_{\mathrm{LIR}}$	0.45	0.53	0.47	0.39	0.46
	$\hat{e}_{\mathrm{LIR}}$	0.38	0.47	0.42	0.32	0.40
Logistic R.	$\bar{e}_{\mathrm{LOR}}$	0.36	0.28	0.10	0.11	0.21
	Acc_{LOR}	68%	75%	94%	89%	82%
Temp. only	$\bar{e}_{\mathrm{TEM}}$	0.67	0.60	0.53	0.56	0.59
(Lin. Reg.)	$\hat{e}_{\mathrm{TEM}}$	0.67	0.85	0.40	0.40	0.58
Neutral	$\bar{e}_{\mathrm{NEU}}$	1.02	1.17	0.94	0.89	1.01
	Acc_{NEU}	33%	28%	49%	43%	38%
Random	$\bar{e}_{\mathrm{RND}}$	1.95	2.05	2.02	1.92	1.99
	Acc_{RND}	15%	15%	14%	14%	15%

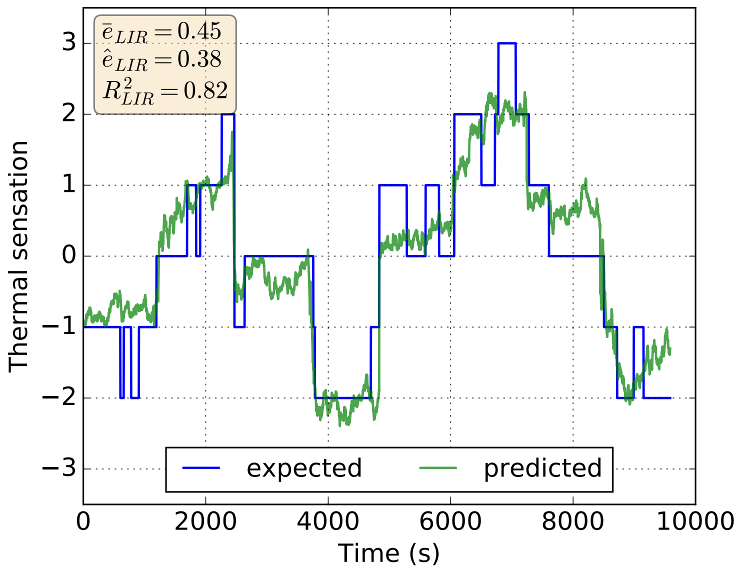


Figure 8.2: P_1 Linear regression.

tracks the ground truth (expected) comfort level quite closely. As the output from the linear regression is continuous, it also seems[1] to capture intermediate comfort levels. However, as the thermal satisfaction is measured on the 7-point scale, these intermediate levels are deemed erroneous.

Thus, as the logistic regression models a categorical variable, one might expect it to show smaller errors. Indeed, Table 8.1 shows that $\bar{e}_{\mathrm{LOR}}$ varies between 0.10 for p_4 and 0.36 for p_1. The Accuracy Acc_{LOR} shows that between 68% (i.e., p_1) and 94%

[1]The votes captured by the Comfstat infrastructure are expressed on the 7-point ASHRAE scale and thus do not allow for this granularity.

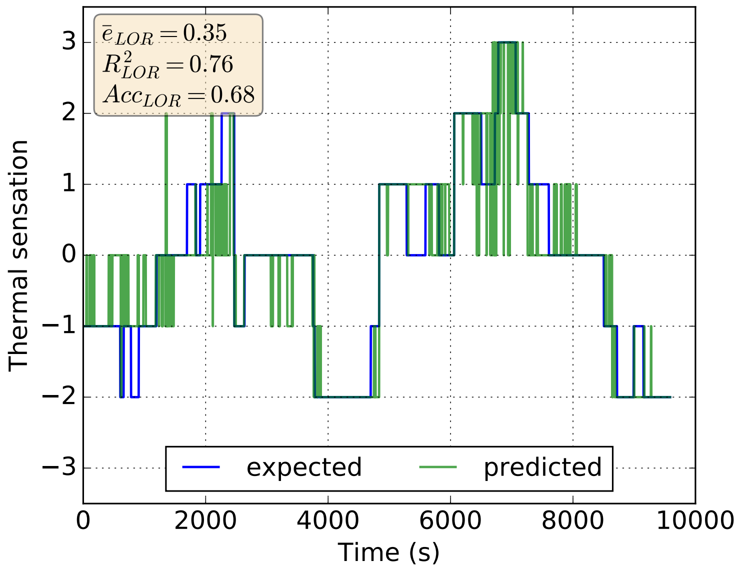


Figure 8.3: P_1 Logistic regression.

(i.e., p_4) of intervals are classified correctly.

To understand why the logistic regression fails to achieve a higher accuracy for p_1, Figure 8.3 shows the result of the regression over the whole duration of the "controlled" temperature experiment. The uncertainty regarding the current comfort level results in a lot of fluctuations of the predicted thermal sensation. When the linear regression outputs a value between two distinct comfort levels (cf., Figure 8.2), the logistic regression often oscillates between them. While having a lesser effect on $\bar{e}_{\mathrm{LOR}}$, this reduces the overall accuracy of the regression.

8.3.1 Cold experiment

Table 8.2 shows the results for the evaluation on the data from the *cold temperature* experiment (cf., Section 6.1). The inclusion of the cold experiment also allows us to have a look at p_2, who did not participate in the controlled temperature experiment. In contrast to the controlled temperature experiment, the latter covers a smaller range of thermal sensations.

With an average $\bar{e}_{\mathrm{TEM}}$ of 0.53, the smaller range means using only the room temperature to deduce thermal comfort works well. The other baseline strategies perform similarly to the previous experiment with $\bar{e}_{\mathrm{NEU}}$ at 1.14 and 0.82 for p_1 and p_2, respectively. This means that choosing to always predict a neutral environment results in an error of approximately one point on the thermal sensation scale. As expected, the random strategy performs worse, yielding only $Acc_{\mathrm{RND}} = 14\%$ and an

Table 8.2: Regression performance (cold experiment).

		p_1	p_2	**Avg.**
Linear R.	$\bar{e}_{\mathrm{LIR}}$	0.45	0.38	0.42
	$\hat{e}_{\mathrm{LIR}}$	0.38	0.35	0.37
Logistic R.	$\bar{e}_{\mathrm{LOR}}$	0.24	0.08	0.16
	Acc_{LOR}	77%	92%	85%
Temp. only	$\bar{e}_{\mathrm{TEM}}$	0.55	0.50	0.53
(Lin. Reg.)	$\hat{e}_{\mathrm{TEM}}$	0.49	0.26	0.38
Neutral	$\bar{e}_{\mathrm{NEU}}$	1.14	0.82	0.98
	Acc_{NEU}	35%	53%	44%
Random	$\bar{e}_{\mathrm{RND}}$	2.08	1.99	2.04
	Acc_{RND}	14%	14%	14%

average error of $\bar{e}_{\mathrm{RND}} = 2.4$.

The linear regression yields the same $\bar{e}_{\mathrm{LIR}} = 0.45$ for p_1 as in the controlled temperature experiment, albeit at a slightly higher median error of $\hat{e}_{\mathrm{LIR}} = 0.38$. The result for p_2 is better with $\bar{e}_{\mathrm{LIR}} = 0.38$ and $\hat{e}_{\mathrm{LIR}} = 0.35$. Again, the logistic regression performs better, with $\bar{e}_{\mathrm{LOR}} = 0.24$ and $\bar{e}_{\mathrm{LOR}} = 0.08$ for p_1 and p_2, respectively. Unsurprisingly, as the range of measured thermal sensations is lower in the cold experiment, the accuracy of the logistic regression is slightly higher for p_1 at $Acc_{\mathrm{LOR}} = 77\%$. The accuracy of the logistic regression for p_2 is even higher at 92%, reflecting the low average error of $\bar{e}_{\mathrm{LOR}} = 0.08$.

8.3.2 Discussion

The two regression approaches follow different goals. While the linear regression tries to model the relationship between the input variables (e.g., heart rate and temperature) and the output (i.e., thermal sensation) on a continuous scale, the logistic regression follows a classification (i.e., assigning input data to a number of distinct classes) approach. Thus, both strategies have advantages and disadvantages. The linear regression results in a higher average error also because it may produce values outside the $[-3, 3]$ interval. On the other hand, it allows for detecting fractional comfort levels – something that the logistic regression is not capable of. The logistic regression may thus oscillate between two comfort levels as the available input data cannot be used to conclusively determine a single level.

These fluctuations are not good for heating and cooling systems as they may cause the system's setpoint temperature to fluctuate as well. In the worst case, this may lead to further oscillations breaking the control loop. In order to alleviate this problem, an additional smoothing step should be employed to reduce the number of fluctuations. A similar post-processing step could remove extreme values for the linear regression, effectively capping its output at −3 and 3.

However, the choice of method to predict thermal comfort also depends on how the individuals' thermal sensations are used. If the smart thermostat subsequently combines all votes from multiple inhabitants to compute a single assessment of the current thermal comfort level like Fanger's PMV, individual fluctuations may be less important. As our sample of five participants is too small for such an analysis, we leave this question for future work.

8.4 Generalizability of trained model

During our preliminary analysis of the data set in Section 6.4 we observed that thermal sensations varied significantly between participants for the same thermal environments. To understand how this affected the trained regression models, we used 5-fold cross validation. By leaving one participant out and training on all available data from the other participants we want to examine how well the regression generalizes over different participants. Figure 8.4 shows the setup we used for the 5-fold cross validation. For this experiment, features f_6 to f_9 were introduced to model the weight, height, age and gender of the participants.

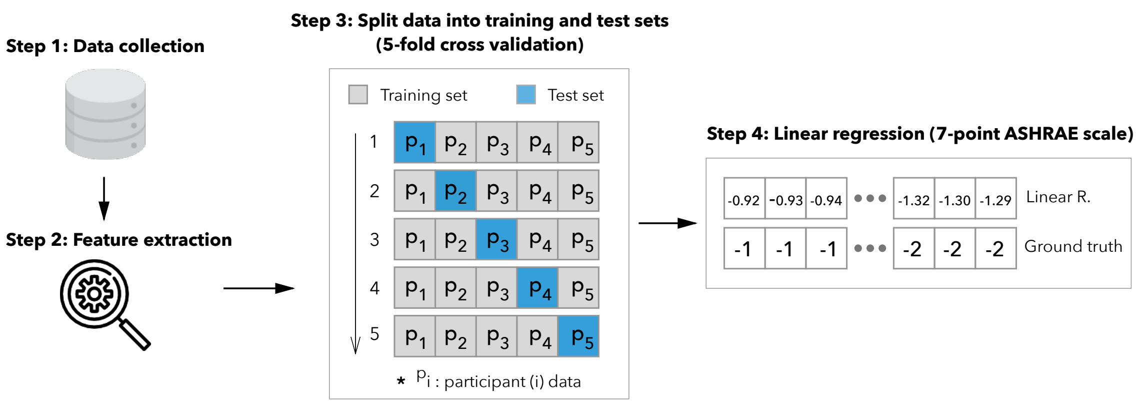


Figure 8.4: Setup of the 5-fold cross validation – predict user's thermal comfort by using others participants data as training set.

Figure 8.5 shows the result of this experiment for the logistic regression. As before, $\bar{e}$ denotes the average absolute error, while *Acc* denotes the accuracy. With the exception of p_1, $\bar{e}$ is above 1. This means that by using the other participants' data to predict p_2 to p_5, the logistic regression is wrong by a whole comfort level on average. This figure is similar to the performance of the Neutral baseline for both the controlled and cold temperature experiments. As the Neutral approach has no knowledge about any of the participants, thermal sensation does not seem to generalize for multiple people. This is important to note when considering alternative approaches like measuring the six primary factors defined in ASHRAE 55 and using equations derived from climate chamber experiments to deduce comfort [4]. By introducing a small training overhead that is made less strenuous through the use of smart watches, our Comfstat approach offers personalized comfort prediction.

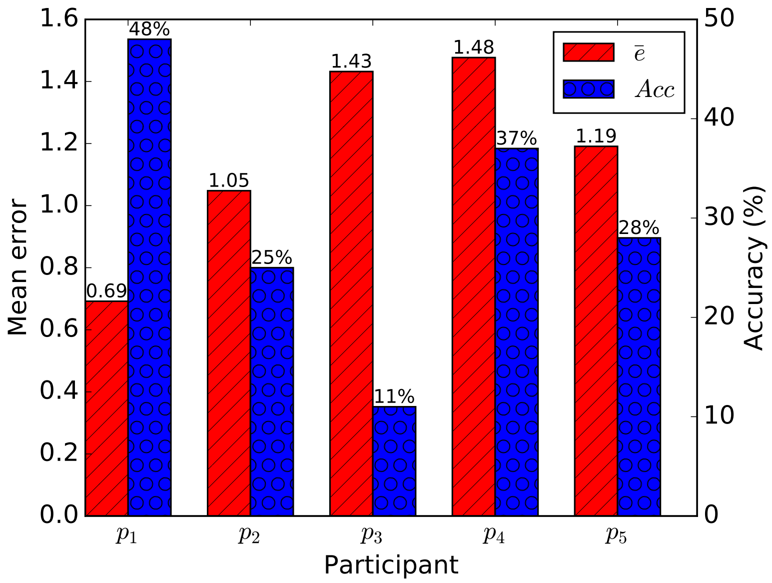


Figure 8.5: Generalizability - Using other participants' data to predict comfort.

8.5 Replacing the chest strap

The major drawback of our current system is that it relies on a chest strap to measure the participants' heart rates. To understand whether current smart watches might be a suitable substitute, we used the Comfstat infrastructure to collect heart rate data from a LG Watch R (W110) Android Wear smart watch. In contrast to the Polar H7 chest strap which was sampled at 1 Hz, the smart watch was only sampled every minute. Higher sampling frequencies were not possible as the watch would often time out as no value was detected.

Figures 8.6 and 8.7 show the result of a two-hour experiment during which we tested both the accuracy and the resulting battery drain. During this experiment, the smart watch was only used to measure the heart rate. Notifications were disabled and the watch was not otherwise used.

Figure 8.6 shows that the heart rate measured by the smart watch can deviate substantially from the chest strap, at times logging only half the value and well outside a reasonable range. This means that without significant thresholding and smoothing, the values from the smart watch cannot currently be used to monitor comfort. The sampling interval is also restricted by the battery drain of the sensor.

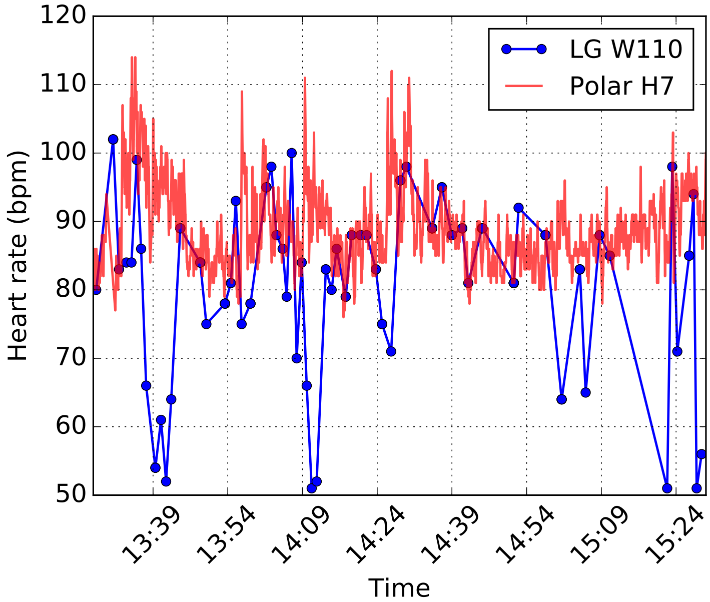


Figure 8.6: HR monitoring accuracy (smart watch vs chest strap). Pearson correlation: -0.045.

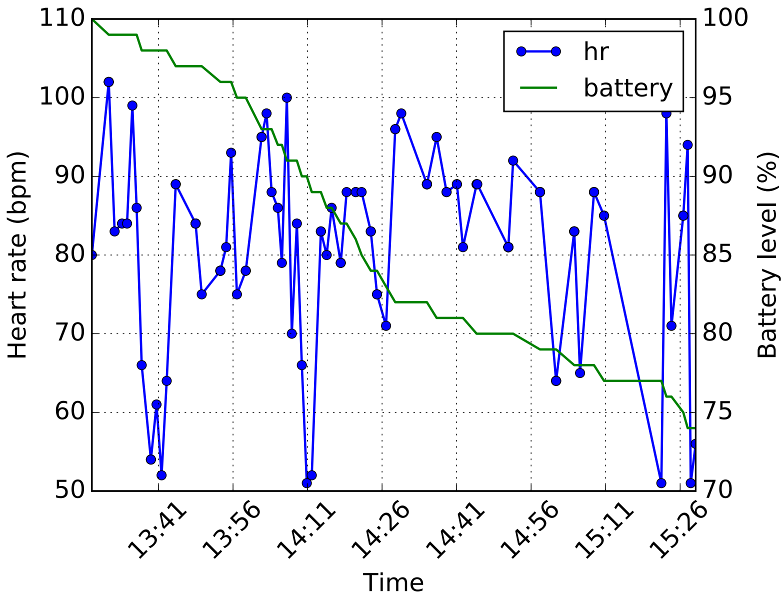


Figure 8.7: Smart watch battery drain.

Over the course of the two-hour experiment, the smart watch lost 25% of its capacity. This means that even if it was only used for sensing comfort, a smart thermostat could depend on the smart watch for merely eight hours a day.

The low accuracy and restricted sampling interval thus make current smart watches an unsuitable candidate for sensing the heart rate. However, as previous work has shown how pedometers and accelerometers can be used to monitor physical activity [11], future work might show how these can be integrated with the heart rate data to overcome periods of low accuracy and to reduce battery drain.

8.6 PMV calculation using heart rate monitor

Throughout this thesis, we have discussed the importance of the metabolic rate for estimating thermal comfort. In section 6.4.2 we observed that the heart rate can be used as an indicator for changes in user's thermal comfort level. Hence, in this section we explore the accuracy of the PMV calculation using three different methods for estimating metabolic rate, and we compare their results against our approach. The three methods we explore are: (i) using ISO 8996 equation for estimating metabolic rate from heart rate (cf., Section 3.3.2), (ii) using ISO 8996 simplified equation for estimating metabolic rate from heart rate as a function of age and weight of the subject (depending on gender) [22], (iii) lastly we assumed metabolic rate to be a constant value.

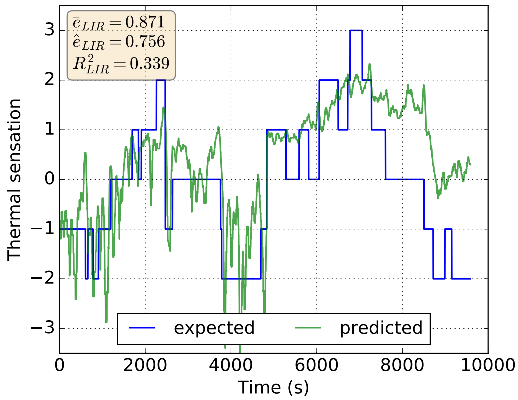
The ASHRAE standard [4] provides a computer program for calculating PMV-PPD based on the ISO 7730 standard [24]. We implemented the program and used it to evaluate the accuracy of PMV calculations using the three previously mentioned approaches for estimating participants' metabolic rate. Due to the complexity involved in calculating mean radiant temperature and air temperature—key parameters of the PMV equation—we assumed a median radiant temperature equal to the air temperature, similarly to other researchers [1, 29], and air velocity of $0.1m/s$ as in [8].

In this part of our research, we only used p_1's data, as it was required that the participant engaged in different activities in order to calibrate the parameters of the metabolic rate equation (cf., Equation 3.2). For the second method we use equation 8.1 which we obtained from annex C of the ISO 8996 standard [22]. Finally, for our third approach we assumed a constant metabolic rate of $70Wm^{-2}$, which is the value suggested by ISO 8996 for sedentary activities in places such as offices, schools and dwellings.

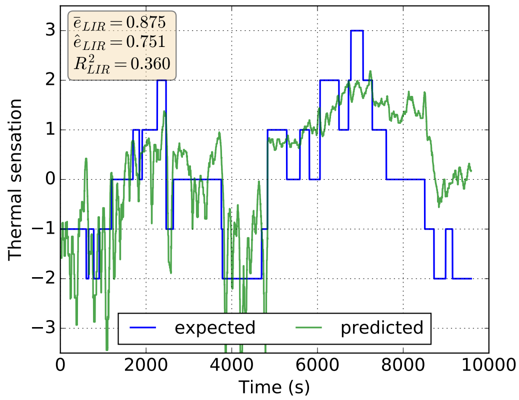
$$M = 3.3 * HR - 173 \tag{8.1}$$

Figure 8.8a to figure 8.8c show the results obtained from our implementation of the PMV calculation using three different ways of estimating metabolic rate. Figures 8.8a and 8.8b depict that the equations provided by ISO 8996 do not work sufficiently well when estimating metabolic rate for sedentary activities. These results were expected as the standard [22] establishes that the linear relationship between heart rate and metabolic rate is found when the heart rate is higher than 120bpm.

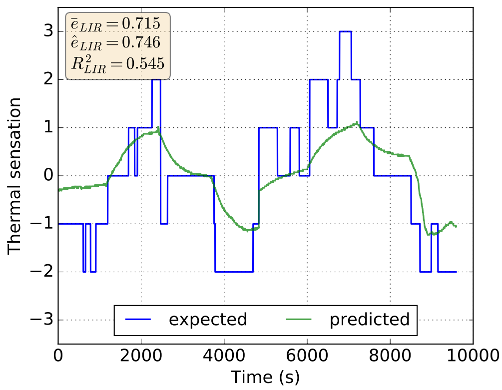
Moreover, Havenitha *et al.* in their research [15] state that a heart rate over 120 bpm implies work beyond office work, which is precisely the scenario we evaluated. Another indicator that the equations provided in ISO 8996 are not suitable for this use case is that we obtained lower mean error when assuming metabolic rate to be constant (cf., Figure 8.8c). Nevertheless, neither of the three approaches used provide acceptable estimations for thermal comfort as the predictions result in an error of approximately one point on the thermal sensation scale. Besides the low accuracy of the metabolic rate, another factor that could have affected the accuracy of the PMV calculations is the assumptions made for mean radiant temperature and air velocity.



(a) ISO:8996 metabolic rate estimation with equation 3.2



(b) ISO:8996 metabolic rate estimation with equation 8.1



(c) Constant metabolic rate of $70 W m^{-2}$

Figure 8.8: PMV calculation using different approaches to estimate metabolic rate.

9 Conclusion

In this thesis we introduced the Comfstat, a system for automatically sensing users' thermal comfort. Our work comprised three stages. First, we started by designing and implementing Comfstat's infrastructure. Following, we conducted a series of empirical studies with the aim of collecting thermal comfort data from participants under different environmental conditions. Finally, we used the previously collected data to train a machine learning model capable of predicting thermal comfort. Thus demonstrating the feasibility of our approach. In this final stage, we also compared our results against other existing approaches for predicting thermal comfort.

Our work shows how thermal comfort may be derived from participants' heart rates as well as environmental data including the room temperature and humidity. We show that high accuracies are possible when training a regression model using individual thermal sensation data and highlight that one cannot easily generalize the thermal sensation experienced by one participant in a particular environment to other participants. We propose to solve this problem by offering an easy-to-use calibration tool on both smart phones and smart watches that allows occupants to periodically vote on the 7-point ASHRAE scale.

Additionally, we examine the suitability of current smart watches to measure the participants heart rates and conclude that further developments in sensor technology are necessary before they may be used to sense comfort.

Finally, we explore the possibility of using the ISO 8996 equations for predicting the metabolic rate based on the heart rate as support for the PMV equation provided in ISO 7730 standard, and conclude that their combination is not suitable for predicting thermal comfort when participants engage mainly in sedentary activities, which is the usual activity level in an office environment.

With our work, we showed that building an infrastructure for sensing thermal comfort is feasible. Particularly, we show which avenues can work: using an accurate heart rate sensor; and which do not work: using a smart watch with heart rate capabilities, nor estimating the metabolic rate from the heart rate as suggested in the ISO 9886 standard. Furthermore, our approach offers a simplification when compared to other methods that depend on metabolic rate estimations. By directly using machine learning techniques over our data set without calculating the metabolic rate, we avoid its calibration process, which is time consuming because it requires participants to engage in different activity levels.

As future work, we propose integrating new sensor data to the Comfstat, such as pedometers, accelerometers and external weather conditions. From each new sensory data, new features should be derived and added to the model. We recommend to perform further feature engineering. Particularly, by exploring different windows' sizes and aggregation methods. Moreover, we propose to evaluate the performance of different models such as neutral networks or support vector machines. Additionally, we suggest adding more convenient ways for collecting ground truth thermal comfort data—essential for training the data model—such as allowing users to provide their thermal comfort by using voice commands instead of manually interacting with the smart phone or smart watch. Lastly, it would be interesting to implement an online learning algorithm capable of processing big data fed from different sources such as real world interactions with thermostats.

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A Appendix

This chapter's content was taken from the laboratory thesis “The Comfstat Automatically sensing thermal comfort for smart heating”, done at the distributing system group at ETH during Fall 2015 by Liliana Barrios.

A.1 Scenarios

Comfstat's design is based on scenarios and use cases. The basic argument behind scenario-based methods is that descriptions of people using technologies are essential in discussing and analyzing how the technology is (or could be) reshaping their activities [3]. Use cases specify all possible interaction between between user and system. Combining both methods allow to better understand user context and therefore design a suitable application to address users' needs. The first step in the design phase was to elaborate problem scenarios to better understand existing difficulties and opportunities. Afterwards, activity scenarios were written. Finally, use cases were specified.

A.1.1 Problem Scenarios

A problem scenario is a story about the problem domain as it exist prior to technology introduction. In another words, the name "problem scenario" is not because they focus attention on problematic aspects of the current practice, but rather because they describe activities in the problem domain [5]. Therefore, in order to reveal aspects of the stakeholders and their activities that have impact on the solution design, the following problem scenarios were developed.

Problem Scenario I

Billy is a 32 years old, he is married and has two children (3 and 5 years old respective). Billy is very sportive, he usually goes hiking two times per week, although since became a father it has been difficult to have free time. Billy is a graphic designer working in a start-up company is Zurich. He loves his job. Currently, there are around 25 employees working at the company. As a graphic designer Billy works very close to the development team, in fact, Billy's desk was recently moved into the development team office. The office is around 25 m^2, and it is shared by four persons Billy, Matthias, Johannes and Dominik. Each of them have different opinions regarding the right room temperature.

Matthias normally arrive very early to the office. He always feels the office is too warm, every morning as he arrives, he turns the heating off. Billy on the other hand, usually feels that the office is cold. Every time Billy has a chance, he tries to set the room temperature higher. Johannes does not complain much about the temperature and Dominik tends to support Billy. Dominik works normally in the evening, when no one else is at the office. During this time he always sets the office temperature higher. Actually, the heating stays on this setting (warm) until the next morning when Matthias arrives at the office and turns it off. Today was no exception, as Billy arrived at the office, he said hello to Matthias who was already working. Billy sat down and started to read his emails, after a some minutes he started to feel cold. He waited until Matthias was distracted to adjust the office temperature. Mattias get easily irritated, specially when he sees people changing the room temperature.

Billy and his colleagues do not notice that they are actually wasting energy by arbitrarily setting the temperature at their personal preference without taking into account how their colleagues feel. Also, they do not notice that by constantly changing the heating settings none of them manage to be at a comfortable temperature.

Problem Scenario II

Clair is a 28 years old women, working as a recruiter for one of the largest banks in Switzerland. She works in the main building located at Zurich. The building is huge. She works at the twelfth floor. The office is big, it is an open office and she shares it with another 50 employees. This morning Clair woke up as usual at seven in the morning to go to work. As always she is dressed with business clothes. Before going outside she checks the weather forecast. She notices it is a beautiful summer day, the outside temperature is rather warm (27 degrees), she takes her jacket and drives to the office. Clair never forgets her jacket, no matter if it is summer or winter because her office is always very cold. As she comes inside the building lobby she noticed is cold and puts her jacket on. As she walks to her desk, she looks around the office and notices everybody is wearing jackets. She wishes the office were not so cold. However, she remembered that there is an specific reason why the office is so cold. When the HVAC (heating, ventilating, and air conditioning) system was install, all employees were told that they must not change the HVAC system settings, because, it was configured in a way that provides comfort for the majority of the employees and at the same time safe energy. However, the technicians who installed the system do not know that actually all the employees are uncomfortable and that setting the office temperature higher would make them feel better and will also save more energy.

A.1.2 Activity Scenarios

After considering the problems scenarios described above, the following activities scenarios were developed. These envision how *Comfstat* will be and how it will support users with their current activities.

Activity Scenario I

Background on Billy, his motivations ...

Billy is excited about Comfstat. He wonders if now it will be possible to get consensus regarding the office temperature. Also he is happy to know that he does not have to hide from Matthias to change the room temperature, because Comfstat allows him to give his thermal comfort feedback privatively from his cellphone or smartwatch. Comfstat was install three days ago at the office. Billy remembers he and his colleagues installed the application and created their profile on Comfstat. Since the installation no one is able to manually change the room temperature. Billy and his colleagues are using Comfstat application (mobile and smartwatch) to provide their thermal comfort levels. This morning as Billy arrived to the office he said hello to Matthias who was already working. Billy sat down and started to read his emails. For the first time in a long time Billy did not feel cold, he actually felt comfortable. He opened his Comfstat application on the smartphone and provided feedback about his current thermal comfort. Then quickly checked the application configurations, it was the same as he left it the day before, meaning his heart rate was programed to be retrieved every 30 minutes, and that notifications are also scheduled every 30 minutes. Before continue reading his email he look for the comfort level overview and noticed that Matthias was feeling also comfortable during his last feedback, which was 25 minutes before. Billy felt happy, closed his application and continue his work.

Activity Scenario II

Background on Clair, her motivations ...

This morning Clair woke up as usual at seven in the morning to go to work. As always she is dressed with business clothes. Before going outside she checks the weather forecast. She notices it is a beautiful summer day, the outside temperature is rather warm (27 degrees), she takes her jacket and drives to the office. As she drive to the office she remembers that today they are suppose to install Comfstat on their smart-phones and smartwatches. She is excited because finally the office temperature will be modify. Moreover, the office temperature will consider not only Clair's comfort, but also Clair's colleagues comfort level. As she arrived to the office, she noticed it is already a bit warmer than usual, which is good. She arrive to her desk, sits, installs the application and creates her profile. She is all excited about Comfstat, she checks all the functionality; she checks her heart rate. Then, she checks current environment conditions, she notices the office temperature is 20 degrees Celsius, while the outside temperature is 27 degrees. Clair feels a bit more curious and looks for the comfort level overview. On the overview, she notices from early in the morning people are already using Comfstat, as she sees some people already provided their comfort level at 7 am. Susan who is one of Clair's colleagues was the last person to provide feedback, she was feeling slightly cool at 7:40 am. Now is 8:00am and Clair wants to try out the feedback functionality. Hence, she decides to report she is feeling quite ok with the current temperature. She checks for the *configurations and schedules notifications and heart rate retrieval every 30 minutes. Additionally, she activates the vibrate and smartwatch notification functionality. After exploring a bit more the new application. Clair decides is time to work. Thirty minutes afterwards, Clair receives the first notification reminding her to provide feedback. Clair is happy to use the smartwatch, she finds very convenient. She replies she is feeling slightly cool and continues working. Clair notices is the first time in a long time that she is not wearing a jacket in the office without feeling cold. She already thinks Comfstat was a great idea.*

B Appendix

An initial set of use cases was specified in the laboratory thesis “The Comfstat Automatically sensing thermal comfort for smart heating”, done at the distributing system group at ETH during Fall 2015 by Liliana Barrios. In this appendix, we present the resulting use cases after adding corresponding data retrieval functionality—essential for thermal comfort prediction.

B.1 Use case specification

Use case	**Sign in**
Actor	User
Preconditions	User is logout and already has an account in Comfstat
Basic flow	1. User opens Comfstat's smart phone application 2. Comfstat displays sign in form 3. User enters all required values 4. User tabs on sign in button 5. User is logged in 6. Comfstat displays application main menu
Alternative Flows	3.a User forgets one or several required values 3.b Comfstat prompts an alert 3.c User taps "ok" on the prompt 3.d User enters missing value(s) 3.e Use case continues in step 4 of the normal flow 5.a Login failed, Comfstat prompts error message

Table B.1: Use case: sign in

Use case	Sign up
Actor	Potential user
Preconditions	None
Basic flow	1. Potential user opens Comfstat application on smart-phone 2. Tabs on the sign up option 3. Comfstat displays sign up form 4. Potential user enters all required values in required format 5. Potential user tabs on sign up button 6. User is logged in 7. Comfstat displays application main menu
Alternative Flows	4.1a User forgets one or several required values 4.1b Comfstat prompts an alert 4.1c User taps "ok" on the prompt 4.1d User enters missing value(s) 4.1e Use case continues in step 5 of the normal flow 4.2a User enter values in wrong format 4.2b Comfstat prompts an alert 4.2c User taps "ok" on the prompt 4.2d User enters required values in right format 4.2e Use case continues in step 5 of the normal flow 6.a Sign up failed, Comfstat prompts error message

Table B.2: Use case: sign up

Use case	Submit comfort feedback
Actor	User
Preconditions	User is logged in and on Comfstat's main menu screen
Basic flow	1. User tabs on the voting button 2. Comfstat displays thermal comfort list of options 3. User tabs on the desired option 4. User is redirected to main menu screen 5. Toast message confirms feedback was saved correctly
Alternative Flows	3.a User tabs smartphone return button 3.b Comfstat displays main menu screen 4.a Communication with server failed, Comfstat prompts error message

Table B.3: Use case: submit comfort feedback

Use case	**Check heart rate**
Actor	User
Preconditions	User is logged in and on Comfstat's main menu screen
Basic flow	1. User tabs on the heart rate button 2. Comfstat displays heart rate screen and requests user's current heart rate 3. Comfstat displays current heart rate
Alternative Flows	3.a Comfstat prompts error message 4.a User makes new request by tapping on reload button 4.b Use case continues in step 2 of normal flow

Table B.4: Use case: check heart rate

Use case	**Check comfort overview**
Actor	User
Preconditions	User is logged in and on Comfstat's main menu screen
Basic flow	1. User tabs the overview button 2. Comfstat displays overview screen and requests last votes 3. Comfstat displays a list with the last submitted comfort level feedbacks (votes)
Alternative Flows	3.a Comfstat prompts error message

Table B.5: Use case: check comfort overview

Use case	Check environment state
Actor	User
Preconditions	User is logged in and on Comfstat's main menu screen
Basic flow	1. User tabs the stats button 2. Comfstat displays environment screen and requests current environment state 3. Comfstat displays current environment data including room temperature, outside temperature, humidity and pressure
Alternative Flows	3.a Comfstat prompts error message 4.a User makes new request by tapping on reload button 4.b Use case continues in step 2 of normal flow

Table B.6: Use case: check environment state

Use case	Activate/deactivate notifications vibrate function
Actor	User
Preconditions	User is logged in and on Comfstat's main menu screen
Basic flow	1. User tabs the settings button 2. Comfstat displays settings options 3. Under notifications, user taps vibrate option 4. Comfstat displays/hides vibrate check mark
Alternative Flows	None

Table B.7: Use case: activate/deactivate vibrate function

Use case	Activate/deactivate smart watch notifications
Actor	User
Preconditions	User is logged in and on Comfstat's main menu screen
Basic flow	1. User tabs the settings button 2. Comfstat displays settings options 3. Under notifications, user taps smartwatch option 4. Comfstat displays/hides smartwatch check mark
Alternative Flows	None

Table B.8: Use case: activate/deactivate smart watch notifications

Use case	**Modify notifications frequency**
Actor	User
Preconditions	User is logged in and on Comfstat's main menu screen
Basic flow	1. User tabs the settings button 2. Comfstat displays settings options 3. Under notifications, user taps frequency level 4. Comfstat prompts frequency level options 5. User taps desired frequency 6. Users is redirected to settings options
Alternative Flows	5.a User taps cancel button 5.b Users is redirected to settings options

Table B.9: Use case: modify notification frequency

Use case	**Activate/deactivate smart watch sensor**
Actor	User
Preconditions	User is logged in and on Comfstat's main menu screen
Basic flow	1. User tabs the settings button 2. Comfstat displays settings options 3. Under heart rate monitor, user taps smartwatch option 4. Comfstat displays smartwatch settings screen 4. User taps sensor switch (on/off)
Alternative Flows	None

Table B.10: Use case: activate/deactivate smart watch sensor

Use case	Modify heart rate retrieval frequency
Actor	User
Preconditions	User is logged in and on Comfstat's main menu screen
Basic flow	1. User tabs the settings button 2. Comfstat displays settings options 3. Under heart rate monitor, user taps smartwatch option 4. Comfstat displays smartwatch settings screen 5. User taps frequency level 6. Comfstat prompts frequency level options 7. User taps desired frequency 8. Users is redirected to settings options
Alternative Flows	7.a User taps cancel button 7.b Users is redirected to smart watch settings screen

Table B.11: Use case: modify heart rate retrieval frequency

Use case	Connect/disconnect polar device
Actor	User
Preconditions	User is logged in and on Comfstat's main menu screen
Basic flow	1. User tabs the settings button 2. Comfstat displays settings options 3. Under heart rate monitor, user taps polar strap option 4. Comfstat displays polar strap settings screen 5. User taps devices that wants to connect to 6. Comfstat shows that is connected to device
Alternative Flows	5.a User taps back button 5.a Comstat displays settings screen 6.b Comfstat shows error message, explaining device is not heart rate monitor

Table B.12: Use case: connect/disconnect polar device

Use case	Connect/disconnect arduino device
Actor	User
Preconditions	User is logged in and on Comfstat's main menu screen
Basic flow	1. User tabs the settings button 2. Comfstat displays settings options 3. Under environment, user taps arduino option 4. Comfstat displays arduino settings screen 5. User taps devices that wants to connect to 6. Comfstat shows that is connected to device
Alternative Flows	5.a User taps back button 5.a Comstat displays settings screen 6.b Comfstat shows error message, explaining device does have the required sensors

Table B.13: Use case: connect/disconnect arduino device

Use case	Modify server url
Actor	User
Preconditions	User is logged in and on Comfstat's main menu screen
Basic flow	1. User tabs the settings button 2. Comfstat displays settings options 3. Under application , user taps server button 4. Comfstat prompts server url form 5. User enters url 6. User tabs "ok" button 7. Users is redirected to settings options
Alternative Flows	5.a User taps cancel button 5.b Users is redirected to settings options 6.a User taps cancel button 6.b Users is redirected to settings options

Table B.14: Use case: modify server url

Use case	**Modify router MAC address**
Actor	User
Preconditions	User is logged in and on Comfstat's main menu screen
Basic flow	1. User tabs the settings button 2. Comfstat displays settings options 3. Under application , user taps wifi button 4. Comfstat prompts mac address input form 5. User enters office router mac address 6. User tabs "ok" button 7. Users is redirected to settings options
Alternative Flows	5.a User taps cancel button 5.b Users is redirected to settings options 6.a User taps cancel button 6.b Users is redirected to settings options

Table B.15: Use case: modify router MAC address

Use case	**Sign out**
Actor	User
Preconditions	User is logged in and on Comfstat's main menu screen
Basic flow	1. User tabs menu dots 2. Comfstat displays logout option 3. User taps logout 4. Comfstat application is closed
Alternative Flows	3.a User taps outside logout button 3.a Logout button is hidden

Table B.16: Use case: Sign out

Use case	Replay smart-phone notification
Actor	User
Preconditions	User is logged in and notifications are active
Basic flow	1. Comfstat sends feeback notification 2. Comfstat notification is displayed on smartphone main screen 3. User tabs notification 4. User is redirected to vote screen 5. Comfstat displays thermal comfort list of options 6. User tabs on the desired option 7. User is redirected to main menu screen 8. Toast message confirms feedback was saved correctly
Alternative Flows	3.a User swipes notification 3.b Notification is dismissed 6.a User tabs smartphone return button 6.b Comfstat displays main menu screen 7.a Communication with server failed, Comfstat prompts error message

Table B.17: Use case: reply smart-phone notification

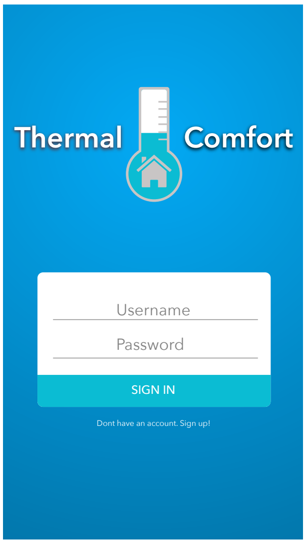
Use case	**Replay smart-watch notification**
Actor	User
Preconditions	User is logged in, notifications and smart watch options are active
Basic flow	1. Comfstat sends feedback notification 2. Comfstat notification is displayed on smart watch 3. User swipes notification right 4. Comfstat displays reply option on watch 5. User tabs reply 6. Comfstat displays thermal comfort list of options 7. User tabs on the desired option 8. Comfstat displays reply confirmation 9. Notification screen disappears
Alternative Flows	3.a User swipes notification left 3.b Notification is dismissed 4.a User swipes left to dismiss reply option 4.b Notification is dismissed 6.a User swipes left to dismiss thermal comfort list of options 6.b Notification is dismissed

Table B.18: Use case: reply smart-watch notification

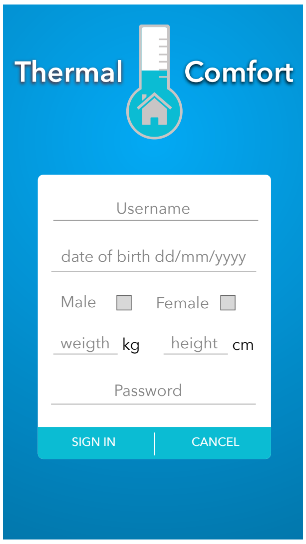
C Appendix

C.1 High fidelity prototype

An initial high fidelity prototype was developed for the laboratory thesis "The Comfstat Automatically sensing thermal comfort for smart heating", done at ETH's distributing system group during Fall 2015 by Liliana Barrios. In this chapter, we present the resulting prototype after adding corresponding data retrieval functionality—essential for thermal comfort prediction.


Thermal
Comfort
Username
Password
SIGN IN
Dont have an account. Sign up!

(a)


Thermal
Comfort
Username
date of birth dd/mm/yyyy
Male
Female
weigth kg
height cm
Password
SIGN IN
CANCEL

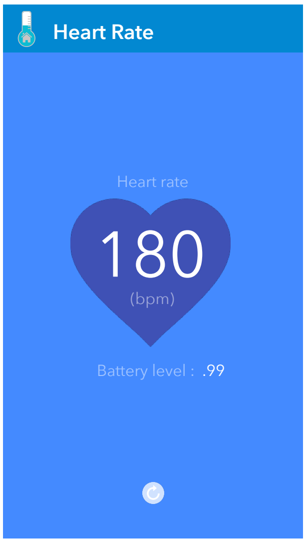
(b)


Thermal Comfort

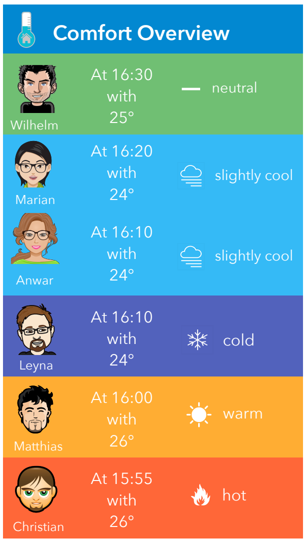
(c)


Comfort Level
cold
cool
slightly cool
neutral
sligtly warm
warm
hot

(d)


Heart Rate
Heart rate
180
(bpm)
Battery level : .99

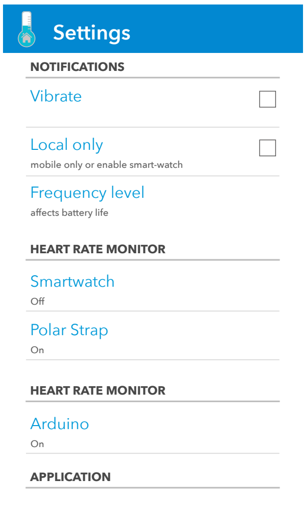
(e)


Comfort Overview
Wilhelm
At 16:30 with 25°
neutral
Marian
At 16:20 with 24°
slightly cool
Anwar
At 16:10 with 24°
slightly cool
Leyna
At 16:10 with 24°
cold
Matthias
At 16:00 with 26°
warm
Christian
At 15:55 with 26°
hot

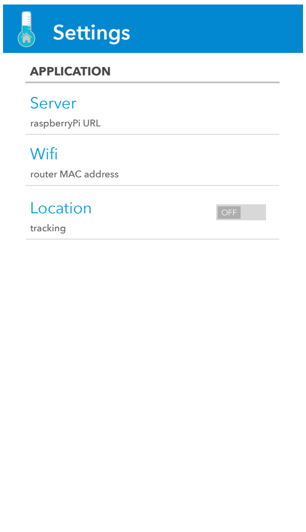
(f)


Environment
At 10:55
Outdoor
5°
Indoor
18°
HUMIDITY
30%
PRESSURE
60%

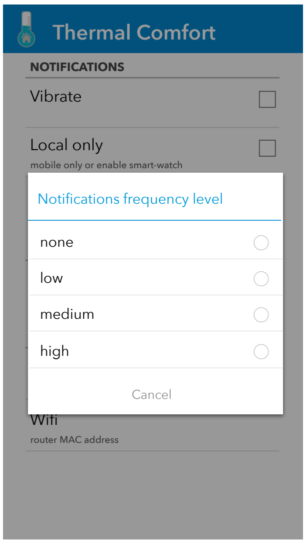
(g)


Settings
NOTIFICATIONS
Vibrate
Local only
mobile only or enable smart-watch
Frequency level
affects battery life
HEART RATE MONITOR
Smartwatch
Off
Polar Strap
On
HEART RATE MONITOR
Arduino
On
APPLICATION

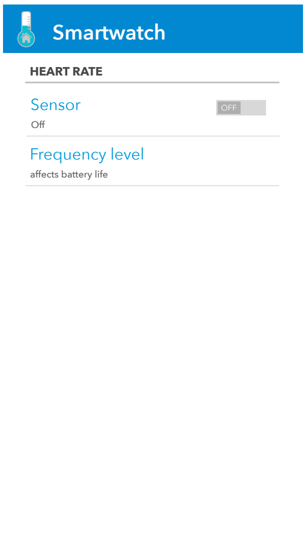
(h)


Settings
APPLICATION
Server
raspberryPi URL
Wifi
router MAC address
Location
tracking
OFF

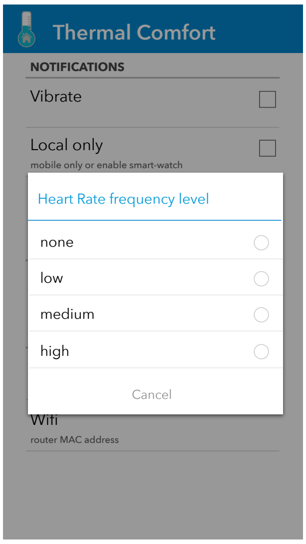
(i)


Thermal Comfort
NOTIFICATIONS
Vibrate
Local only
mobile only or enable smart-watch
Notifications frequency level
none
low
medium
high
Cancel
Wifi
router MAC address

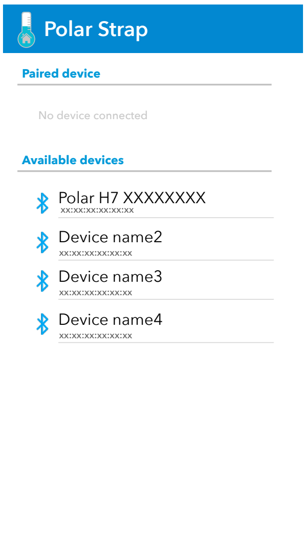
(j)


Smartwatch
HEART RATE
Sensor
Off
OFF
Frequency level
affects battery life

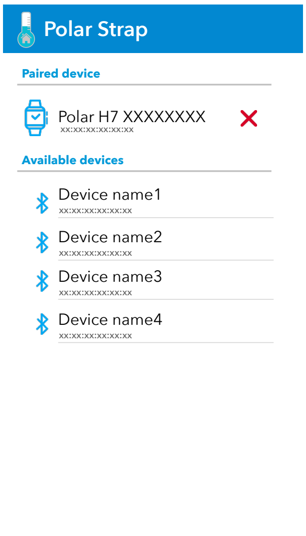
(k)


Thermal Comfort
NOTIFICATIONS
Vibrate
Local only
mobile only or enable smart-watch
Heart Rate frequency level
none
low
medium
high
Cancel
Wifi
router MAC address

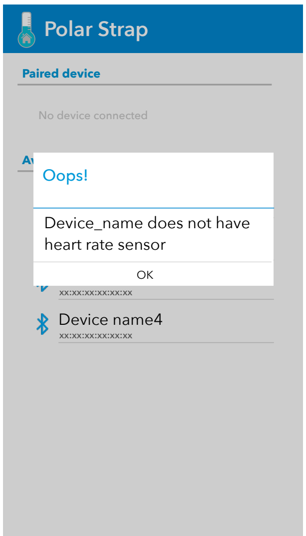
(l)


Polar Strap
Paired device
No device connected
Available devices
Polar H7 XXXXXXXX
Device name2
Device name3
Device name4

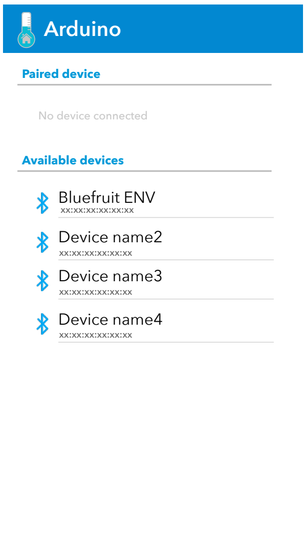
(m)


Polar Strap
Paired device
Polar H7 XXXXXXXX
Available devices
Device name1
Device name2
Device name3
Device name4

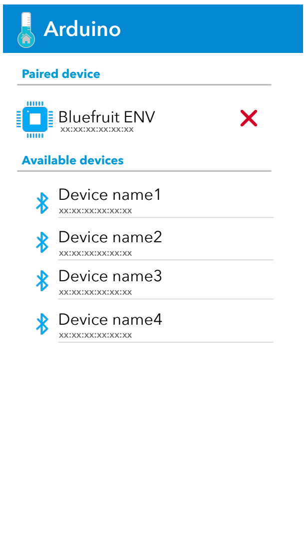
(n)


Polar Strap
Paired device
No device connected
Oops!
Device_name does not have heart rate sensor
OK
Device name4

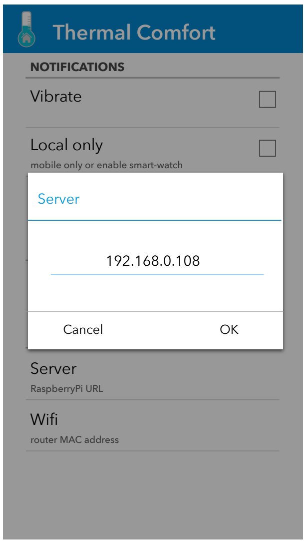
(o)


Arduino
Paired device
No device connected
Available devices
Bluefruit ENV
Device name2
Device name3
Device name4

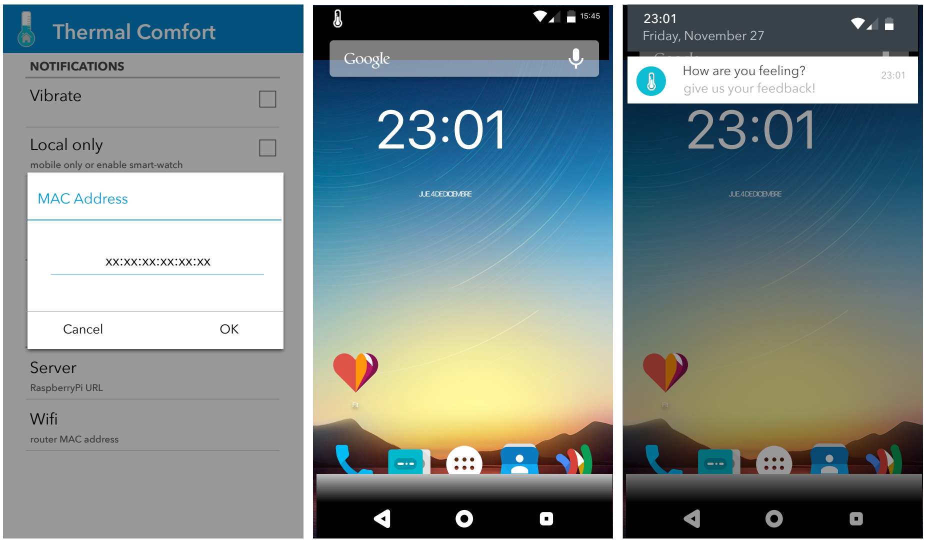
(p)


Arduino
Paired device
Bluefruit ENV
Available devices
Device name1
Device name2
Device name3
Device name4

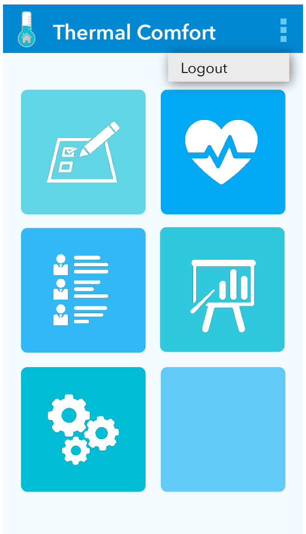
(q)


Thermal Comfort
NOTIFICATIONS
Vibrate
Local only
mobile only or enable smart-watch
Server
192.168.0.108
Cancel
OK
Server
RaspberryPi URL
Wifi
router MAC address

(r)

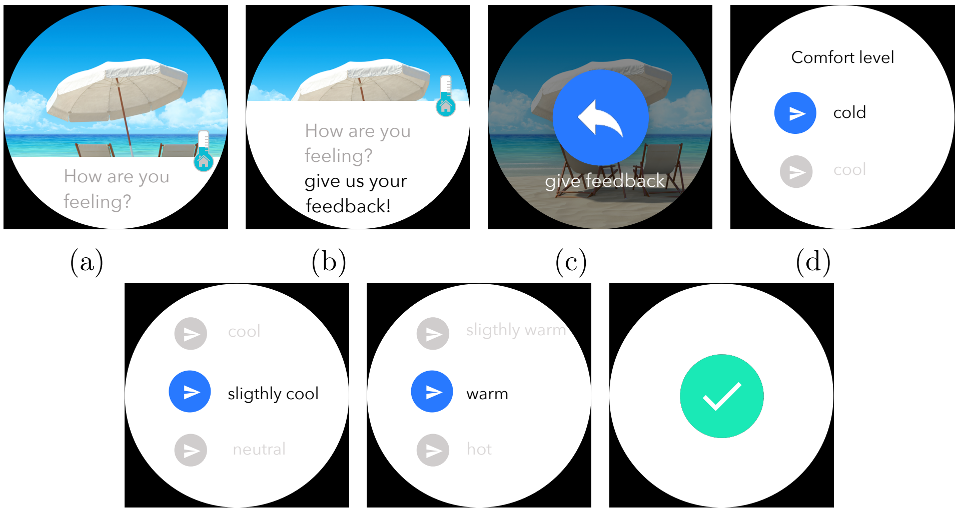


(s) (t) (u)



(v)

Figure C.1: Smart phone application



(a) (b) (c) (d)

(e) (f) (g)

Figure C.2: Smart watch application

D Appendix

The content of this appendix was abstracted and adapted from the laboratory thesis "The Comfstat Automatically sensing thermal comfort for smart heating", done at ETH's distributing system group during Fall 2015 by Liliana Barrios.

D.1 Smart watch application

The smart watch application is also developed in Android. It is composed of three services, whose main goal is to reply to Comfstat's heart rate retrieval requests. All processes related to heart rate retrieval happen on the background. Users cannot start these services through the smart watch interface. The only way users can directly interact with Comfstat through the smart watch is by replying incoming notifications. Otherwise, Comfstat does not offer an independent smart watch application where users can start services or preform actions. Figure D.1 displays the smart watch application code structure.

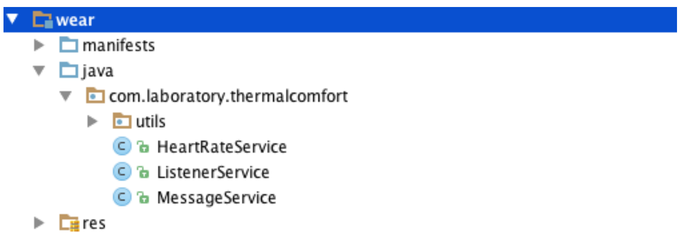


Figure D.1: Smartwatch application code structure

ListenerService class handles incoming messages (MessageApi) from Comfstat's GoogleApiClient instance in the mobile application. Every incoming message indicates a new heart rate retrieval request. Code snippet D.2 depicts *ListenerService* class structure. This class has only one method, *onMessageReceived* which is executed everytime a new message arrive to this listener class. *onMessageReceived* is responsible for getting the id of the node who sent the request, this id is necessary in order to reply directly to the instance making the request. Additionally, *onMessageReceived* is in charge of starting the heart rate retrieval service and making sure this service is started holding a wake lock.

Android's heart rate sensor is a non-wake-up sensor. Non-wake-up sensors are sensors that do not prevent the system on a chip (SoC) from going into suspend mode and do not wake the SoC up to report data. In particular, the drivers are not allowed to hold wake-locks. It is the responsibility of applications to keep a partial wake lock should they wish to receive events from non-wake-up sensors while the screen is off.[1] Therefore, *onMessageReceived* uses the method *startWakefulService* to indicate Android that the service most hold a wake lock. Wake locks can also be handled directly. However, this makes the implementation more complicated. Moreover, when it comes to background services directly handling locks is not the preferred approach.

Code snippet D.1: Extract from HeartRateAlarmReceiver class

```
public class ListenerService extends WearableListenerService {
    @Override
    public void onMessageReceived(MessageEvent messageEvent) {
  }
```

HeartRateService class, as its name indicates, is responsible for retrieving user's heart rate. Code snippet D.2 outlines the class structure. As mention above, this service is started holding a wake lock. The method *onHandleIntent* register the heart rate sensor listeners. The listener is registered with a sampling rate (data delay) *SENSOR_DELAY_NORMAL*, which is equivalent to $200,000$ microseconds. This is the default data delay, and it is suitable for monitoring typical screen orientation changes.[2]. The *onSensorChanged* method is executed every time a new data value is retrieved, if the data accuracy is unreliable or the heart rate is zero then the value is dismissed, and listeners keep waiting for new data. Otherwise, the heart rate value is transfered to the *MessageService*, the wake lock is released, the sensor is stopped and the listener unregistered. In case *onSensorChanged* gets ten times zero readings, the service stops and unregisters the listener to avoid battery drain.

Code snippet D.2: Extract from HeartRateService class

```
public class HeartRateService extends IntentService
  implements SensorEventListener {

    @Override
    protected void onHandleIntent(Intent workIntent)
    @Override
    public void onSensorChanged(SensorEvent event)
    private String checkStatus(SensorEvent event)
  }
```

Finally, *MessageService* collects all data to be store on the server, these include heart rate, time sensor took to get value, battery level. Afterwards, by means of the Android *MessageApi*, the data is sent to Comfstat's mobile application, which later

[1]Google Devices (2015). Sensors. Suspend mode. Retrieved from `https://source.android.com/devices/sensors/suspend-mode.html`

[2]Google Devices (2015). Sensors Overview. Retrieved from `http://developer.android.com/guide/topics/sensors/sensors_overview.html`

takes care of sending it to the server. Figure D.2 outlines how the three services interact in order to get the heart rate.

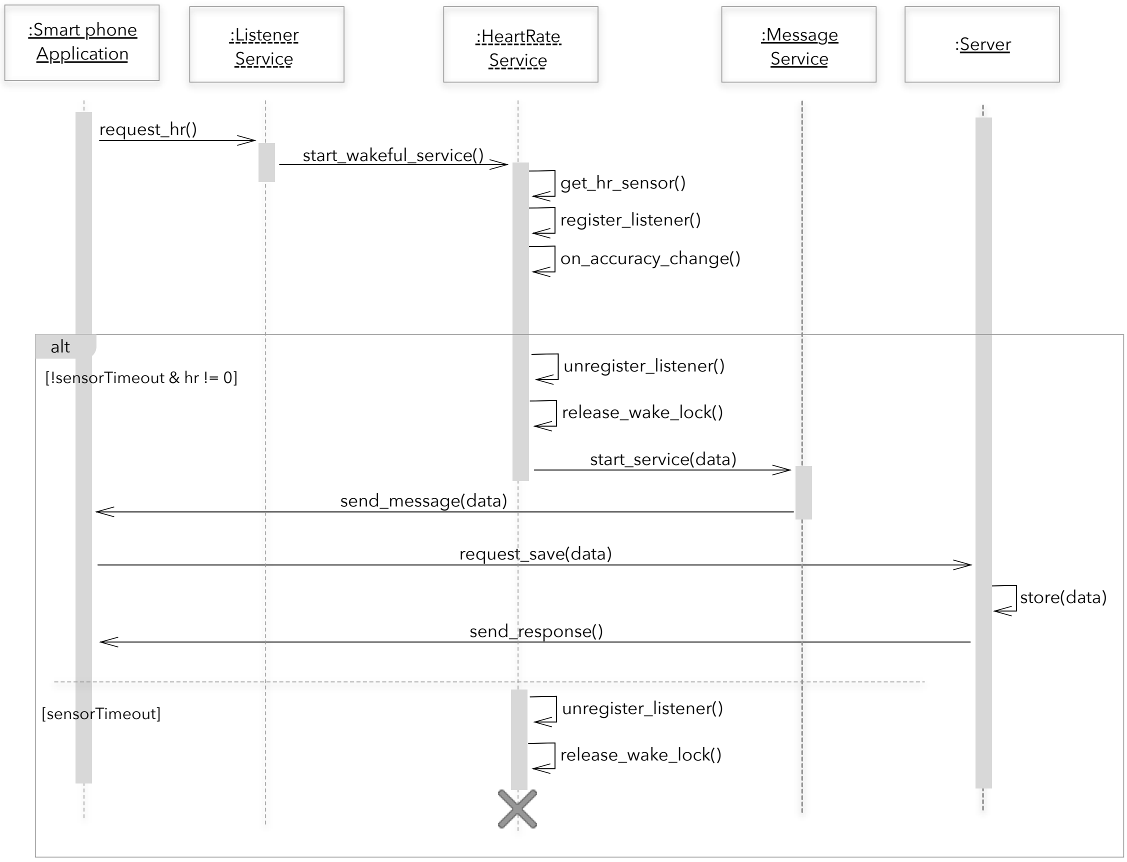


Figure D.2: Heart rate retrieval service sequence diagram.

Notifications

Notifications are implemented with the Android's *NotificationManager*. Depending on the user's settings they can be sent to the smart phone and/or smart watch. The smart watch notification is built with an action that includes a *RemoteInput*. Together, these two features allow users to directly reply to notifications from the smart watch. Users are presented with seven different options to specify their thermal comfort level at a given time. If a user never dealt with notification before a new one is triggered, the old one will be replaced by the most recent notification.

Assuming that Comfstat's notifications are active, figure D.3 highlights the most relevant processes that take actions while triggering a notification and replying it from the smart watch.

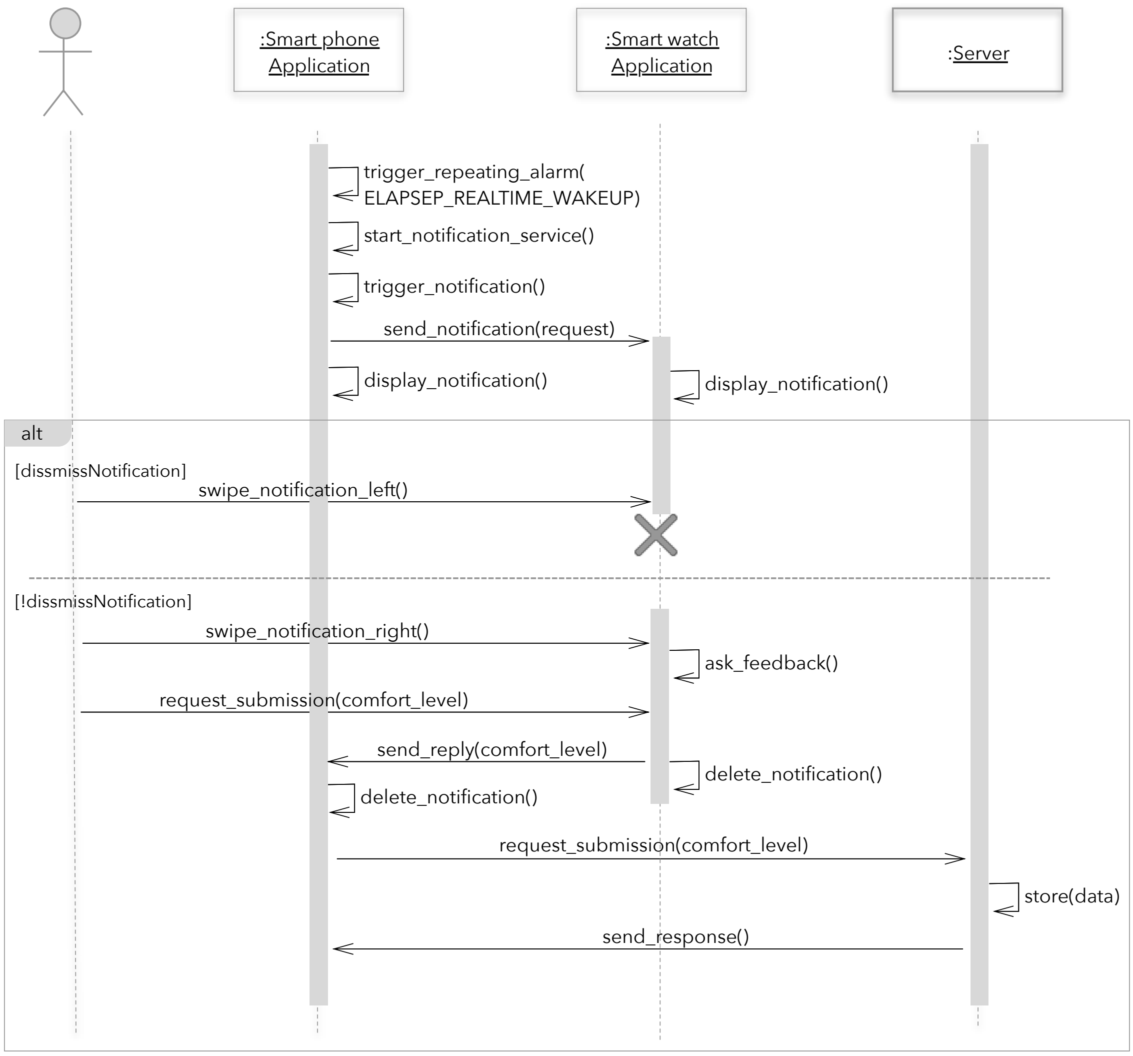


Figure D.3: Reply notification from smart watch sequence diagram.

E Appendix

E.1 ISO Consent form

IN CONFIDENCE

Name: ______________________ Age ___ years Sex: Female/Male

1. I am willing to participate as an experimental subject in the study of

____

Conducted by ____

at ____

2. I have received an explanation of the nature and purpose of this study and of any risks to my health which are foreseen.
3. I agree to provide accurate information about my health and to be medically examinated if this is considered necessary. I agree that my normal medical advisor can provide information about my medical history to the authorized medical adviser to the study (independent medical officer). I understand that all information about my health will be treated as confidence.
4. I agree to cooperate fully with the investigators and not knowingly to do anything which might invalidate the results.
5. During the course of the investigation to which I am now giving my consent, I will not participate as subject in any other study, without first informing the investigators and obtaining their approval, which may be withheld.
6. I understand that I am free to withdraw my consent to participate in the study at any time without the need to give an explanation for my decision.

Signed ________________________ Date ________________________

Statement by investigator

In connection with the study described above, I have explained to ______________________ the nature of the study and the foreseeable risks from participation in the study.

Signed ________________________ Date ________________________

Figure E.1: ISO Consent form.

F Appendix

F.1 Data analysis

This appendix contains a complete data analysis for all participants in each experiment.

F.1.1 Heart rate per thermal comfort sensation

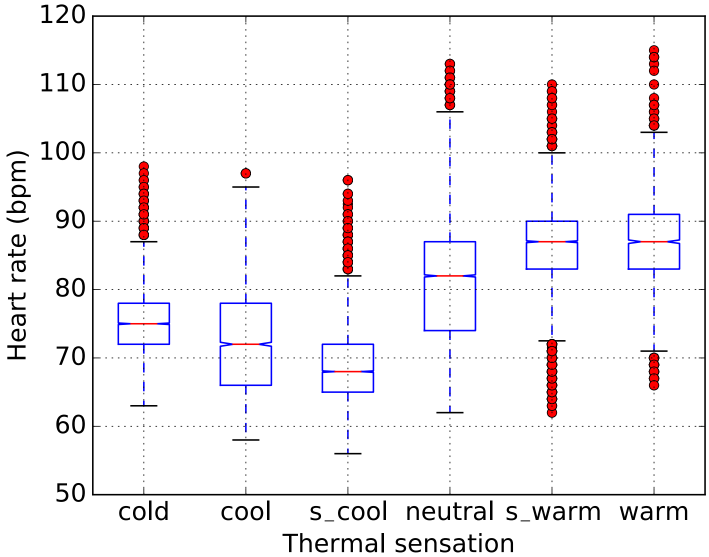


Figure F.1: P_1 heart rate per thermal comfort level.

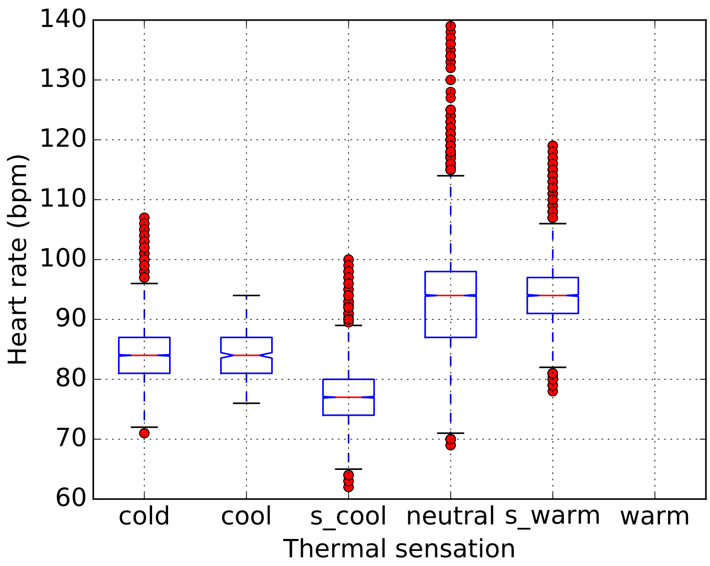


Figure F.2: P_2 heart rate per thermal comfort level.

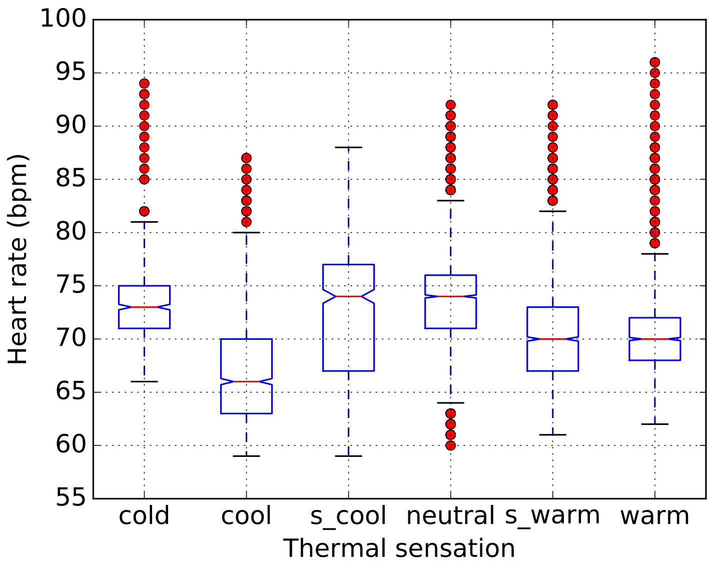


Figure F.3: P_3 heart rate per thermal comfort level.

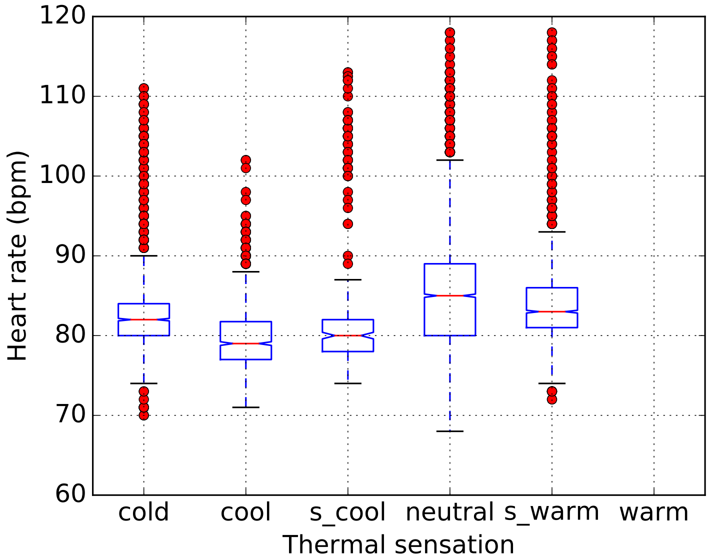


Figure F.4: P_4 heart rate per thermal comfort level.

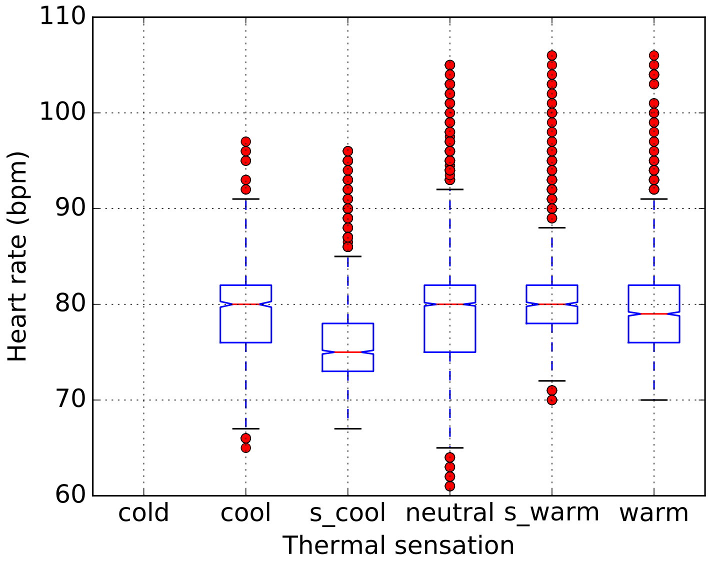


Figure F.5: P_5 heart rate per thermal comfort level.

F.1.2 Thermal comfort and temperature correlation

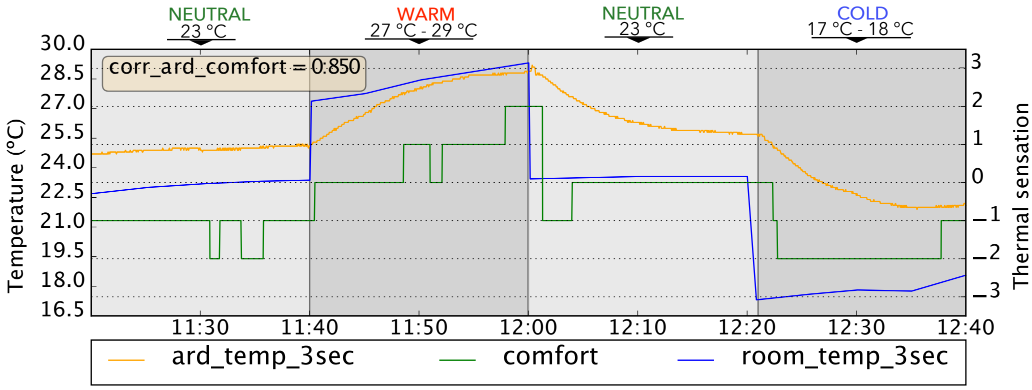


Figure F.6: P_1 Thermal comfort and temperature correlation (session 1 – "controlled" temperature experiment).

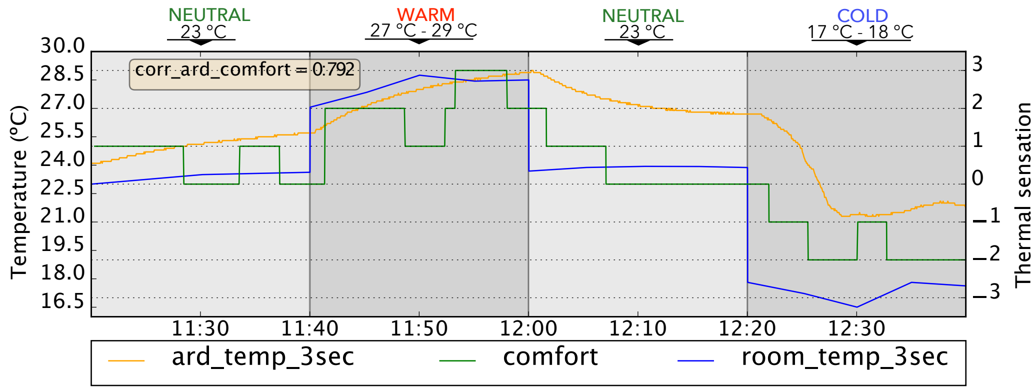


Figure F.7: P_1 Thermal comfort and temperature correlation (session 2 – "controlled" temperature experiment).

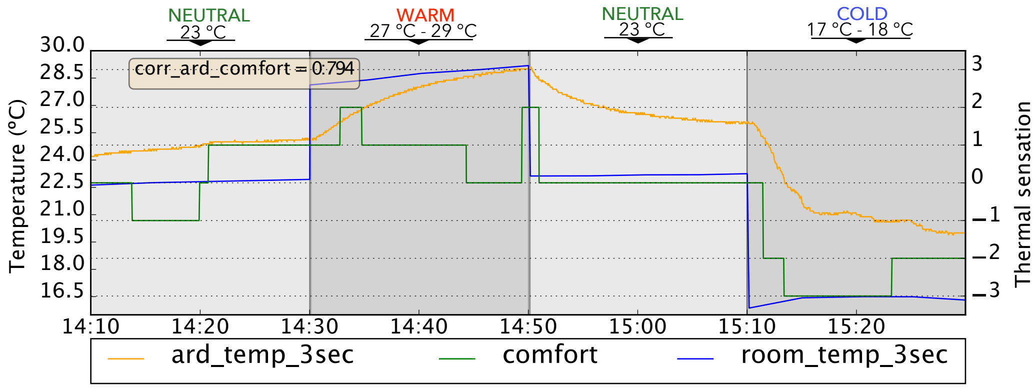


Figure F.8: P_3 Thermal comfort and temperature correlation (session 1 – "controlled" temperature experiment).

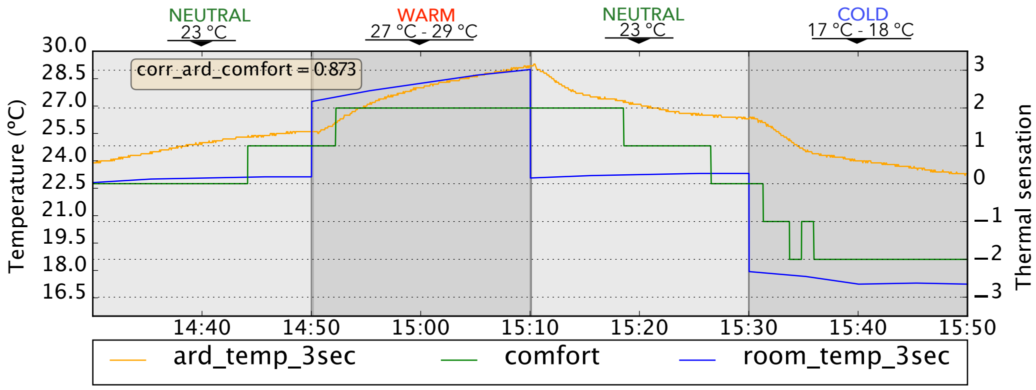


Figure F.9: P_3 Thermal comfort and temperature correlation (session 2 – "controlled" temperature experiment).

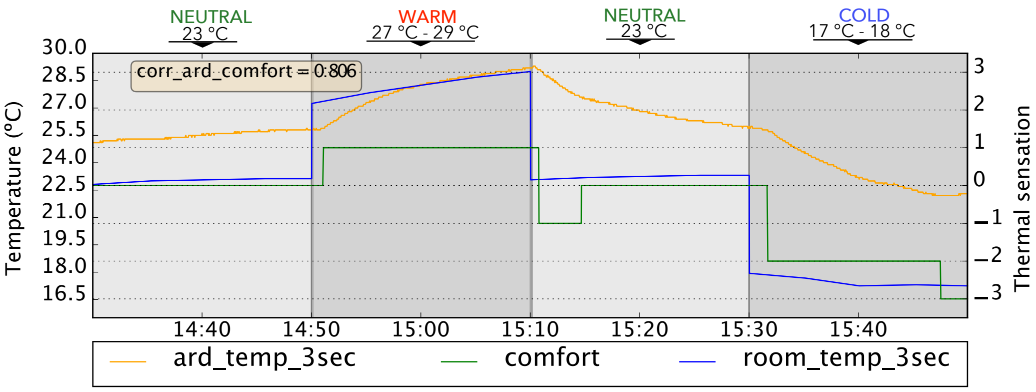


Figure F.10: P_4 Thermal comfort and temperature correlation (session 1 – "controlled" temperature experiment).

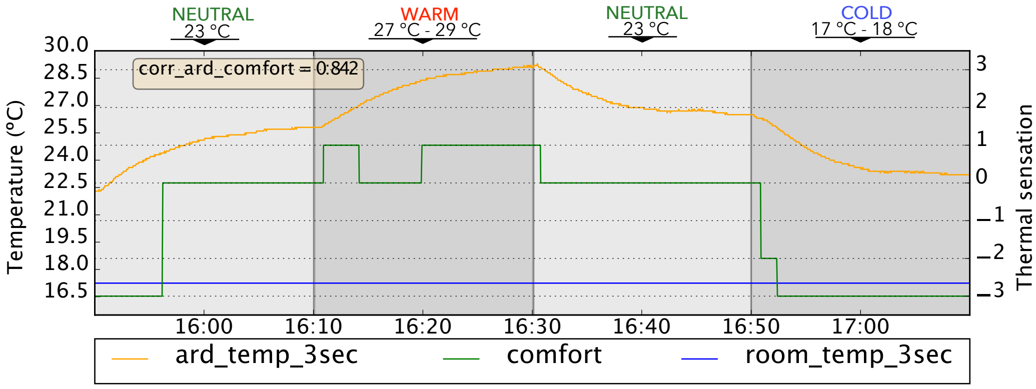


Figure F.11: P_4 Thermal comfort and temperature correlation (session 2 – "controlled" temperature experiment).

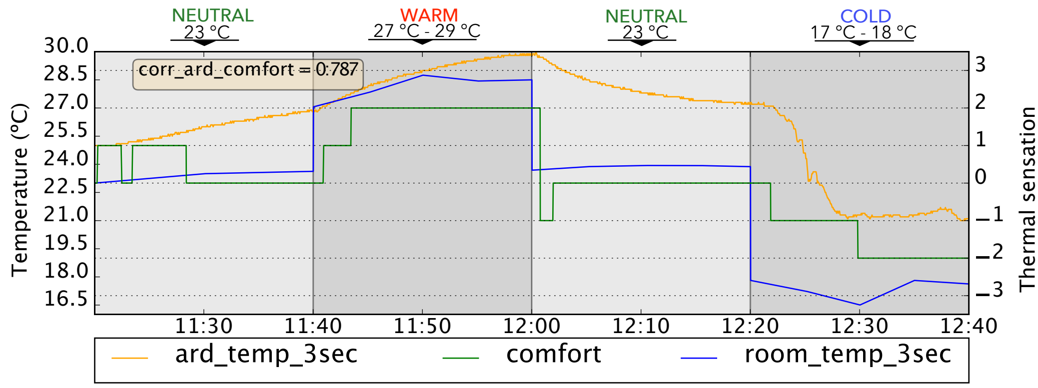


Figure F.12: P_5 Thermal comfort and temperature correlation (session 1 – "controlled" temperature experiment).

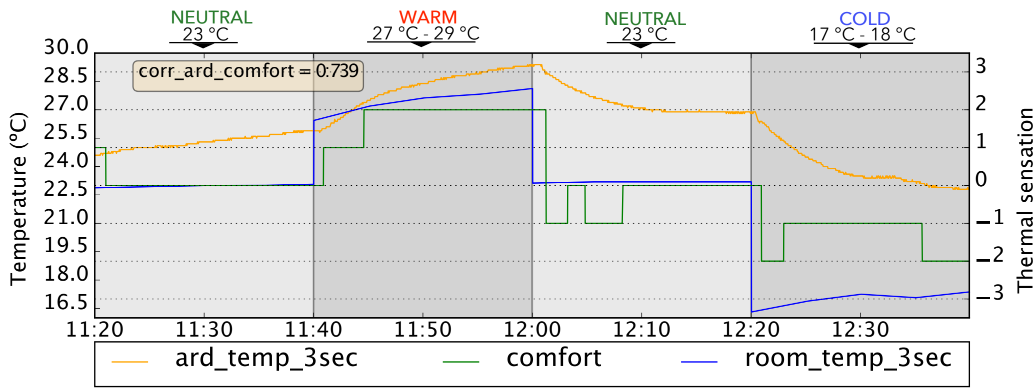


Figure F.13: P_5 Thermal comfort and temperature correlation (session 2 – "controlled" temperature experiment).

F.2 Regression performance plots

F.2.1 Controlled temperature experiment

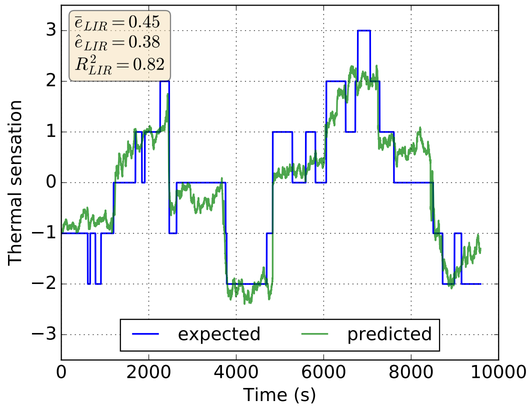


Figure F.14: P_1 Linear regression.

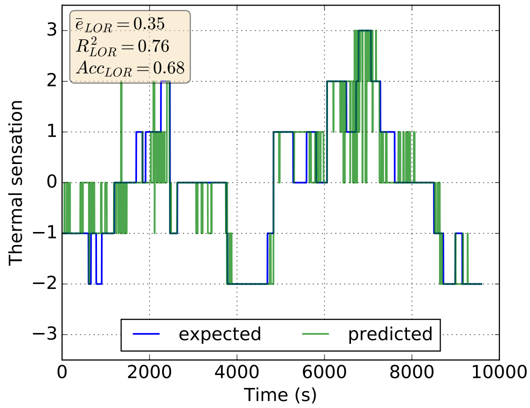


Figure F.15: P_1 Logistic regression.

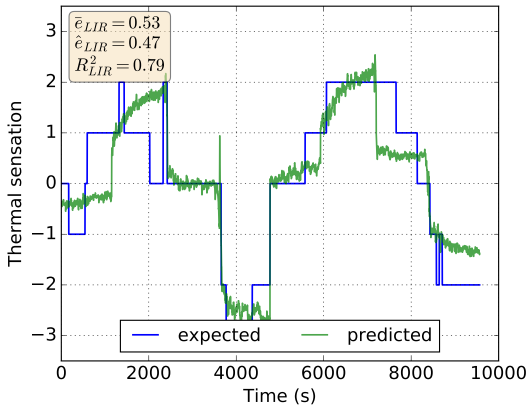


Figure F.16: P_3 Linear regression.

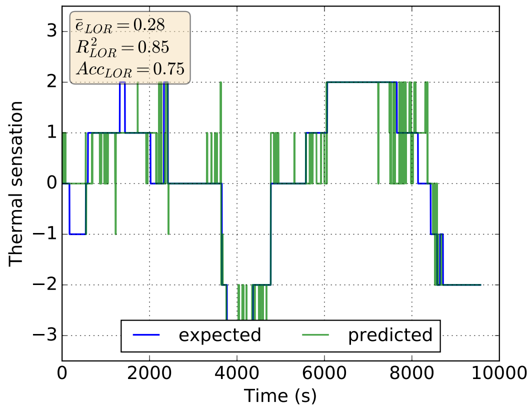


Figure F.17: P_3 Logistic regression.

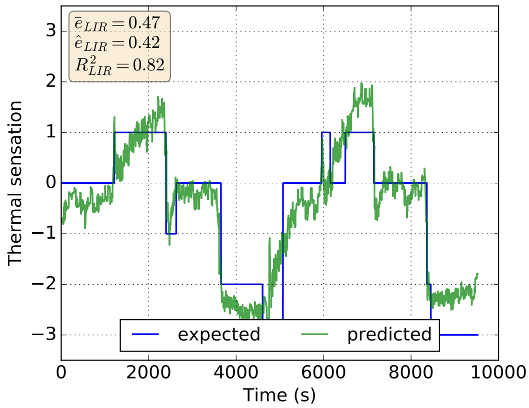


Figure F.18: P_4 Linear regression.

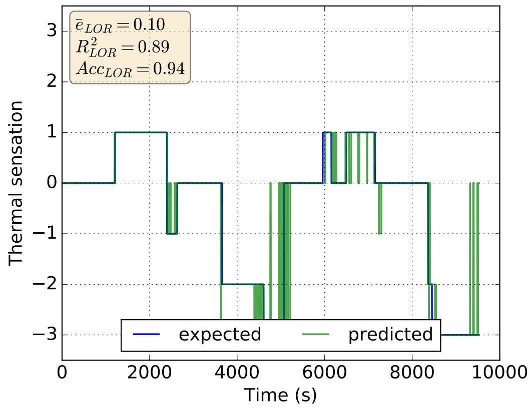


Figure F.19: P_4 Logistic regression.

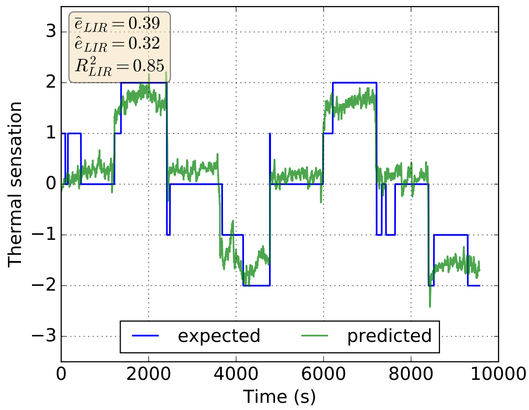


Figure F.20: P_5 Linear regression.

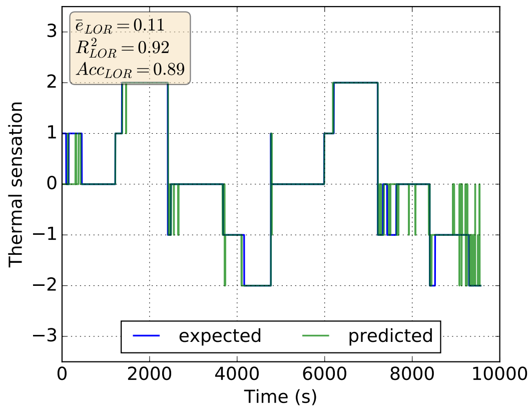


Figure F.21: P_5 Logistic regression.

F.2.2 Cold temperature experiment

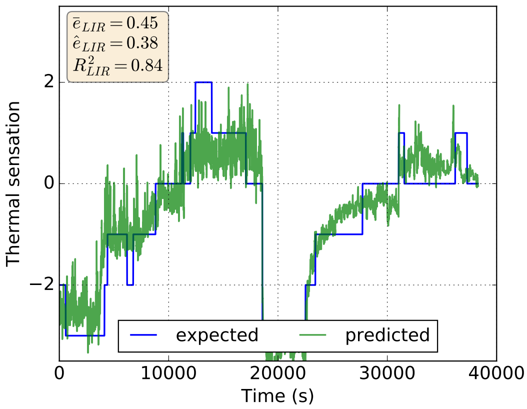


Figure F.22: P_1 Linear regression.

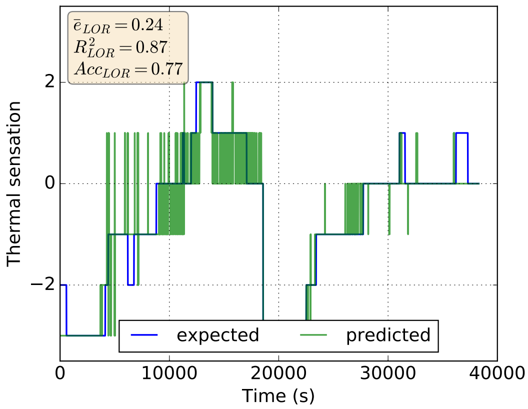


Figure F.23: P_1 Logistic regression.

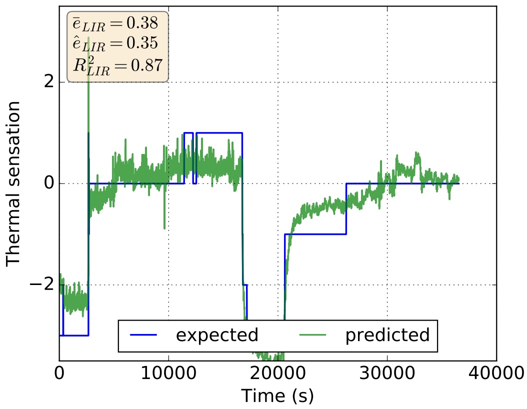


Figure F.24: P_2 Linear regression.

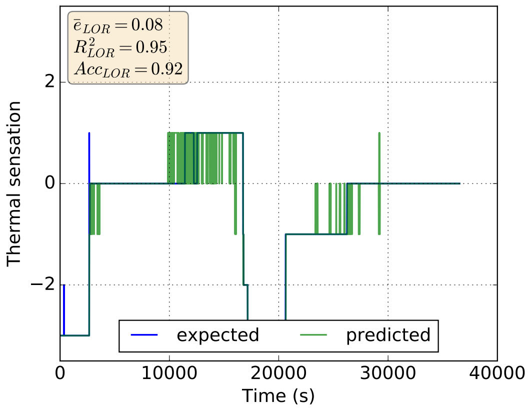


Figure F.25: P_2 Logistic regression.