# Investigation of Thermal Comfort in Multi-Occupant Office Spaces

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This is to certify that the thesis prepared

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# ABSTRACT

## Investigation of thermal comfort in multi-occupant office spaces

### Emilios Athienitis

Canadians spend 80 to 90% of their time indoors and previous studies show that the vast majority are typically unsatisfied with their thermal comfort, especially in their workplaces. Building occupancy patterns have also dramatically changed in the past two years after the COVID-19 pandemic, given the unprecedented increase in telecommuting and the shift towards alternative office arrangements such as hot-desking, which are gaining widespread popularity. These changes pose new challenges to building operators, particularly due to larger variability in occupancy and occupant preferences compared to standard assumptions. Therefore, discovering personal comfort preference is key in optimizing room temperature for co-working spaces with variable occupancy. To this end, the goal of this research was to assess thermal comfort of occupants in a co-working space and investigate the differences in their comfort assessment under varying conditions using near real-time surveying methods. Other factors that might influence office comfort such as clothing and air velocity from ceiling diffusers were also investigated. The primary objective of this study is to leverage novel technologies such as wearables to identify thermal comfort levels in multi-occupant spaces in a continuous near real-time approach. The secondary objective is to find the statistical differences between surveyed occupants' thermal comfort perception with respect to personal factors such as clothing, metabolic rates, and perception of air movements.

This research was conducted in the recently established living lab at Concordia university which features modern co-working spaces. Temperature ranges that correspond to survey responses continuously collected using a smartwatch have been analyzed and compared to assess if there are any statistical differences between the survey respondents when they are changing their clothing levels. Results showed statistically significant differences between respondents with regard to their thermal preferences (p-value = $2.2 * 10^{-6}$), which also varied based on their clothing levels and metabolic rates. Finally, recommendations for using the results of this research to develop a control strategy for selecting optimal thermostat setpoints in response to variable occupancy were provided. This work is significant as co-working spaces with variable occupancy are on the rise. Therefore, identifying individual thermal comfort preferences can be used to formulate algorithms to satisfy most people who occupy (or are expected to occupy) these spaces while minimizing energy waste during under occupied periods.

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**To my supportive parents: Andreas and Iliada Athienitis**

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## List of Abbreviations

H.V.A.C.: Heating, ventilation and air conditioning

B.P.M: Beats per minute

Clo: unit that expresses the thermal insulation provided by clothing layers: 1 clo=0,155 $m^2$.°C/W

A.S.H.R.A.E.: The American Society of Heating, Refrigerating and Air-Conditioning Engineers

B.M.S.: Building management system – graphical interface which shows all the mechanical systems and their control points and is where programming tools are.

## Nomenclature

$q_{sk}$ = total rate of heat loss from skin, W/$m^2$

$q_{res}$ = total rate of heat loss through respiration, W/$m^2$

$E_{sk}$ = total rate of evaporative heat loss from skin, W/$m^2$

$C_{res}$ = rate of convective heat loss from respiration, W/$m^2$

$E_{res}$ = rate of evaporative heat loss from respiration, W/$m^2$

$S_{sk}$ = rate of heat storage in skin compartment, W/$m^2$

$S_{cr}$ = rate of heat storage in core compartment, W/$m^2$

PMV equation

M= metabolic rate (W/$m^2$)

W=effective mechanical power (W/$m^2$)

$I_{cl}$= Clothing insulation ($m^2$*K/W)

$F_{cl}$= Clothing surface area factor

$T_{ai}$= Air temperature (ºC)

$T_{mr}$= Mean radiant temperature(ºC)

V = air velocity (m/s)

$P_v$ =water vapour partial pressure (Pa)

$H_c$=Convective heat transfer coefficient (W/($m^2$K)

$T_{cl}$= clothing surface temperature(ºC)

# 1 Chapter I: Introduction

Heating and cooling systems in buildings are traditionally designed to satisfy room temperatures specified by The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) which are typically based on dated assumptions on occupant comfort. Recent studies have shown that not everybody in a room is satisfied with those standardized room temperatures ranges due to different factors such as clothing levels and other personal preferences [1] [2]. Adjustable room temperature setpoints have proven to be essential in satisfying some users of the HVAC (Heating, Ventilation, and Air Conditioning) system, while others in the room are driven to compromise their thermal comfort since not everyone will be comfortable with the temperature set by one user [3]. It is also reported in the literature reviewed that gender plays a significant role in these different temperature preferences [4][3][5].

Office comfort surveys have proliferated significantly in the past 20 years. The Center for the Built Environment's (CBE) conducted an extensive building comfort survey from 90,000 respondents from approximately 900 buildings [6]. The authors reported the following satisfaction rates: light levels (74%), cleanliness (71%). Dissatisfaction rates were as follows: sound privacy (54% dissatisfied), temperature (39% dissatisfied), noise level (34% dissatisfied). ASHRAE STANDARD 55 [7] specifies graphical methods to identify acceptable conditions to maintain an acceptable thermal environment, which translates to keeping minimum 80% of the occupants in the room satisfied. Results from this large-scale survey indicate that only 61% of occupants feel that they are in acceptable thermal comfort conditions which suggests that HVAC systems do not often satisfy the goals set by ASHRAE STANDARD 55 [7].

Reviewed literature did report a link between productivity and room temperature [8][9]. The reviewed literature indicated that few studies were conducted to assess thermal comfort in multi-occupant spaces and open plan spaces [10]. Further, a smaller number of studies proposed methods to control the HVAC system to minimize thermal discomfort of multiple an variable occupancy in a shared space [11],[12],[13]. There is thus a need to conduct investigations of thermal preferences in multi-occupant and/or open plan offices, especially as office occupancy has become more variable after the covid-19 pandemic and is likely to remain so with partial tele-working. Individual comfort preference profiling is important to be assessed to identify temperature setpoint that will satisfy most people present at a given time in a room.

## 1.1 Problem statement, goal, and scope

It is reported that some occupants feel discomfort at temperatures within the comfort ranges specified by ASHRAE STANDARD 55[14],[15],[16]. To this end, understanding individual thermal preference is key to proposing novel sequences of operations to maximize thermal comfort in co-working spaces for each occupant. In the reviewed literature, it was reported that individuals of different genders, socioeconomic classes and ethnicities have different thermal preferences, which are investigated in this experiment. Therefore, the goal of this research is to understand how occupants feel towards indoor environmental parameters in a co-working setting with varying indoor conditions. To achieve this goal, the following objectives are established:

1) Investigate individual thermal comfort preferences and airflow perception in multi-occupant settings (i.e., co-working spaces) over different temperatures ranges.

2) Identify statistical differences between survey respondents' thermal preference votes with and without clothing variation, subject to the same indoor conditions.
3) Identify statistical differences between survey respondents' airflow perception with and without clothing variation.
4) Propose a method to minimize thermal discomfort in multi-occupant office spaces.

The experiment conducted as part of this research seeks to gather data on thermal preference for persons of different ages and genders to formulate algorithms that will potentially allow exceeding 80% of minimum satisfied occupants with respect to room temperature as specified in ASHRAE STANDARD 55. To investigate thermal comfort in a co-working space, Fitbit smart watches were used to collect occupant comfort data using Cozie, which is an app that been developed by the BUDS (Building and Urban Data Science) lab [2] to facilitate the surveying of office space comfort: thermal comfort, visual comfort, and more. Traditionally surveys have been done by web and paper questionnaires, however, this relatively new survey administration approach provides real-time and continuous data collection while improving the survey experience for subjects. The research study that was conducted as part of this thesis took place in the recently established living lab at Concordia University, Montreal which features modern co-working spaces. Six survey respondents were recruited and asked to answer questions regarding their thermal comfort and draft perception on a provided Fitbit versa 2 watch for 15 business days. Temperature ranges that correspond to survey responses continuously collected have been analyzed and compared to assess if there are any statistical differences between readings from the survey respondents.

## 1.2 Thesis Organization

This thesis is organized into the following 5 chapters. Chapter 1: Introduction, goes over the basics of thermal comfort and motivation for this research. Chapter 2: Literature review covers representative previous studies on thermal comfort. Chapter 3: Methodology presents the details of the experiment procedure. Chapter 4: Results and analysis goes over the results of the experiment and suggests new methods to control the HVAC system to satisfy most occupants in the room with respect to room temperature. Finally, Chapter 5: Conclusion summarizes the results, introduces future research opportunities.

# 2 Chapter II: Literature Review

This chapter presents an overview of the heat transfer concepts related to thermal regulation and thermal comfort parameters. Further, a literature review of the previous experimental works related to thermal comfort is presented.

## 2.1 Thermal comfort overview

ASHRAE STANDARD 55 [7] defines thermal comfort as “that condition of mind that expresses satisfaction with the thermal environment”. ASHRAE STANDARD 55 stipulates conditions for acceptable thermal environments and is used in design, operation, and commissioning of buildings and other occupied spaces [7]. Operative temperature is the uniform temperature of a fictitious black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual nonuniform environment[17]. Figure 1 shows the ranges of operation where there is acceptable comfort in the winter season and in the summer season. Operative temperature is often used in ASHRAE STANDARD 55 to identify thermal comfort temperatures and other psychrometric properties.

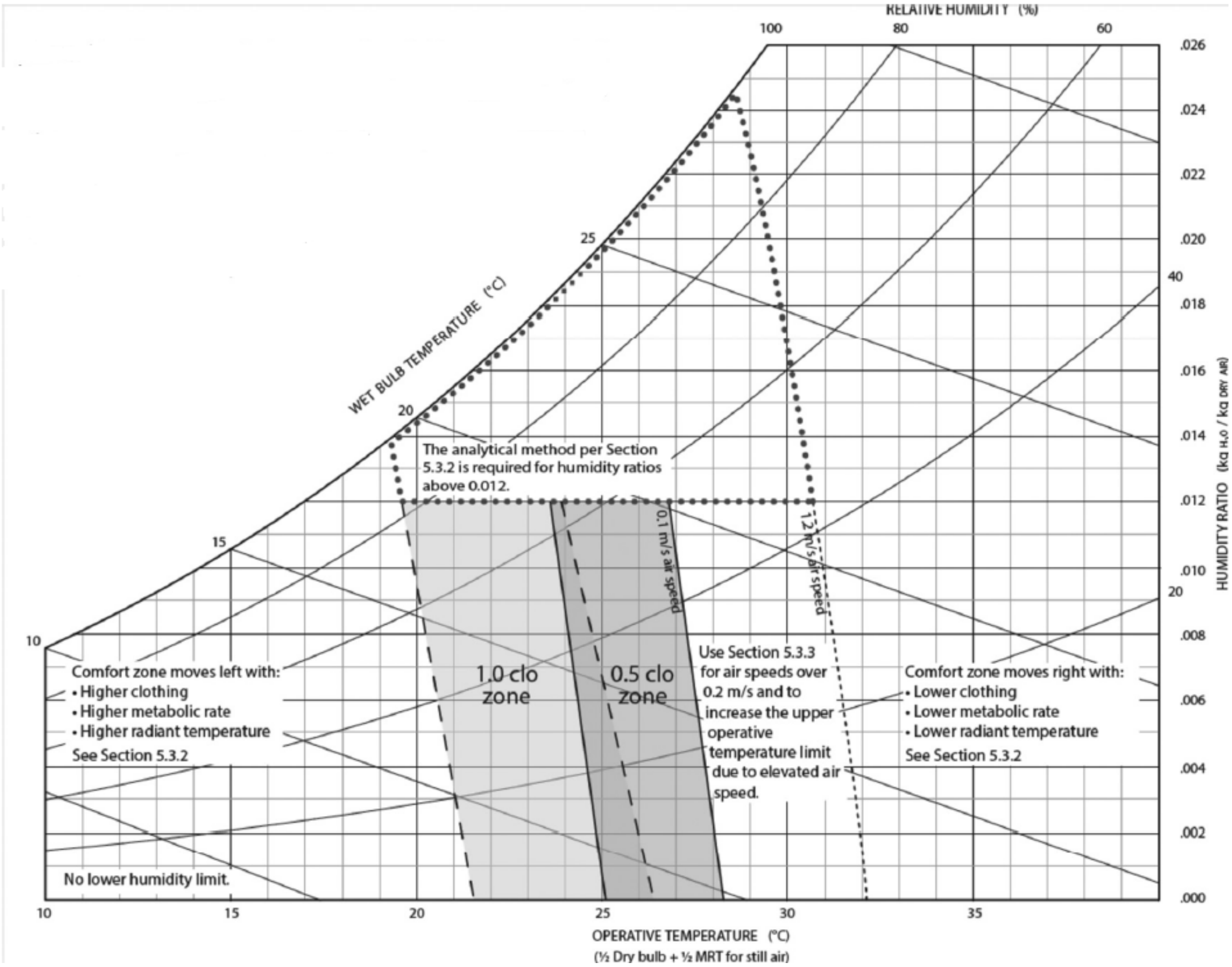


Figure 1: Graphic Comfort Zone Method - Acceptable range of operative temperature to and humidity for spaces [7]

Further from Figure 1, Table 1 shows the acceptable ranges of temperatures and humidity for spaces. The swing, so called “shoulder” season, is when there are two consecutive months in which heating is enabled the first month and the cooling system is enabled the second month, or vice versa. Thus, the heating system or the cooling system shall be activated for these months [18].

Radiant asymmetry ”is the difference between the plane radiant temperature of the two opposite sides of a small plane element” [18]. When one person stands in front of a cold window, he or she is experiencing radiant asymmetry. The recommended limits for thermal comfort which includes the limits when using radiant walls and ceilings are also shown in Table 1[19]. It should be noted that in this study we consider the radiant asymmetry is to be low and the mean radiant temperature close to the air temperature as it is an interior zone.

Table 1: Acceptable range of temperatures and humidity for spaces

| Measured parameter | Details on parameter | Range |
|---|---|---|
| Air temperature | Cooling season | 23.3-27.8 °C |
| | Heating season | 20–25.5°C |
| | Swing season | 20–27.8°C |
| Relative humidity | | Lower than 65% |
| Radiant symmetry | Horizontal | Maximum 10°C difference |
| | Vertical | Maximum 5°C difference |
| Air speed | | Lower than 0.2 m/s |

### 2.1.1 Thermoregulation

Thermoregulation is a mechanism that mammals perform instinctively to maintain body temperature with autonomous self-regulation independent of external temperatures. Temperature regulation is of homeostatic type and is a mechanism preserving a stable internal temperature in order to survive [20]. Heat is generated by the human body by metabolism. Heat is exchanged with the environment via radiation, convection, and conduction. Heat is lost by evaporation of body fluids. Figure 2 illustrates this concept.

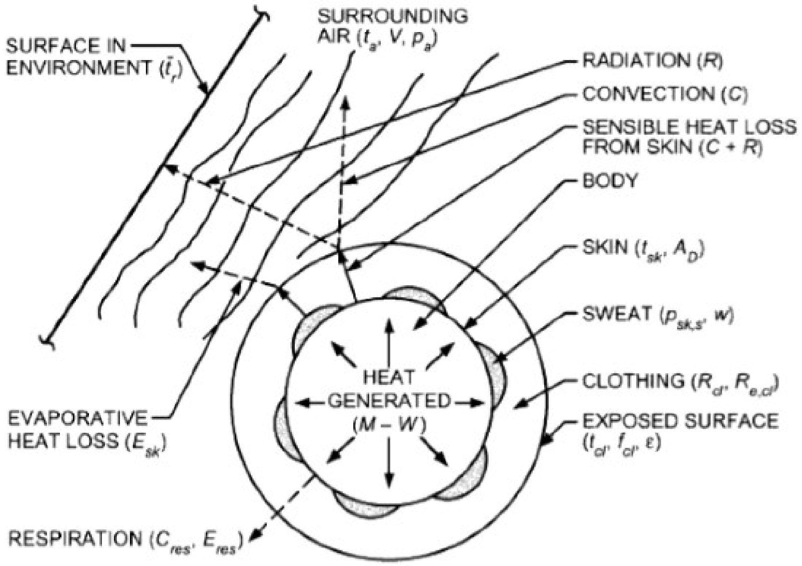


Figure 2: Heat transfer between the human body and surroundings[21]

The human heat balance equation explains how the human body sustains an internal body temperature close to 37 °C [22]. The mechanical work (W) has its energy provided by the metabolic rate of the body (M), with the remainder released as heat (M-W). Heat transfer occurs from the body via conduction (K), convection (C), radiation (R), and evaporation (E). The heat production that is not transferred from the body provides a rate of heat storage (S). Therefore, the conceptual heat balance equation is:

$$M - W = E + R + C + K + S \tag{1}$$

or

$$\mathrm{M} - \mathrm{W} = \mathrm{q}_{\mathrm{sk}} + \mathrm{q}_{\mathrm{res}} + \mathrm{S} = (\mathrm{C} + \mathrm{R} + \mathrm{E}_{\mathrm{SK}}) + (\mathrm{C}_{\mathrm{res}} + \mathrm{E}_{\mathrm{res}}) + (\mathrm{S}_{\mathrm{sk}} + \mathrm{S}_{\mathrm{cr}})$$

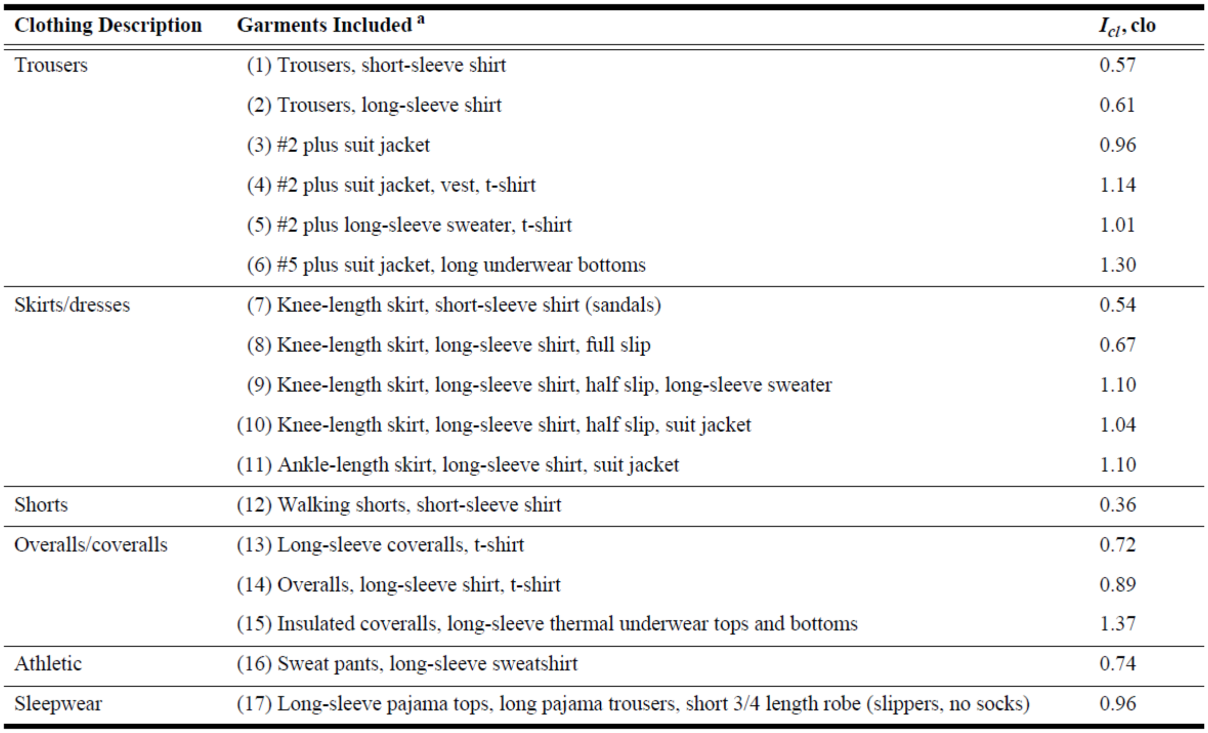
where:

$q_{sk}$ = total rate of heat loss from skin, W/m$^2$
$q_{res}$ = total rate of heat loss through respiration, W/m$^2$
$E_{sk}$ = total rate of evaporative heat loss from skin, W/m$^2$
$C_{res}$ = rate of convective heat loss from respiration, W/m$^2$
$E_{res}$ = rate of evaporative heat loss from respiration, W/m$^2$
$S_{sk}$ = rate of heat storage in skin compartment, W/m$^2$
$S_{cr}$ = rate of heat storage in core compartment, W/m$^2$

### 2.1.2 Clothing

Clothing adds thermal resistance, thus limits heat loss from the human being and affects thermal sensation felt by the human being. Table 2 indicates clothing types and their respective insulation values as per ASHRAE STANDARD 55 [7] that will help in gauging the clothing type in previous experiments listed in Table 3 while ISO 9920 is the standard for calculating a clothing resistance number. Clothing affects the thermoregulation cycle as reported in various studies [23][24]. Some fabrics enhance heat transfer between the person and environment thus allowing them to enhance their performance during exercise or maintain warmth in harsh climates [23]. Materials include natural fibres, synthetic fibres, natural and synthetic fibre blends, and chemically treated fibres. Zolfaghari et al. [25] showed that there is a significant difference between thermal sensation of the skin exposed than that of clothing covered body parts. Lee. et al. [26] showed that 80% of the respondents felt cold, cool, or slightly cool when wearing lighter clothing (short sleeve shirt, short trousers). Conversely, 80% of the subjects wearing heavier clothing (long sleeve shirt, long pants), felt slightly warm or neutral. However, this study was limited to maintaining the room temperature fixed at 19°C.

Table 2: ASHRAE STANDARD 55 Clothing insulation values [7]



| Clothing Description | Garments Included [a] | $I_{cl}$, clo |
|---|---|---|
| Trousers | (1) Trousers, short-sleeve shirt | 0.57 |
| | (2) Trousers, long-sleeve shirt | 0.61 |
| | (3) #2 plus suit jacket | 0.96 |
| | (4) #2 plus suit jacket, vest, t-shirt | 1.14 |
| | (5) #2 plus long-sleeve sweater, t-shirt | 1.01 |
| | (6) #5 plus suit jacket, long underwear bottoms | 1.30 |
| Skirts/dresses | (7) Knee-length skirt, short-sleeve shirt (sandals) | 0.54 |
| | (8) Knee-length skirt, long-sleeve shirt, full slip | 0.67 |
| | (9) Knee-length skirt, long-sleeve shirt, half slip, long-sleeve sweater | 1.10 |
| | (10) Knee-length skirt, long-sleeve shirt, half slip, suit jacket | 1.04 |
| | (11) Ankle-length skirt, long-sleeve shirt, suit jacket | 1.10 |
| Shorts | (12) Walking shorts, short-sleeve shirt | 0.36 |
| Overalls/coveralls | (13) Long-sleeve coveralls, t-shirt | 0.72 |
| | (14) Overalls, long-sleeve shirt, t-shirt | 0.89 |
| | (15) Insulated coveralls, long-sleeve thermal underwear tops and bottoms | 1.37 |
| Athletic | (16) Sweat pants, long-sleeve sweatshirt | 0.74 |
| Sleepwear | (17) Long-sleeve pajama tops, long pajama trousers, short 3/4 length robe (slippers, no socks) | 0.96 |

## 2.2 Thermal comfort surveys

Comfort surveys have proliferated significantly in the past 30 - 40 years [6]. Traditionally, paper-based surveys were used but more recently, they have been given out to participants through various platforms which include :Tablets [27], smartwatches [2], computers [28] and most recently social media queries [29]. A quantitative comfort model was first developed through surveys conducted by P.O. Fanger who introduced the predicted Mean Vote Index (PMV) [30], a seven point scale [-3,-2,-1,0,+1,+2,+3] with -3 feeling cold, +3 feeling hot and 0 feeling neutral. PMV can be calculated as a function of mean radiant temperature, air temperature, relative humidity, the metabolic rate of the person (activity level), air speed, the clothing level along with convective and radiative heat transfer coefficients between a person and the air in the zone or zone surfaces respectively [30]. The PMV equation was built from thermal comfort surveys at its inception but cannot be generalized to all people.

The PMV equation is as follows:

$$PMV = (0.303e^{-0.036M}+0.028)*L \tag{2}$$

Where L is thermal load on the body, defined from ASHRAE fundamentals 2017 " as the difference between internal heat production and heat loss to the actual environment for person hypothetically kept at comfort values of the mean skin temperature and sweat secretion at the actual activity level" [21], and calculated as follows:

$$L = M - W - ((3.96 * 10^{-8} * f_{cl}((T_{cl} + 273)^4 \ + (T_{mr} + 273)^4 \ ) + f_{cl} * h_c * (T_{cl} - T_{ai})) + C1 + C2$$

$$C1 = 3.05 * (5.73 - 0.007 * (M - W) - p_v$$

$$C2 = \Big(0.42 * \big((M - W) - 58.15\big)\Big) + 0.0173 * M * (5.87 - p_v) + 0.0014 * M * (34 - T_{ai})$$

$$T_{cl} = 35.7 - 0.0275 * (M - W) - 0.155 * I_{cl} * ((M - W) - C1 - C2))$$

$$h_c = \max\left(\begin{matrix} 2.38 * (T_{cl} - T_{ai})^{0.25} \\ 12.1\sqrt{V} \end{matrix}\right)$$

$$f_{cl} = 1.05 + 0.1 * I_{cl}$$

Where:

M= metabolic rate (W/m$^2$)

W=effective mechanical power (W/m$^2$)

$I_{cl}$= Clothing insulation (m$^2$*K/W)

$F_{cl}$= Clothing surface area factor

$T_{ai}$= Air temperature (ºC)

$T_{mr}$= Mean radiant temperature(ºC)
V = air velocity (m/s)
$P_v$ =water vapour partial pressure (Pa)
$H_c$=Convective heat transfer coefficient (W/(m$^2$K)
$T_{cl}$= clothing surface temperature(ºC)

Kim et al. [28] created a machine learning model to predict occupant thermal comfort from a chair fitted with heat strips, fans, sensors, and a wireless controller that recorded adaptive inputs from the surveyed office occupants as well as their thermal comfort state (hot, neutral, cool) in a separate survey 3 times daily. The authors deployed 6 machine learning algorithms to predict occupant thermal comfort preference: Classification Tree (61% accuracy), Gaussian Process Classification (70% accuracy), Gradient Boosting Method (68% accuracy), Kernel Support Vector Machine (71% accuracy), Random Forest (71% accuracy) and Regularized Logistic Regression (70% accuracy). They found out that PMV only had an accuracy of 52% in predicting comfort accuracy and that the adaptive control method showed a prediction accuracy of 50%. Cheung et al. (2019) reported PMV model accuracy as low as 34%. PMV accuracy was calculated using the ASHRAE Global Thermal Comfort Database II. The ASHRAE Global Thermal Comfort Database II combines datasets of objective indoor environmental measurements with accompanying 107,000 subjective evaluations by occupants from buildings around the globe from more 50 field studies[31].

Along with poor accuracy in predicting thermal comfort and requiring many sensors, PMV has other limitations including its failure to consider behavioral variations and the ability of humans to adapt to thermal environments [30]. There is therefore a need to create personalized comfort models to control HVAC systems due to limitations of the PMV model. The reviewed literature showed that multiple occupants in an office setting is a relatively new research area in the occupant centric controls domain and needs more research [10].

The heat transfer is affected by body and air movements [32] thus calculating PMV for estimating thermal comfort might be inaccurate as clothing resistance value is overestimated. Further, Havenith et al. reported that the ISO 8996 estimates the metabolic rate with a margin of error of 15 % and can require new methods of calculating thermal comfort if an accuracy of 0.3 PMV or less is required, thus necessitating more direct forms of recording metabolic rate such as with heart rate (beats per minute) [32]. Heart rate is correlated with the rate of oxygen consumption and therefore with rate of energy expenditure (metabolic rate) [33]. This indicates that hybrid models based on PMV can be developed with some directly recorded parameters. This also suggests that thermal sensation vote measurements are more accurate than PMV comfort predictions as PMV has been formulated from statistical real comfort data itself from real occupants and thus is not tailored to the individuals occupying an office in real time. Social-media query is the latest form of thermal comfort assessment where thermal discomfort was found from a mass twitter search and revealed that there are more overcooling complaints or complaints from the occupants that are too cold [29].

## 2.3 Experiments with wearable technologies

Cozie is a Fitbit app that prompts thermal comfort and other office comfort questions on Fitbit versa smartwatches. Further it will also be available on apple watch. There are other apps developed for surveying thermal comfort such as Wearable Weather Station for Fitbit smartwatches [34]. A sensor was added to the strap to measure room temperature humidity and wind speed as shown in Figure 3.

Figure 3: Wearable weather station

The first time the cozie Fitbit app was introduced was in 2019 by P. Jayathissa et al. [2]. The experiment was part of the Coolbit project initiated by NUS University of New South Wales, Sydney, Australia where there is a new focus to introduce a human-centric approach to thermal comfort data collection. The experiment lasted one month, had 15 respondents, and collected 1460 labelled responses. They asked thermal comfort questions and used an unsupervised k-means clustering technique to group occupants in a percentage of comfy votes (eg. 50,70% etc) [2]. The comfort data was correlated to other measured variables such as heart rate (BPM), room temperature (°C), and relative humidity (RH). The authors proposed that clusters (groups) of occupants with the same preferences could be grouped in the same rooms to keep them comfortable. However, this can be impractical in normal life scenario as rooms often have adjustable room setpoints.

Another experiment from Jayathissa et al. [35] was published in 2020. The experiment lasted two weeks and collected 4378 survey responses. They used a random forest classifier to predict thermal comfort states (prefer cooler, no change, prefer warmer) with a max accuracy of around 85%. They also mentioned that predicting comfort is useful in the case that a limited number of watches can be bought. Further, it was suggested the possibility to control the HVAC system from thermal comfort survey to offer personalized comfort as the next step forward in occupant-centred buildings controls though the use of reinforcement learning [10].

Sae-Zhang et al. 2020, used the Fitbit smartwatch equipped with the cozie application to measure the time it took for one group of persons to reach uncomfortably cold and uncomfortable hot to reach comfort zones. The authors used clustering to split the individuals into 2 groups. Group 1, with the average of 8.9, 18 and 25 minutes, took less time than Group 2 which took change at 22.4, 33.5 and 27.1 minutes to reach and leaving their comfortable states [36]. The authors did not vary or record room temperature during the experiment. Another study by Miller et al. 2022, used a custom version of the cozie app to assess risk of covid-19 propagation [37]. Virus propagation source was assessed by asking respondents the most likely source of virus propagation. Results from this study indicated that a majority of participants felt for a short duration that there was an increase of risk of infection from ventilation (being the most major concern) followed by surface transmission of viruses and then people density. The study conducted as part of the thesis is an extension of a paper published (E. Athienitis et al. 2022) in the Proceedings of the 5th International Conference on Building Energy and Environment (COBEE 2022) [38].

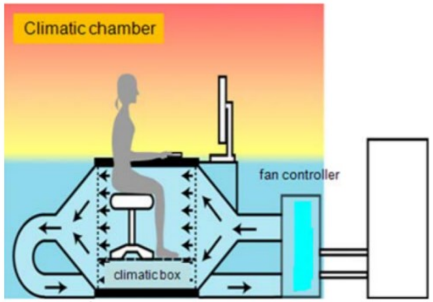
## 2.4 Summary and main limitations

Table 3 and Table 4 tabulate previous thermal comfort and air movement survey experiments conducted in the reviewed literature. It is noted that thermal insulation (clothing) was fixed for most of these experiments (at a rate of 0.6-0.8 clo) which does not depict reality as most people can change their clothing in the span of a few weeks especially if it is between two seasons. Further, there was no proposed method to control the HVAC system to satisfy most people in a room with multiple and variable occupancy. Finally, for most studies there was no test conducted to see if there are any statistical differences between the survey respondents in terms of thermal, visual, or auditory comfort [39].

Table 3: Summary of major thermal comfort experiments reported in the literature

| **Authors** | **Temperature ranges and duration of experiments** | **Number of participants and gender** | **Clothing levels** | **Measured parameters** | **Other** | **Results** |
|---|---|---|---|---|---|---|
| Nevins et al., 1966[16] | 72 temperature humidity combinations were test on survey subjects. | 360 female and 360 male college students between the ages of 18 and 23. | Cotton shirts and twill shirts and trousers (0.52 clo) | | | Thermal sensation votes show that females voted lower temperatures in the 19°C to 22°C range cooler than males. At higher temperatures gender differences were smaller. |
| Fanger, 1970[41] | 21.1, 23.3,25.6 and 27.8°C | Danish samples with 128 females and 128 males. American samples with 360 females and 360 males | Light clothing | | | No significant difference in preferred temperature was found between the genders. Among the American group of students, females preferred temperatures (25.91°C) than males (25.09°C). |
| Beshir et al., 1981[15] | 23.3, 32.2, 37.8, and 43.3°C | 31 males 15 females | Light clothing (0.6 clo) | Heart rate, oral temperature | | Preferred temperature for males was 22°C and for females 25°C. Females experienced discomfort more than males at high and low temperature limits of the experiment. |

| | | | | | | |
|---|---|---|---|---|---|---|
| Pellerin et al., 2004 [43] | 3 hour experiments in a study that combined effects of noise (35, 60 and 75 dBA) and temperatures of 18, 24 and 30 °C (operative temperatures) | 16 females and 14 males | Light clothing (0.6 clo) | | | Auditory perception is altered by the thermal strain for both short- and long-term exposures. High noise levels boost thermal discomfort. No differences between gender in thermal and auditory discomfort. |
| Lee et al., 2004[26] | 19 °C | 7 females, 15 males | Light clothing: short trousers, short sleeve shirt<br>Heavy clothing: long sleeve, shirt long trouser | Skin temperature, rectal temperature, heart rate, oxygen consumption | | Females felt more uncomfortable, than males in the identical cool environment. |
| Lan et al., 2008[14] | 21, 24, 26, 29, and 32°C,<br>5 days, one temperature, per day. | 20 | Light clothing 0.8 clo | Skin temperature and heart rate variability | Experiment location: China | Females preferred slightly warmer conditions (26.3 °C), and males slightly cooler conditions (25.3°C). |

| | | | | | | |
|---|---|---|---|---|---|---|
| Tiller et al.,2010 [40] | 18,20,22,24, 27°C | 16 females,15 females | 0.87 clo | Dry bulb temperature, relative humidity and operative temperature | Hearing test at five octave frequency bands (250 Hz, 500 Hz,1000 Hz,2000 Hz and 4000 Hz) | Females rated lower temperatures colder than males, and higher temperatures more comfortable than males: thermal comfort of both sexes converged at about 72°F (22°C). |
| Hashiguchi et al. 2010 [42] | 16, 19, 22 and 25°C | 8 males and 8 females  Figure 4: Climate chamber schematic | | Skin temperatures of the upper and lower parts of the body were recorded as different chambers controlled the temperature on the upper and lower body as in Figure 4. | Mental tasks performed | Difference between upper and lower body skin temperature was higher in females compared to men in cooler conditions. Females felt more discomfort in cooler conditions. |

|  |  |  |  |  |  |
|---|---|---|---|---|---|
| Choi et al. 2010, [44] | Studies conducted in 38 floors of 20 commercial office buildings in the U.S. from 2005 through 2008 during all seasons. | 212 are female and 190 are male.170 are between 19 and 39 years old. 230 are between 40 and 69 years old. |  | Camera for contrast ratio and unified glare index estimation.<br>Air temperature (at 0.1m, 0.6m and 1.1m), humidity sensors ,CO2, CO, TVC and particulates sensors | Females are more dissatisfied with their thermal environments than males especially in the summer season with high significance.<br>Occupants over 40 years old showed more satisfaction with their thermal comfort than under 40 in the cooling season with little significance. |

|  |  |  |  |  |  |
|---|---|---|---|---|---|
| Choi et al., 2012 [3] | One chamber was cool where temperature was kept 18 °C to 20°C while the other was warm and kept from 25 °C to 27°C. 4 activity levels tested during 15 minutes for cool and hot chambers<br>Mean radiant temperature, CO2, air velocity, and relative humidity were kept at constant levels.<br>Each experiment lasted 3 hours. | 14 volunteers 19 to 34 years old |  | Students from college in Korea recruited. 4 activity levels investigated:<br>-Lied down on the floor, 0.8 met<br>-Sitting in Indian position on the floor, 1 met<br>-Sitting and working on a desk 1.2 met<br>-Using a cycling exercise machine 2.5 met | Analysis of the absolute level of heart rate depicted a proportional relation to metabolic rate based on activity level. Male group had significantly higher heart rates in the warm chamber than in the cool chamber compared to women at an activity level of 2.5 Met. No statistical difference between genders regarding perception of thermal comfort was reported. |

Table 4: Summary of major air movement experiments reported in the literature

| Authors | Air velocity ranges and duration | Number of participants and gender | Clothing levels | Measured parameters | Other | Results |
|---|---|---|---|---|---|---|
| Fanger et al., 1986[47] | Exposed to increasing mean velocities from 0.05 to 0.40 m/s, Experiment was 2.5 hours long | 100 subjects (50 males and 50 females) were tested for air velocity profiles. | During first hour, subjects were told to change their clothing so they can feel thermally neutral (comfortable). During hours 1 to 2.5 they could change not change their clothing. | Air temperature, air velocity | Temperatures: 20,23,26 °C | No significant sensitivities were found between women and men for draught perception. Draught chart was formulated (see Figure 5). Most sensitive part of the human body towards draught is the head. Gender did not indicate a difference in air perception movement. Further studies are advised to identify the range of turbulence intensities. |

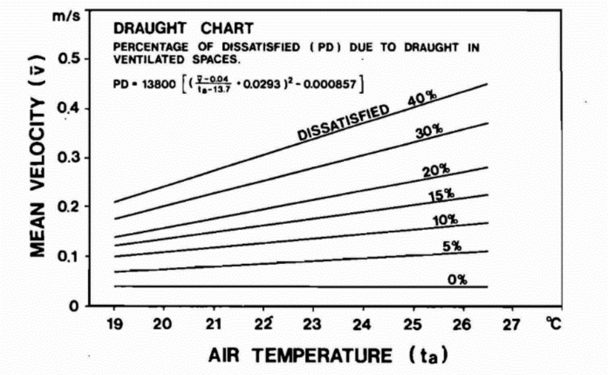


Figure 5: Draught chart

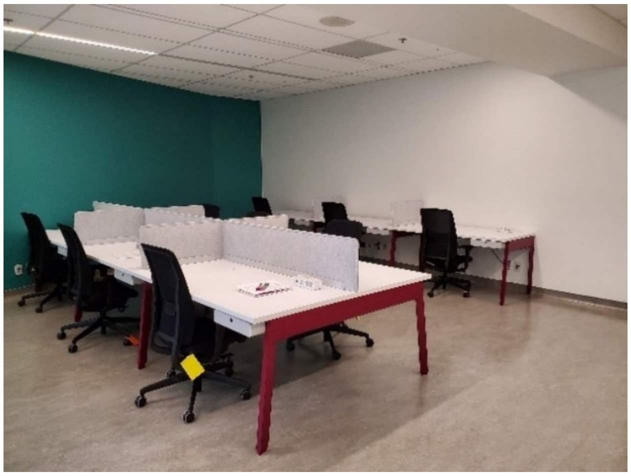
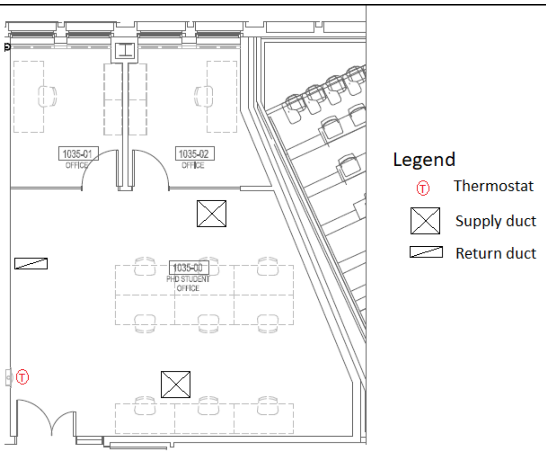
| | | | | | | |
|---|---|---|---|---|---|---|
| Fanger et al., 1988 [45] | 0.05 to 0.4 m/s<br>2.5 hours in total | 25 females and 25 males of approximately 22 years old | Respondents asked to modify clothing continuously during experiment to feel thermally neutral | Mean air velocity, turbulence intensity, air temperature | Room temperature kept constant 23°C | No difference was reported in the sensing of any air movement, females were slightly more dissatisfied than males from a lower air velocity stream toward the head region. |
| Ishii et al., 1990 [46] | 0.6 m/s | 5 females and 5 males at college | 0.3 clo | | | Females recognize low airflows more with more sensitivity than their male counterpart. |
| Griefahn et al., 2001 [5] | 0 m/s to 0.4 m/s | 70 females and 109 males | | Experiments executed in a climatic chamber Turbulences controlled by 4 ventilators. | Room temperature kept constant 23°C | Females felt more discomfort and cooler with draughts and preferred higher room temperatures than males. Tired persons felt more discomfort in cool conditions. Age did not play a role in susceptibility to draft discomfort. |

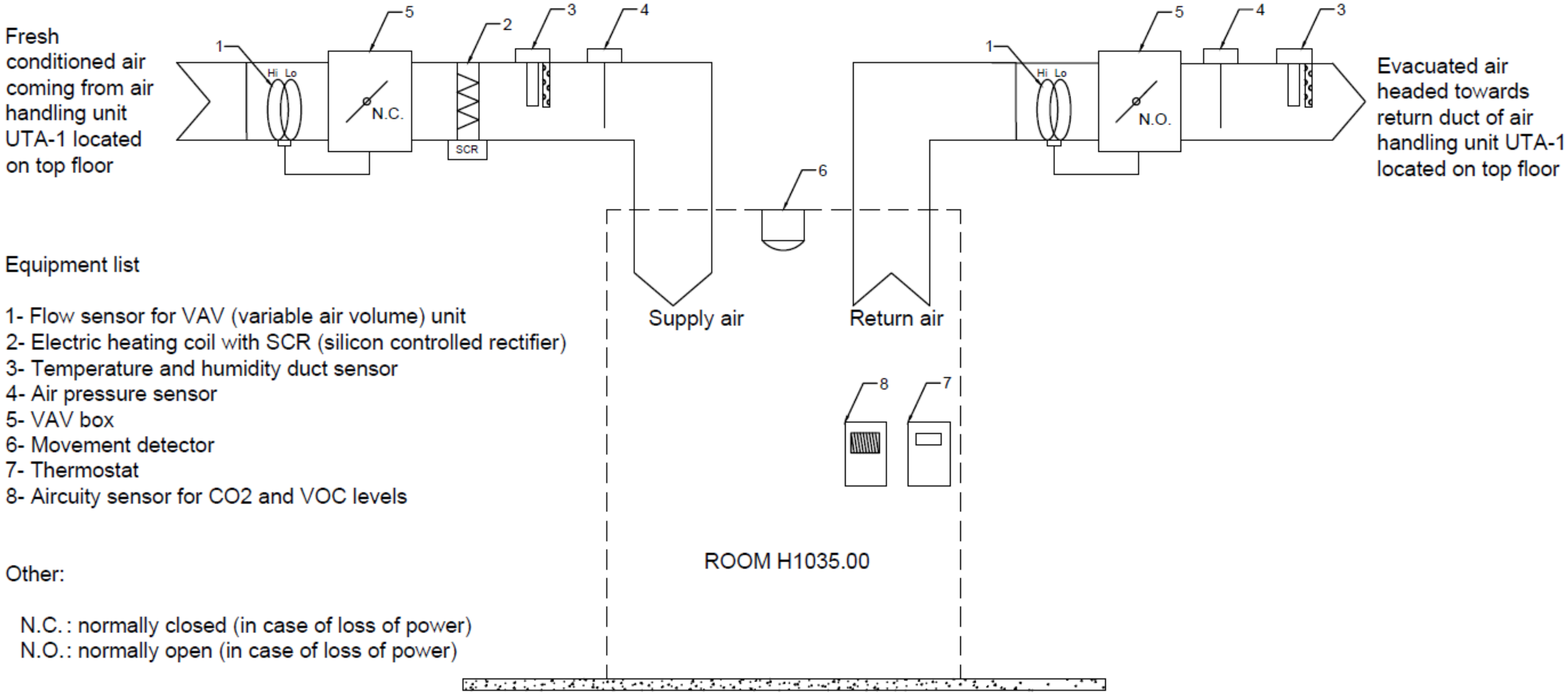
# 3 Chapter III: Methodology

This experiment sought to gather data on thermal comfort in a co-working space with multiple occupants subject to varying indoor conditions. Air movement from the heating system was also assessed to investigate its influence on occupants' comfort perception. To achieve this, Fitbit smart watches were used to collect occupant comfort data under different indoor environmental conditions, that were attained by the researcher in Concordia's living lab. In particular, this comfort data was collected using, Cozie which is an app that has been developed for the Fitbit smartwatch to facilitate the surveying of office space comfort: thermal comfort, visual comfort, location, and more. The survey respondents had to come to the lab 30 minutes before the beginning of the first day of experiment of the survey to setup and sync the Fitbit smartwatch to their phone, where the Fitbit app is installed. The next subsections provide more details on the following: Experimental set up, Dataset description and Experiment Methodology.

## 3.1 Experimental set up

Thermal comfort data was collected on the span of three weeks by asking 6 survey occupants how they are feeling towards the room temperature, air movement and more on a provided Fitbit versa 2 smartwatch while varying the room temperature setpoint daily from 19°C to 26°C. The experiment was conducted in the Living Lab (see Figure 6 and Figure 7) at Concordia University, which is equipped with control equipment as per Figure 8. The exhaust and return diffuser location plan is adapted from the consultant's mechanical and electrical plans and appear in Figure 7. UTA-1 is the name of the air handling unit that supplies the room H1035.00 with fresh air that is either preheated and\or precooled or unconditioned thermally depending on the season of the year and of the temperature setpoints in the rooms under the UTA-1 Ventilation branch. Around half of the 10th floor of the Hall building is under the UTA-1 ventilation unit. The room temperature setpoint is 21°C during school hours and 18°C at night in unoccupied hours during the year. The ventilation and control schematic of the room H1035.00 where the research study was conducted is depicted in Figure 8 and was derived from the siemens BMS graphics page of the room H1035.00 provided by Siemens. Since the living lab is an interior zone (surrounded by enclosed offices), the mean radiant temperature is close to the air temperature. The air speeds near the persons are assumed to be less than 0.3 m/s.

| | |
|---|---|
|  |  |
| Figure 6: Living Lab at Concordia University | Figure 7: Ventilation diffuser and thermostat locations of Living Lab |



Equipment list

1- Flow sensor for VAV (variable air volume) unit
2- Electric heating coil with SCR (silicon controlled rectifier)
3- Temperature and humidity duct sensor
4- Air pressure sensor
5- VAV box
6- Movement detector
7- Thermostat
8- Aircuity sensor for CO2 and VOC levels

Other:

N.C.: normally closed (in case of loss of power)
N.O.: normally open (in case of loss of power)

Figure 8: Control and ventilation schematic of room H1035.00

Survey respondents were asked to answer questions regarding their thermal comfort and draft perception. They could only sit at their designated desks as airflow changes' perception depended on the position of the occupant in the lab. Note that F1 stands for Female 1 and M1 stands for Male 1. The allocated seating position for each respondent is depicted in Figure 9. Watches had a colored sticker in the back that corresponded to the ID number on the Cozie Fitbit cloud network. The survey respondents had to look at the color of sticker and sit at the desk with the matching color.

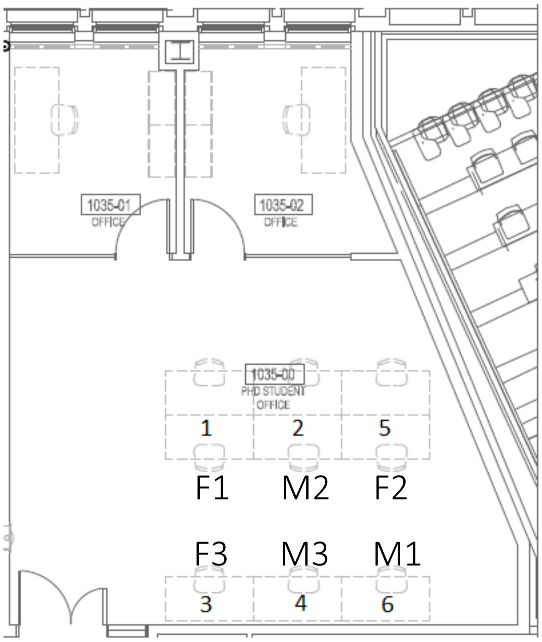


Figure 9: Seating position of respondents during experiment

## 3.2 Dataset description

There were two different sources of data used for this study. The first was data collected from the building management system. The second was data collected from the Fitbit cloud server. Room temperature and airflow rate data were merged with the thermal comfort data from the Fitbit cloud server to form a single dataset. Statistical tests were then performed to find whether there were statistical differences between samples of data coming from all respondents.

### 3.2.1 Data collected from Building Management System

The BMS (Building Management System) is a graphical interface used as a console for programming and visualizing the mechanical and control systems of the building. Siemens is the provider of the control solutions for the room H1035.00. Table 5 tabulates the BMS points that are in the control system of the room H1035.00. The room temperature, supply air temperature, heating setpoint, cooling setpoint, supply air flowrate and heating cooling demand BMS points were monitored for faults as they could signify that some control sequences were malfunctioning. The supply air temperature of main air handling unit UTA1 was also monitored to see if the master system supplying fresh air to the 10th floor (where the experiment is conducted) was in cooling heating or neither mode. The room temperature, heating setpoint, cooling setpoint and supply air flowrate were used for analysis in conjunction with the data from the Fitbit Smartwatch. They appear in bold in Table 5.

Table 5: List of trended BMS points in Siemens Desigo suite

| Name of point in BMS | Description | Unit |
|---|---|---|
| **H_DXR_1035_00 (997) ROOM TEMP 21** | **Room air temperature** | **°C** |
| **H_DXR_1035_00 (068) HTG STPT EFF** | **Effective heating room temperature setpoint** | **°C** |
| **H_DXR_1035_00 (086) CLG STPT EFF** | **Effective cooling room temperature setpoint** | **°C** |
| HUM EXT | Outside relative humidity | % |
| HUM EVAC | Exhaust relative humidity | % |
| HUM ALIM | Supply relative humidity | % |
| TEMP EXT | Exterior air temperature | °C |
| TEMP EVAC | Exhaust air temperature | °C |
| TAMP ALIM | Supply air temperature | °C |
| H_DXR_1035_00 (1233) AIR VOL SP 4 | Supply air volume setpoint | LPS |
| **H_DXR_1035_00 (1233) AIR VOLUME 4** | **Supply air volume** | **LPS** |
| MPA VL-15-1035 | Supply air pressure | in H20 |
| H_DXR_1035_00 (1325) EX VOL SP 4 | Exhaust air volume setpoint | Litters per second |
| H_DXR_1035_00 (1327) EX VOL AI 4 | Exhaust air volume | Litters per second |
| MPE VLG-12-1035 | Exhaust air pressure | in H20 |
| H_DXR_1035_00 (437) DAMPER POS 5 | Supply air damper position | % |
| H_DXR_1035_00 (442) EX DMP POS 5 | Exhaust air damper position | % |
| ALM TEMP | Alarm temperature | % |
| H_DXR_1035_00 (927) NET OCC SEN | Presence detection | Active/inactive |
| H_DXR_1035_00 (014) RM OP MODE | Profile type | Comfort/economy<br>/PrComfrt/Protect |
| H_DXR_1035_00 (780) HC DEMAND | Heating/cooling mode | Heating/cooling/neither |
| AIRCUITY PPM | CO2 level | PPM |
| H_CZ10_DCVISO_MOD57 | Volatile organic compound level | PPM |
| ALM AIRCUITY | Alarm air quality level | On/off |

### 3.2.2 Data collected from thermal comfort survey

Figure 10 shows the communication protocol of the Fitbit watch to the server, which first transfers the comfort data to the phone via Bluetooth connection and the phone then transfers data to the Amazon Web service server.

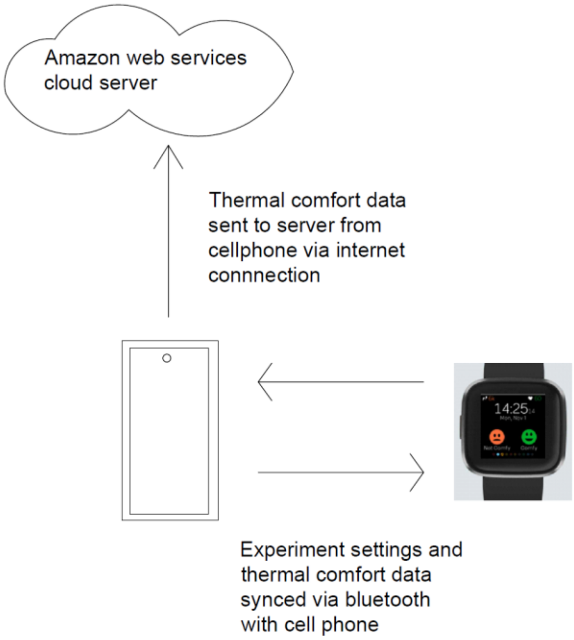


Figure 10: Communication protocol of the watch to the server

Table 6 tabulates the type of data that is retrieved from the Fitbit versa watch. The light, noise, and emotional mood data (sad, neutral, happy) were not investigated as part of this research.

Table 6: Data features and possible answers

| Item in raw python code | Description | Possible answers | | | Automatically collected from watch | |
|---|---|---|---|---|---|---|
| startFeedback | Timestamp when the user started the survey (i.e. pressed one of the two buttons in the clock face) | 2019-11-22T01:57:14.342Z | | | No | |
| heartRate | Heart rate measured when the user completed the survey | 60 | | | Yes | |
| voteLog | Counter which stores information on how many times the user completed the survey (used for debugging) | 40 | | | Yes | |
| comfort | Thermal comfort | 10 = "Comfy" | 9 = "Not Comfy" | | | No |
| indoorOutdoor | Location | 9 = "Outdoor" | 11 = "Indoor" | | | No |
| change | Change location, activity or clothing, | 11 = "Yes Change" | 10 = "No Change" | | | No |
| location | Where are you | 8 = "Portable" | 9 = "Work" | 10 = "Other" | 11 = "Home" | No |

| | | | | | | |
|---|---|---|---|---|---|---|
| thermal | Thermal preference | 9 = "Warmer", | 10 = "No Change | 11 = "Cooler" | | No |
| light | Light preference | 9 = "Brighter", | 10 = "No Change" | 11 = "Dimmer" | | No |
| noise | Noise preference | 9 = "Louder" | 10 = "No Change" | 11 = "Quieter" | | No |
| clothing | Clothing | 9 = "Light" | 10 = "Medium" | 11 = "Heavy" | | No |
| met | Metabolic rate | 8="resting" | 9 = "sitting" | 10 = "standing", | 11 = "exercising" | No |
| air-vel | Perceived air movement | 10 = "Not Perceived" | 11 = "Perceived" | | | No |
| mood | Mood | 9 = "Sad" | 10 = "Neutral", | 11 = "Happy" | | No |
| responseSpeed | Time in seconds it took to complete the survey | 2.577 | | | | Yes |
| endFeedbac | Timestamp when the user completed the survey | 2019-11-22T01:57:16.919Z | | | Yes | |
| lat,lon | Latitude and longitude provided by the GPS of the phone | lat:48.13194 | lon:11.54944 | | | Yes |
| bodyPresence | Passes information whether the user is wearing the watch or not | TRUE | | | | Yes |
| user_id | # User ID as per selection in settings | | | | Yes | |
| experiment_id | # Experiment ID as per selection in settings | | | | Yes | |

## 3.3 Experiment Methodology

The following sections explain the room temperature conditions, survey questionnaire and other protocols regarding the execution of the experiment. Further, the dataset information and participation numbers are also presented.

### 3.3.1 Room temperature conditions

The experiment ran from 9:00 AM to 6:00 PM every day for 15 business days straight (excluding holidays) in the month of September 2022. The room temperature setpoint was mainly increased by 1 degree every hour each day for the duration of the experiment as shown in Figure 11. Simultaneously, the Fitbit versa 2 watch notified the survey respondents via a vibration to answer the survey question at each hour from 9:45 AM to 5:45 PM. Occupants arrived in the lab at 9:00 AM, thus leaving them with 45 minutes to acclimatize as the survey questions were prompted to respond at 9:45, 10:45, 11:45, 12:45, 13:45, 14:45, 15:45, 16:45 and 17:45. Figure 11 displays the data collection and setpoint schedule which is repeated every hour for 8 hours a day and 15 consecutive business days.

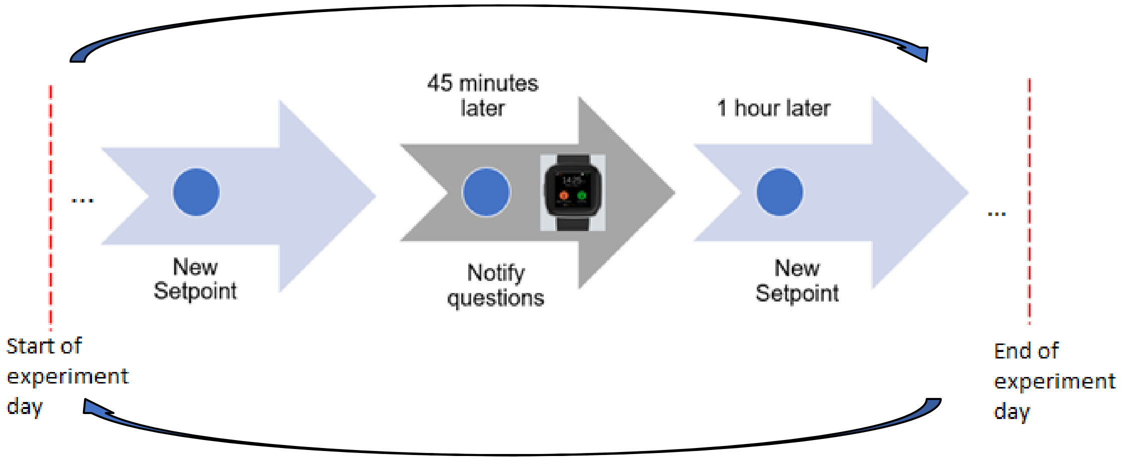


Figure 11: Experiment procedure from 9:00 AM to 6:00 PM repeated for 15 business days

The main system UTA-1 (located on the top floor mechanical room) feeding the room in which the experiment took place (H1035.00) has a fluctuating supply temperature which made it difficult for the rooms to reach the temperature setpoint as the surrounding zones have different cooling or heating needs. This explains why the room temperature was off by 0-4 °C from the room temperature setpoint as shown in Figure 12. There was a separate cooling setpoint and a separate heating setpoint programmed for the room H1035.00 daily to avoid having heating and cooling working at the same time in the room because it wastes energy. Further in the month of September, the main cooling coil and heating coil were not always active in the master air handling unit UTA-1 on the top floor, thus leaving all the heating to be supplied by the electric coil (shown in Figure 8), which proved insufficient to reach the desired room temperature setpoint. None-the-less, we obtained enough temperature variation to conduct the experiment successfully. Mean relative humidity throughout the experiment was 42% with a standard deviation of 10%, which is below the maximum level of 65% as specified by ASHRAE.

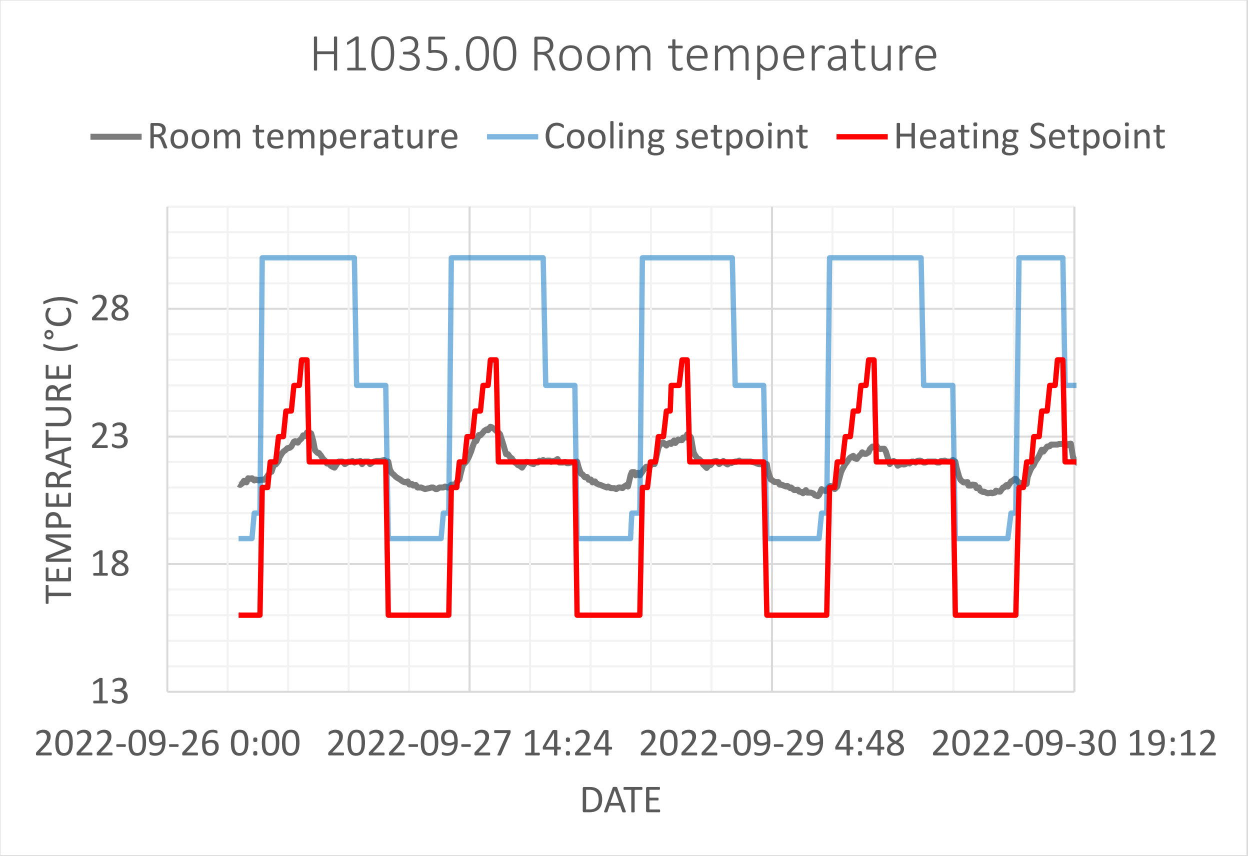
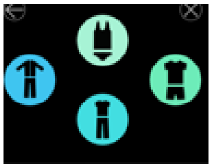


Figure 12: H1035.00 Room temperature profile

### 3.3.2 Survey questionnaire

Conducting research activities with human subjects required approvement from the ethics committee. This study was approved under the ethics committee certificate number: 30016085. The following information was also asked once to each participant before the beginning of the experiment: Age, Gender, where and how long have you lived in the past 10 years in each country listed? Survey respondents were then asked to wear a Fitbit watch for a 4-8 hour period per day on average on their wrist. They were asked to answer six office comfort questions that were notified to them every hour on the Fitbit smartwatch on their wrist as per Table 7.

Table 7: Questions prompted on the Fitbit watch hourly

| Question | Possible answer |
|---|---|
| What is your state of comfort? | Comfy, not comfy |
| What would you prefer to be? | Cooler, no change, warmer |
| Can you perceive air movement around you? | No, yes |
| What are you wearing? |  |
| What is your activity last 10 minutes? |  |
| Have you changed location, activity or clothing over the last 10 minutes | No, yes |

Survey respondents also had to sign the survey consent form as per Concordia ethics regulations. They had to install the Fitbit app on their cellphone before coming to the lab as well as be able to connect to the wireless internet network. During the experiment the heartrate of the respondent and the location of the watch was also recorded with each survey response. If the respondents got tired, they could remove the watch from their wrists, but could still answer the survey questions (they were also allowed to leave the experiment as per the ethics protocol requirements). Each time the survey respondents needed to leave the room for more than 30 minutes for i.e., going to lunch, class, they had to remove the watch and place it on the designed desk. Eating large meals was not permitted in the living lab but eating snacks and coffee was permitted. All respondents had to also leave the watch on the designated desk at the end of each experiment day until the end of the experiment. The recommended time to go to lunch will was 11:50 to 12:35. The researcher had to make sure the watches were charged to full capacity for the next day of the experiment and that they did not have syncing issues with the amazon web services cloud server. They were placed on the designated desk of each respondent before each experiment day.

### 3.3.3 Datasets

The overall dataset included 304 responses coming from 6 survey respondents. Figure 13 shows the number of responses per survey respondent. Female 2 submitted 81 survey response while the rest of 5 respondents averaged 43.6 survey responses. When selecting participants, it was aimed to have a diversified set of ethnicities and time spent in each respective country in which they were born as some countries have hotter climates than others depending on their location relative to the equator. The survey respondents were asked which country and how long have they lived in each country in the past 10 years. Table 8 tabulates some of the participant's answers for this study.

Table 8: Sample participant list with inhabited countries

| Respondent ID | Where have you lived in the past 10 years? Insert each country and duration. |
|---|---|
| **Female 2** | Montreal, Canada – 10 years |
| **Male 3** | Canada- 10 years |
| **Male 1** | India – 9 years, Canada 1 year |
| **Female 3** | Canada – 6 years, USA – 4 years |

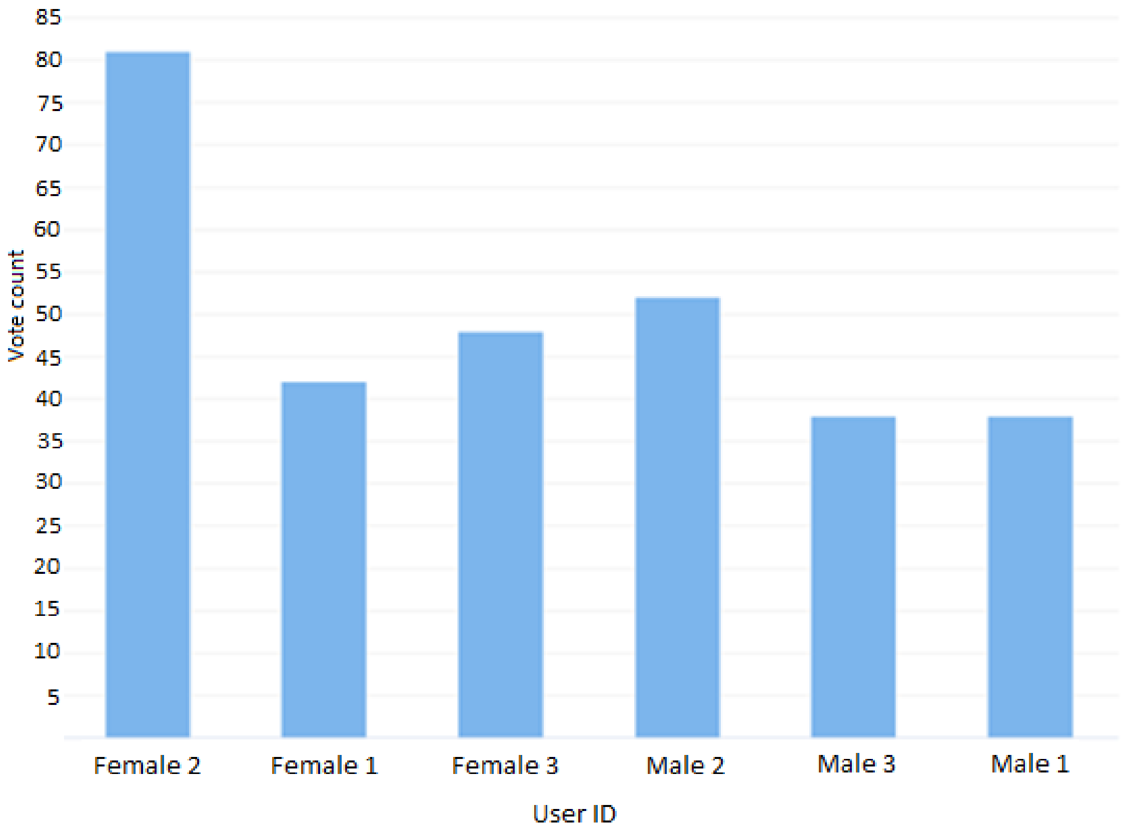


Figure 13: Number of survey inputs per respondent

Out of the 17 attributes from cozie Fitbit app (see Table 6 ) and 2 extra attributes imported from the BMS data (room temperature and airflow rate) heartrate had the most missing values with 45 out of the 299 survey responses (15%). Further, the rest of the attributes such as thermal preferences (prefer warmer, no change, prefer cooler) had 2 missing values and comfort (not comfy, comfy) had 7 missing values.

#### 3.3.3.1 Alterations to original datasets

To facilitate comparing individuals with each other and their feedback towards room temperature, air velocity and heartrate, datapoints with clothing of level 0 (short sleeve shirt and short pants) were removed as they only applied for Female 3 and Male 3 for a total of 5 datapoints out of the 304 (or 1.6 % of the original dataset deleted). Thus, a new reformatted dataset with 299 data points was created. Further the room temperature and supply airflow rate coming from Siemens Desigo software suite were matched to the timestamps of the thermal comfort responses.

## 3.4 Statistical analysis of thermal comfort responses and air movement perception

Statistical tests were conducted to see if there are any statistically significant differences between the means of data gathered from each occupant relating to temperature readings and draft perception. Further, by knowing if there were statistical differences between the samples of each survey respondents, algorithms to control the room temperature and airflow rate could be proposed. The tests used in this analysis described in the upcoming sections are summarized in a decision tree diagram in Figure 14. Note that not all data distributions for each test had to be tested for normality as only one of the samples compared had to be non-normally distributed to qualify it for a non-parametric test.

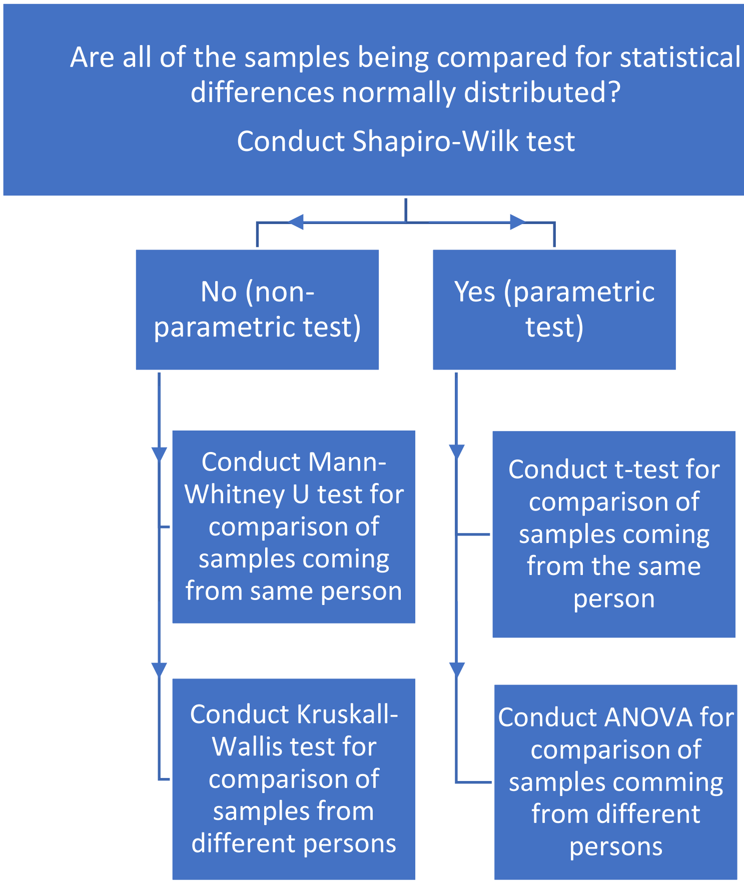


Figure 14: Decision tree for selection of statistical test

### 3.4.1 Test for normality of the samples

In order to select the appropriate statistical test to see if there any statistically significant differences between the means of samples, an evaluation whether the data follows a normal distribution was conducted with the Shapiro-Wilk test at a confidence interval of 95% [48]. A minimum sample size of 3 datapoints was required for usage of Shapiro-Wilk normality test.

### 3.4.2 Analysis of comfort responses between respondents.

Temperature ranges at which every respondent reported thermal responses: prefer warmer, no change and prefer cooler temperature votes were compared. Statistical testing indicated if there are any statistical differences between the respondents. The Kruskal-Wallis was a suitable test to find if there are any statistical differences between samples as long as the following conditions were met:

1) Group samples deviated to a great degree from normal
2) Samples sizes were small and not equal
3) Data was not symmetric (data does not have a normal distribution)
4) Group variances varied because of the presence of outliers
5) Each group sample has a minimum of 5 elements.
6) No population parameters were estimated

The Kruskal-Wallis test was verifying the null hypothesis that the populations from which the group samples were picked were equal in the way that none of the group populations was dominant over any of the others. A group was dominant over the others if one element was drawn at random from each of the group populations, it was more likely that is the biggest element from that group [49] .The test established whether the medians of two or more groups were different. As in the majority of statistical tests, there was a calculation of a test statistic and then a comparison to a distribution cut-off point. The test statistic used in this test is called the H statistic. If the critical chi-square value was lower than the H statistic, the null hypothesis was rejected. If the chi-square value was not less than the H statistic, there was not enough evidence to reject the null hypothesis. The appendix section provides tables with the cut-off statistic values.

To verify if there were any statistical differences in thermal comfort preference between survey respondents in prefer cooler, no change and prefer warmer thermal comfort votes the following hypothesis were formulated for these 3 cases for the application of the Kruskal-Wallis under a statistical significance level $\alpha=0.05$ and a right tail Chi squared distribution:

The null hypothesis for thermal comfort $H_o$ investigated was as follows:

> $H_o$: There are no statistical differences in temperatures at a specific thermal sensation vote between each survey respondent

The alternative hypothesis formulated was as follows:

> $H_a$: There are statistical differences in temperatures at a specific thermal sensation vote between each survey respondent

Further, to verify if there were any statistical differences between each survey respondent when they voted that they did not sense air movement coming from the supply diffuser, the following hypotheses are formulated:

The null hypothesis $H_o$ investigated was as follows:

> $H_o$: There are no statistical differences in airflow rates when there is a lack of air movement perception between each survey respondent.

To verify if there were any statistical differences between each survey respondent when they voted that they did sense air movement coming from the supply diffuser, the following hypothesis were formulated:

The null hypothesis was as follows:

$H_o$: There are no statistical differences in airflow rates when there is air movement perception between each survey respondent.

### 3.4.3 Analysis of responses within each respondents.

The effect of variation of clothing was investigated when comparing different samples of data within the same respondent for thermal comfort responses (prefer warmer, no change, prefer warmer) and perception of air movement on them. The t-test indicated how statistically significant the differences between group means were. It was used when the two compared samples were believed to be normally distributed [50]. The t-test (at a double tail, 95% confidence interval) was chosen (assuming unequal variances) to compare temperature and air velocity profiles for the same person with different clothing indices (2 and 3). An index of clothing 2 translated to short sleeve shirt and long pants or 0.57 clo as per Table 2. An index of clothing 3 translated to long sleeve shirt and long pants or 0.61 clo.

The Mann-Whitney U test is a non-parametric test that was used to compare two sample means that may come from the same population (or person) and used to test whether two sample means are statistically equal or not. This test was used as an alternative to the t-test when at least one the samples was not normally distributed [51]. The Mann-Whitney U test was chosen (at a double tail, 95% confidence interval) to compare temperature and air velocity profiles for the same person with different clothing indices (2 and 3). An index of clothing 2 translated to short sleeve shirt and long pants or 0.57 clo as per Table 2. An index of clothing 3 translated to long sleeve shirt and long pants or 0.61 clo.

To verify if there were any statistical differences for each survey respondent when they vary their clothing level for prefer cooler, no change, or prefer warmer vote the following hypothesis are formulated for usage of t-test or Mann-Whitney U test under a confidence interval of 95%.

The null hypothesis $H_o$ investigated is as follows:

> $H_o$: There are no statistical differences in temperatures at a specific thermal sensation vote within each survey respondent by varying the clothing from long sleeve to short sleeve shirts

The alternative hypothesis is formulated as follows:

> $H_a$: There are statistical differences in temperatures at a specific thermal sensation vote within each survey respondent by varying the clothing from long sleeve to short sleeve shirts

To verify if there were any statistical differences by changing the clothing level on airflow perception within the same individual the hypotheses are as follows:

> $H_o$: There are no statistical differences in airflow rates when there is air movement perception within each survey respondent by varying the clothing from long sleeve to short sleeve shirts.

# 4 Chapter IV: Results and analysis

This section presents the results obtained from conducting the experiment and the statistical tests covered in the methodology section. In the first subsection, the thermal comfort sensation votes of respondents are investigated. The next subsection investigates the perception of airflow coming from the diffuser. Subsequently, the interaction between occupants' heartrate and their comfort responses is presented. Finally, an occupant-centric algorithm to control the room temperature is presented.

## 4.1 Thermal comfort analysis

The first sub-section investigates the thermal sensation votes captured from each respondent for all 3 votes: prefer cooler, no change and prefer warmer. The second sub-section investigates the effect of clothing on thermal comfort for each respondent for all votes. Further, the results from statistical tests are presented.

### 4.1.1 Investigation of thermal sensation votes between the respondents

The following sub-section investigates the thermal sensation votes captured from each respondent for all 3 votes: prefer cooler, no change and prefer warmer. Temperature ranges from everyone are analyzed and presented as boxplots. Moreover, the results from statistical tests are presented.

Table 9 shows the average thermal sensation vote per respondent per room temperature recorded. -1 is prefer cooler, 0 is no change and +1 is prefer warmer. Female 1 was predominantly in the negative range thus indicating she clicked prefer cooler on most of the room temperatures, while Female 2 clicked on prefer warmer on most of the room temperatures until she reached a thermal sensation vote value close to 0 at 23 ºC. Male 2 voted that he preferred warmer at 20.5 ºC and preferred cooler a

23.5 ºC. His preferred temperature thus converged at 22.5 ºC, which got an average thermal sensation value of 0. Male 1 was the only respondent that had more than one preferred temperature, i.e. where he voted a no change thermal sensation vote. Male 1 was comfortable at most temperatures. He had two preferred temperatures: 21.5 ºC and 22.5 ºC. Female 3's thermal sensation vote average was close to 0 for most temperatures. Male 3 was comfortable at 21 ºC as he got a thermal sensation vote value close to 0.

Table 9: Average thermal response value per temperature recorded.

| **Temperature °C** | **Respondent** | | | | | |
|---|---|---|---|---|---|---|
| | Female 1 | Male 1 | Female 2 | Male 2 | Female 3 | Male 3 |
| 20.5 | - | - | 1.0 | 1.0 | - | - |
| 21 | -0.7 | 0.3 | 0.8 | 0.2 | 0.1 | 0.0 |
| 21.5 | -0.8 | 0.0 | 0.6 | -0.4 | 0.2 | -0.3 |
| 22 | -0.6 | -0.1 | 0.6 | -0.4 | 0.1 | -1.0 |
| 22.5 | -0.7 | 0.0 | 0.4 | 0.0 | 0.1 | -0.3 |
| 23 | -0.6 | 0.3 | 0.2 | -0.4 | 0.5 | -0.7 |
| 23.5 | 0.0 | - | - | -1.0 | - | - |

Boxplots of the temperature ranges experienced when the prefer cooler, no change, and prefer warmer thermal sensation votes were voted are first shown for all 6 respondents. Statistical differences, if any, between the 6 respondents in prefer cooler, no change and prefer warmer votes will are subsequentially presented. Table 10 presents the statistics for the temperatures recorded from all respondents corresponding to each of the three comfort choices. From the 299 responses, the average temperature at the prefer cooler comfort vote was 22.11°C, no change vote was 22.15°C and prefer warmer vote was 21.78°C.  Notably, the average temperature corresponding to the no change vote was very close to the “prefer cooler” vote. Medians and means for boxplots of all three thermal sensation votes were at most 10% different from their means in distributions without outliers. Since there was at least one respondent with an outlier for all three thermal sensation votes, the medians for all respondents were used for analysis in this present section. For distributions that have outliers or are skewed, the median is often the preferred measure of central tendency because the median is less sensitive to outliers than the mean[52].

Table 10: Overview of thermal sensation vote responses

| | **Thermal sensation vote** | | |
|---|---|---|---|
| | Prefer cooler | No change | Prefer warmer |
| Mean temperature °C | 22.11 | 22.15 | 21.78 |
| Standard deviation °C | 0.73 | 0.71 | 0.77 |
| Number of responses | 72 | 155 | 72 |
| Minimum value °C | 21 | 21 | 20.5 |
| Maximum value °C | 23.5 | 23.5 | 23 |
| Range °C | 2.5 | 2.5 | 2.5 |

Figure 15 shows boxplots with the room temperatures for prefer cooler temperature votes for all clothing styles (short sleeve, long pants, and long sleeve long pants). It was observed that Female 2 was the only occupant who did not click on the prefer cooler button during the 3-week experiment thus indicating that she preferred warmer temperatures at all the experimental conditions. Moreover, it was observed that there were not many outliers which is an indicator of consistency in the overall thermal comfort perception (only Male 1 displayed one outlier). Since the upper quartile for Male 2 and Male 3 was higher than Female 1 and Female 3, it was implied that men may have felt warmer i.e., prefer cooler at higher temperature ranges and thus were more resistant to temperature increases, which does not correspond to the reviewed literature that suggests that women generally feel warmer than men. It was found that there were no statistical differences between the survey participants in prefer cooler vote thus we failed to reject H₀. All respondents had normal distributions according to the Shapiro-Wilk test.

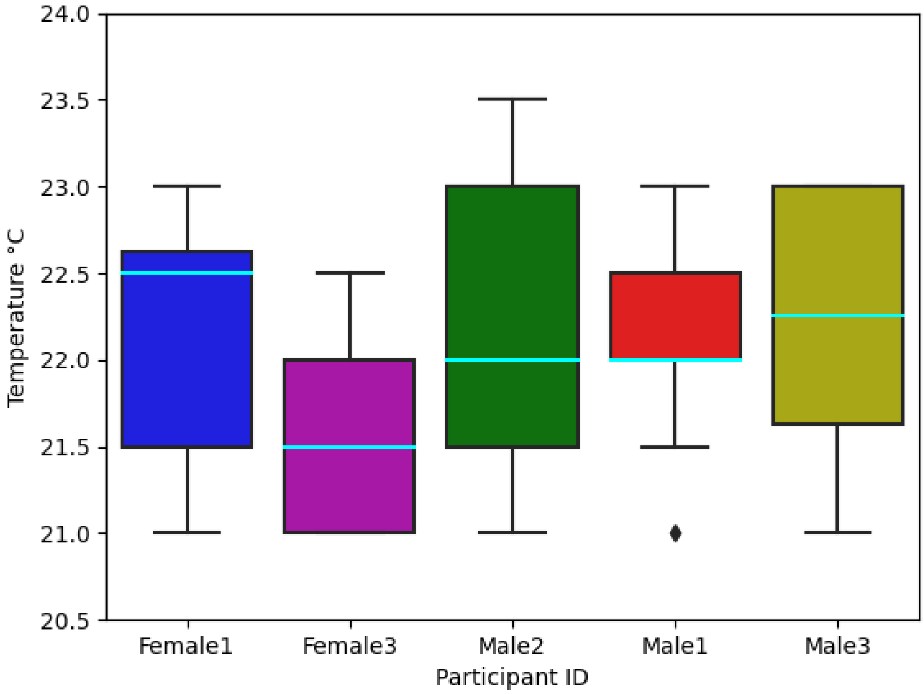


Figure 15: Boxplot of temperature ranges for prefer cooler temperature votes

Figure 16 indicates the temperature ranges for no change temperature votes. Female 1, Male 1 and Female 3 had larger temperature difference between upper and lower quartile ranges than Female 2, Male 2 and male 3. Thus, implying they were easier to satisfy during the experiment as room temperature fluctuated and were satisfied at more room temperatures. Female 2, Male 2 and Male 3 had outliers in their data distribution. It was found that there were statistical differences between the survey participants in prefer no change vote, thus we reject H₀. The p-value, 2.2 *$10^{-6}$, was significantly smaller than α=0.05. This p-value indicates that the results are replicable in future experiments. Further, Female 3 displayed a lower median temperature than all the other participants, thus indicating she is comfortable at lower temperatures than the other respondents. Male 2, Male 3 and Male 1 had median temperatures on average of 22.25 °C. Whereas, Female 2, Female 1 had higher median temperature of 22.5°C. Male 1, Female 2, Male 2, Female 3 and Male 3 had non-normal distributions for their data according to the Shapiro-Wilk test. Female 1 had a normal distribution for its data.

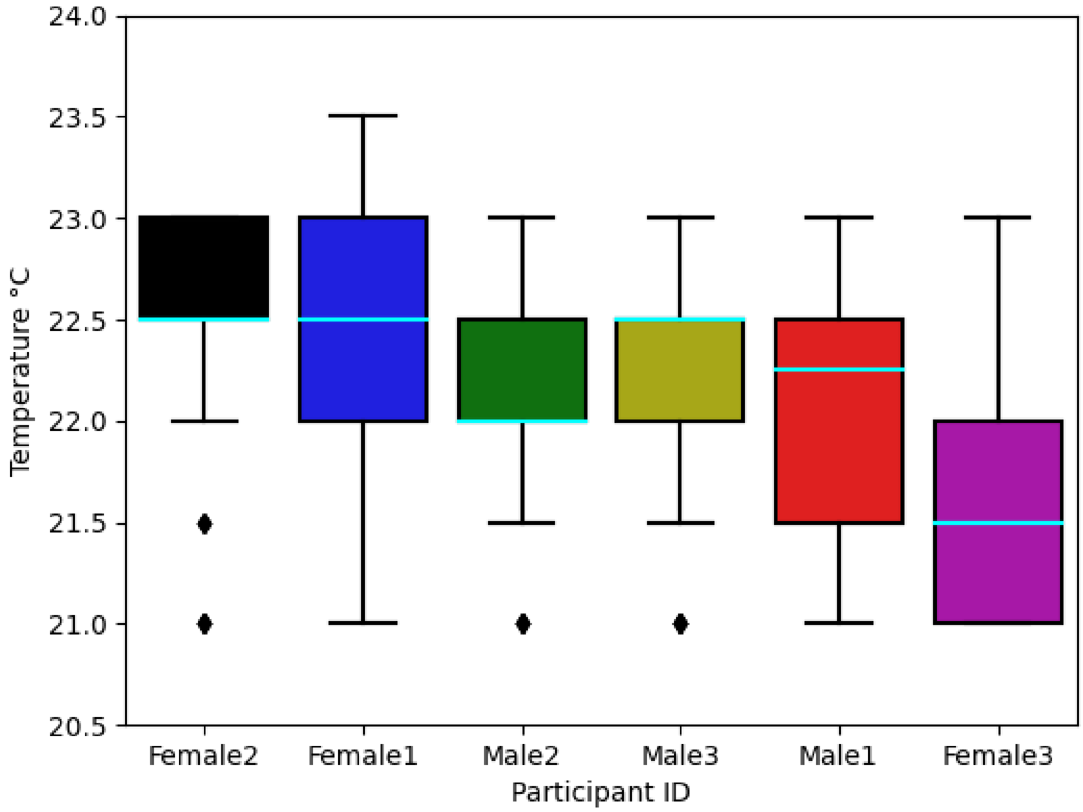


Figure 16: Boxplot of temperature ranges for no change temperature votes

Figure 17 shows the temperature ranges at which the prefer warmer thermal sensation vote was clicked on the smartwatch. It is observed that Female 1 did not click prefer warmer on any of the temperatures provided. Female 3 and Male 1 had a larger difference in upper and lower quartile range than Male 2 and Female 3. It is thus implied they voted prefer warmer on more room temperatures than Male 2 and female 3. Male 3 did not have enough data points for analysis. It was found that there were no statistical differences between the survey participants in prefer warmer vote, thus we fail to reject $H_o$. Only Male 2 had an outlier which is in an indicator of consistency in the data distributions. Male 1, Female 3 had normal distributions in their data according to the Shapiro-Wilk test. Female 2, Male 2 do not have normal distributions in their data.

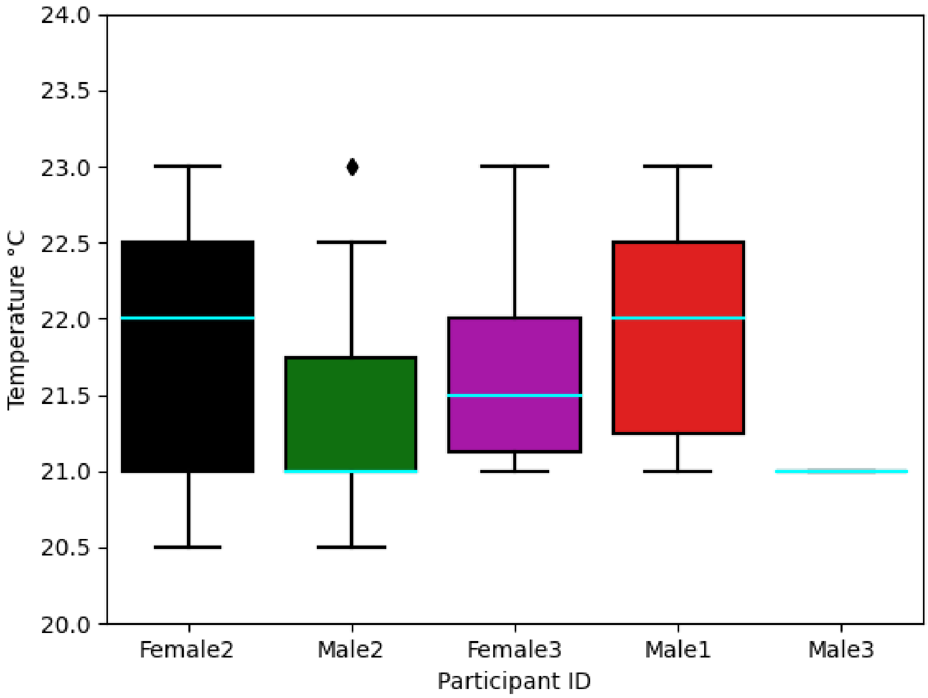


Figure 17: Temperature ranges for prefer warmer temperature votes

### 4.1.2 Investigation of the effect of clothing on thermal comfort

The following sub-section investigates the effect of clothing on all thermal sensation votes: prefer cooler, no change and prefer warmer. Temperature ranges from each respondent are presented as boxplots. Results from statistical test are presented.

Figure 18 shows the temperature ranges that correspond to a prefer cooler thermal sensation vote with clothing variation from light (0.57 clo) to heavy to (0.61 clo). Male 2 and Male 1 displayed a mean temperature that is 1-4% lower after the clothing level goes from short sleeve to long sleeve. This is expected since as the temperature rises and more clothing is on the respondent, he/she will vote prefer cooler at lower temperatures. Female 1 showed a similar mean, in light and heavy clothing. Female 2 did not vote prefer cooler during the experiment, while Female 3 never wore light clothing when she clicked on prefer cooler. For Male 3 we observe an unexpected effect, when he wore long sleeve his heat tolerance increased. In other words, as he wore a longer sleeve shirt, he was expected to click on prefer cooler at lower temperatures than the temperature ranges he clicked on prefer cooler while wearing a short sleeve shirt. One is supposed to feel warmer more easily as he goes from short sleeve shirt to long sleeve shirt because of the presence of more clothing resistance his arms on the later. It was found that there were no statistical differences for the 3 survey participants that voted prefer cooler votes when they changed their clothing from short sleeve shirt (0.57 clo) to long sleeve shirt (0.61 clo) (p-value > 0.275). Female 3 only voted prefer cooler while wearing a long sleeve shirt thus no test was performed with this participant. Female 1, Male 1, Male 2 had normal data distributions for all levels of clothing. Male 3 had non-normal distribution at level 3 clothing. Female 3 had a normal data distribution with level 3 clothing. Further, it can be noticed that by separating the prefer cooler thermal sensation vote by clothing, there are no more outliers.

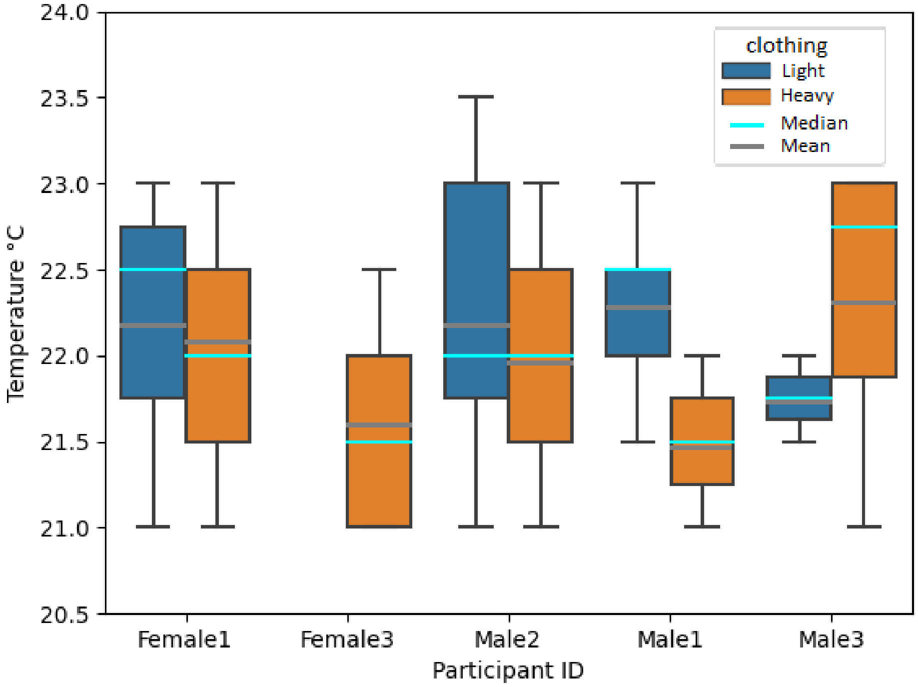


Figure 18: Temperature ranges for prefer cooler vote with clothing variation

Figure 19 shows the temperature ranges for no change thermal vote with clothing variation from light (0.57 clo) to heavy to (0.61 clo). Male 1, Male 2, Female 3 and Female 2 felt comfortable at lower temperatures when their clothing level increases from short sleeve shirt to long sleeve shirt which is expected since they had more thermal resistance on their arms and can sustain lower temperatures with less clothing. Male 3 still felt comfortable with the same median temperature, thus suggesting his thermal comfort was unaffected by changing clothing. It was found that there were no statistical differences for all 6 survey participants that voted prefer no change vote (comfortable) when they changed their clothing from short sleeve shirt (0.57 clo) to long sleeve shirt (0.61 clo) (p-value > 0.275). Female 1 had a normal distribution for all clothing levels. Male 1 had a non-normal distribution with level 2 clothing. Female 2 had a non-normal distribution on level 2 clothing. Male 2 had a normal data distribution with level 2 clothing but a non-normal data distribution with level 3 clothing. Female 3 had a non-normal data distribution on all clothing levels. Male 3 had a non-normal distribution with level 2 clothing but normal distribution for level 3 clothing.

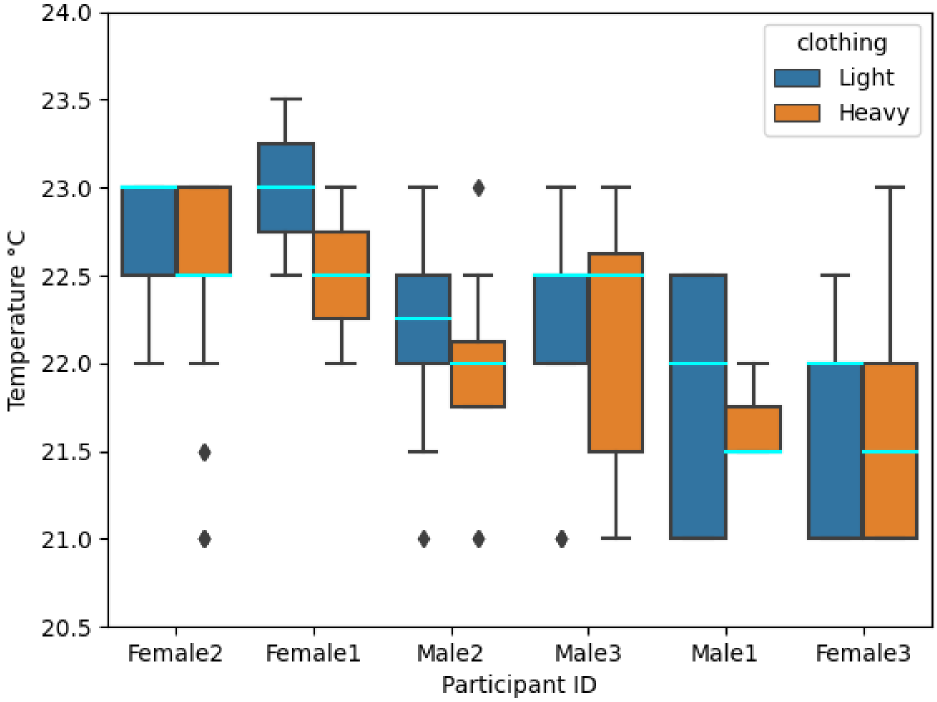


Figure 19: Temperature ranges for no change vote with clothing variation

Figure 20 shows the temperature ranges for prefer warmer vote with clothing variation from light (0.57 clo) to heavy to (0.61 clo). Female 1 did not click on prefer on warmer during the experiment. The mean temperature is used for analysis as the data does not have any outliers. Only Female 3 had enough datapoints for both levels of clothing to conduct a statistical analysis. Female 3 did not show a significant decrease in mean temperature after increasing her clothing suggesting her thermal comfort was not affected by clothing variation. It was found that there were no statistical differences for Female 3 who voted prefer warmer when she changed their clothing from short sleeve shirt (0.57 clo) to long sleeve shirt (0.61 clo) (p-value > 0.275). Male 1 had a non-normal distribution with level 3 clothing. Female 2 had a non-normal data distribution with level 3 clothing. Male 2 had a non-normal data distribution with level 2 clothing. Female 3 had a normal data distribution for both level 2 and 3 clothing.

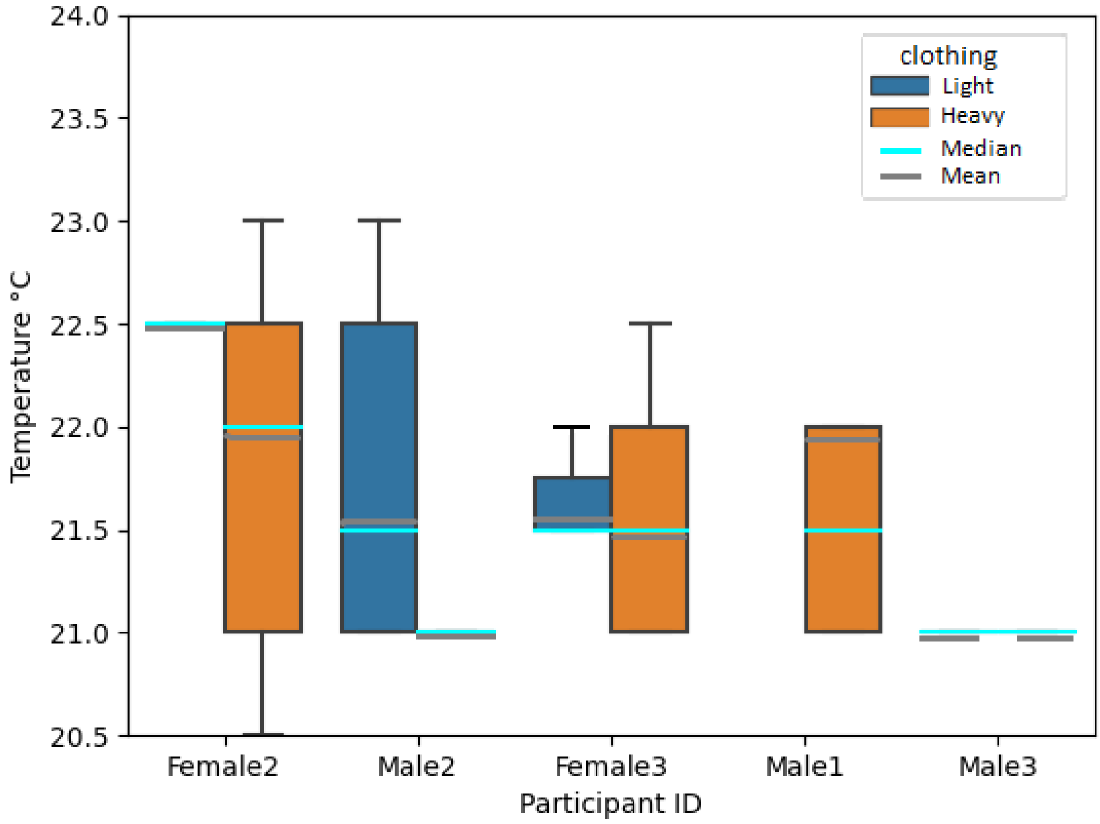


Figure 20: Temperature ranges for prefer warmer vote with clothing variation

## 4.2 **Air flowrate analysis**

Figure 21 shows the boxplots for airflow rates where the survey respondents voted that they perceived air movement on them coming from the supply air diffuser as prompted in Table 7. Inspection yielded a mean flowrate of 52 L/s where Female 1, Female 3, Male 2 and Male 1 reported feeling the air movement on them. Female 1, Female 3 and Male 1 reported not feeling the air movement on them at a mean flowrate of 50 L/s which is consistent with HVAC design theory as the higher the flowrate is the higher the air velocity will be, and the air will be felt on the occupants in the room at a higher degree. Male 2 reported feeling and not feeling the air movement on him at the same median flowrate of 52 L/s which differentiates him from the rest of the participants. There was a difference in the 25% to 75% boxplot boundaries when comparing the positive air movement perception (orange boxplot) to the negative air movement perception (blue boxplot) for all survey respondents. It can also be seen that Male 3 and Female 2 did not report feeling the air draft coming from the diffuser. Female 1 had a normal data distribution when perceiving air movement. Male 1 had a non-normal data distribution when perceiving and not perceiving air movement. Female 2 had a non-normal data distribution when perceiving air movement. Female 3 had a normal distribution when perceiving air movement and a non-normal data distribution when not perceiving air movement. Male 3 had a non-normal data distribution when perceiving air movement.

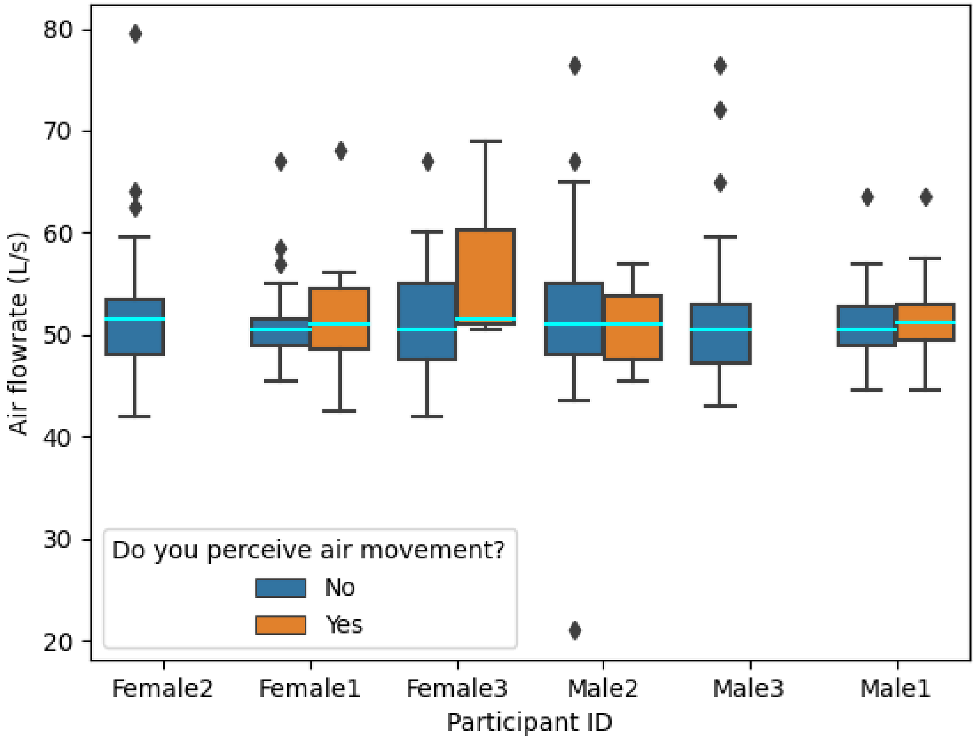


Figure 21: Air movement perception

There was perception of air movement in 15% of survey responses. For all participants, out of the 45 responses, there was 12 times which occurred on prefer cooler vote, 22 times which occurred on no change vote and 11 times which occurred on prefer warmer vote. There was a question on the Fitbit watch asking for if you are comfy or not comfy and another one asking if you prefer cooler, no change, prefer warmer. If one person clicked that they sensed air movement, were not comfy overall but were comfy with respect to air temperature (thermal), that would indicate they were uncomfortable with respect to the air movement coming from the diffuser. From the Kruskal-Wallis test, it was found that that were no statistical differences between the survey respondents' perception and non-perception of air movement coming from the diffuser thus we failed to reject $H_o$ (p-value>0.85).

By varying the level of clothing from 0.57 (short sleeve shirt and long trousers) to 0.61 clo (long sleeve shirt and long trousers), Figure 22 shows that the median flowrate for the Female 1, Male 1 and Male 2 was higher (by 1-8%) to detect air movement from the diffuser. This trend is logical given the fact that more percentage of their body is covered by clothing; more precisely because their wrists and forearms are covered with clothing (long sleeve shirt vs long sleeve shirt). Female 3 depicted an opposite phenomenon, but this is likely due to the lack of flowrate data for this respondent. Female 1, Male 1 and Male 2 respondents did not show a statistical difference (p-value > 0.089) and Female 3 did not have enough data to conduct a statistical test. Female 1 had a normal data distribution for level 2 and 3 clothing. Male 1 had a non-normal data distribution with level 2 clothing.

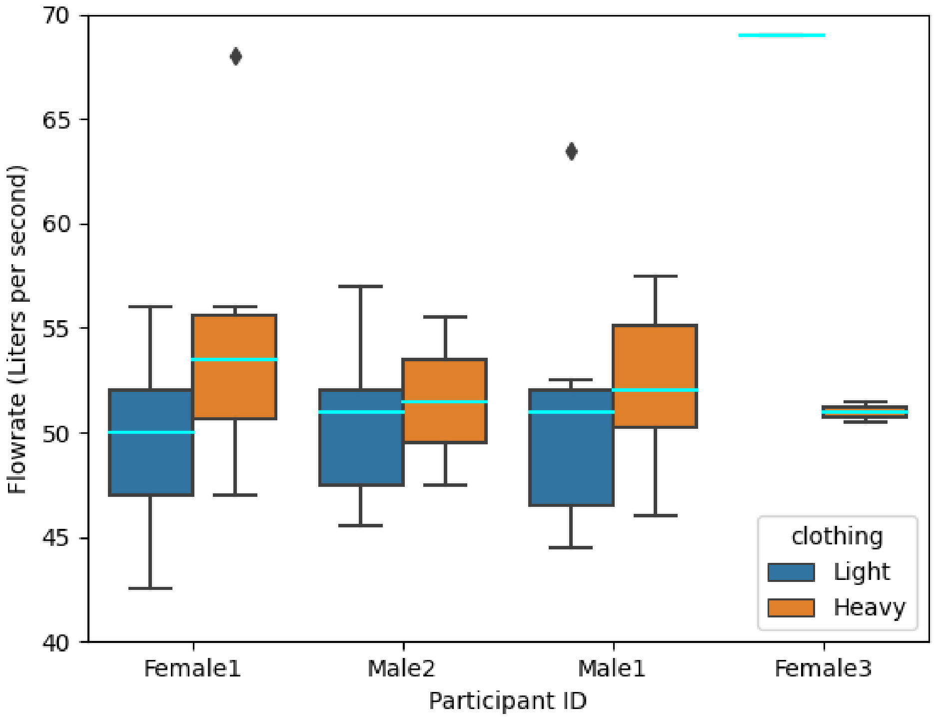


Figure 22: Flowrate ranges for air movement perception with clothing variation

### 4.3 Heartrate analysis

Examining Figure 23, it was found that that most of heartrates fall between 60-100 beats per minutes which is the normal range for healthy individuals doing office work [14]. However, it can be observed that respondents: Female 1, Female 3 and Male 3 when the preferred cooler had their median heartrate increase by 2-6%. Female 2, Male 2 and Male 1 do not show any pattern in their thermal preference when their heartrate varies. Male 1 only recorded 5 heart rate inputs out of his 43 thermal comfort survey inputs, thus indicating that perhaps he was wearing the watch too loosely on his wrist or not wearing it but still answering the thermal sensation survey.

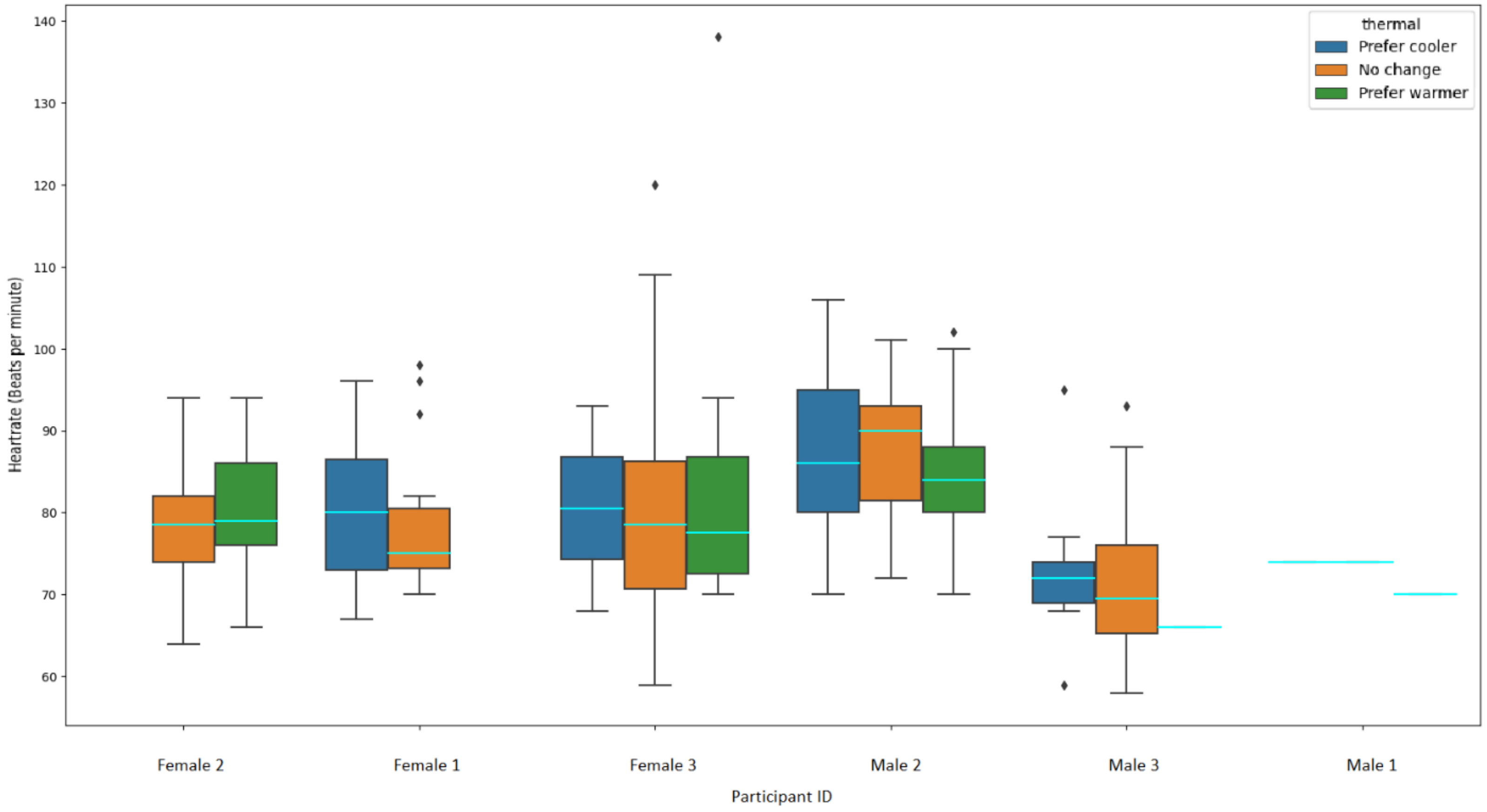


Figure 23: Heartrates of respondents with different thermal sensation

## 4.4 Algorithm to control room temperature setpoint

Results in the previous sections demonstrate the possibility of identifying comfort profiles for each occupant based on their responses under various indoor conditions. In this sub-section, we propose a control algorithm that could leverage the median temperature at which occupants preferred “no change” (i.e., felt comfortable – which is shown in Table 11) to optimize HVAC operations by maximizing comfort while minimizing energy use in multi-occupant / co-working office spaces. To integrate these comfort preferences in a room’s control, it is crucial to establish a comfort profile and median temperature corresponding to no change thermal preference vote for each occupant using the methodology presented in this work. This means collecting personal thermal sensation votes for 15 business days to identify occupant preferences under a wide range of indoor conditions, and calculate the median temperature at which each occupant prefers “no change” in temperature, similar to the ones shown in Table 11.

Table 11: Median preferred room temperature for no change thermal preference vote

| | **Female 1** | **Male 1** | **Female 2** | **Male 2** | **Female 3** | **Male 3** |
|---|---|---|---|---|---|---|
| Median temperature (°C) | 22.5 | 22.3 | 22.5 | 22 | 21.5 | 22.5 |

Figure 24 depicts a flow chart of the proposed occupant-centric control sequence to control room temperature based on occupancy. If no occupancy is detected, a temperature setback is used to minimize energy use. If one occupant is in the room, (which is a frequent occurrence in offices with hybrid work; whereby many employees are typically working remotely), the median temperature for no change thermal preference vote (thereafter referred to as “comfort” setpoint) for this occupant would be used based on previously established comfort profile. If more than one occupant is present in the room, the average of their median comfort setpoints would be used to minimize discomfort, while potentially reducing energy consumption. For example, from the studied sample in this work, the average median comfort setpoint for Female 3 and Male 2 would be lower the standard heating setpoint typically used in office buildings which ranges between 22 °C and 22.5 °C. The median temperature at which occupants prefer “no change” would continuously be re-adjusted on a daily basis based on responses collected during these deployments. Since the distributions were skewed for half of the respondents in the prefer “no change” vote, the medians will be used for the algorithm presented in Figure *24*.

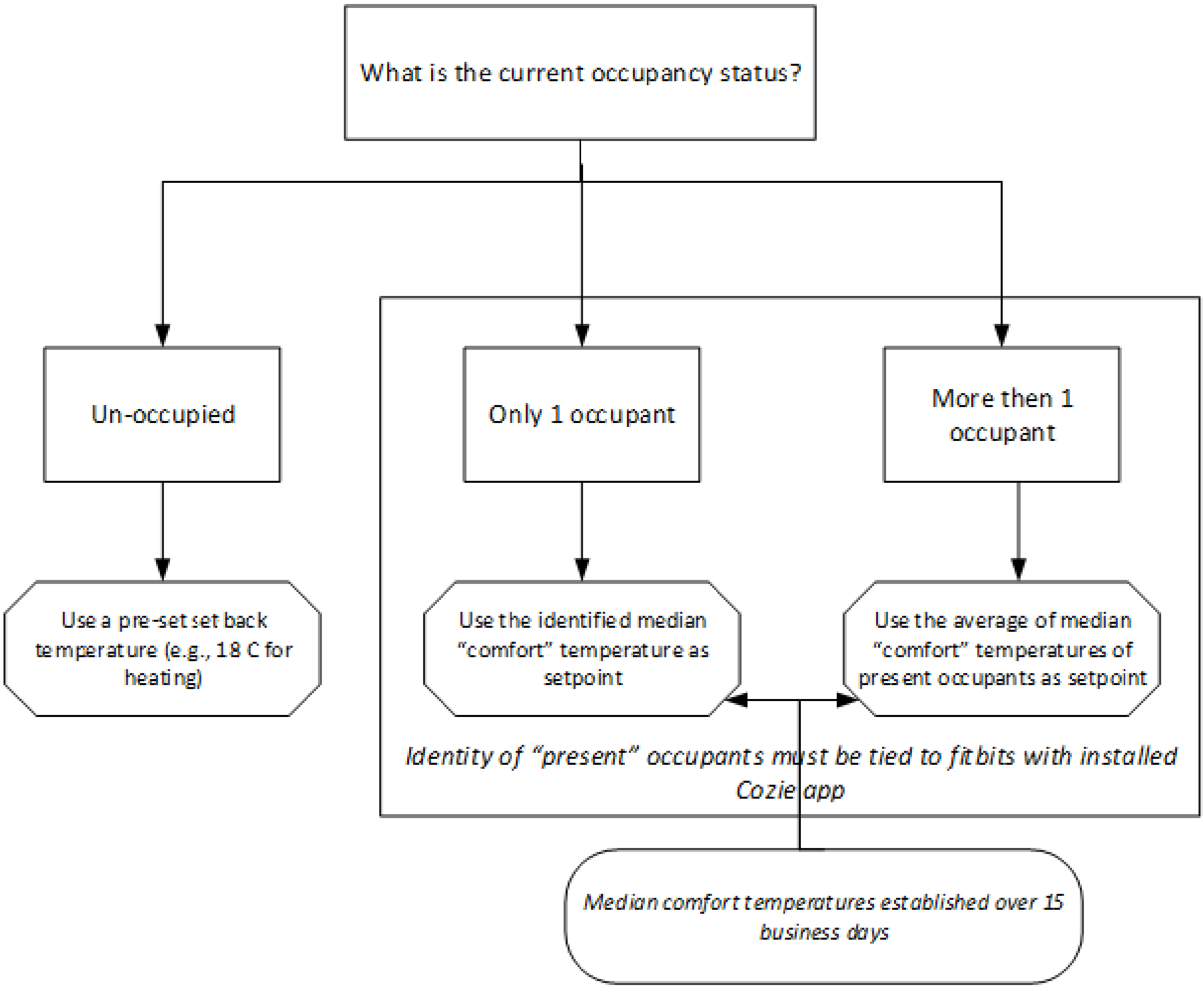


Figure 24: Proposed occupant-centric control sequence for temperature setpoint

A variation of the proposed control sequence is also proposed to integrate predictive modelling of occupancy. This would allow for pre-emptively reaching the average comfort temperatures for prospective occupants based on historical patterns that identify which occupants are typically present at different times during the week (and their respective comfort profiles). This control sequence would leverage the work previously introduced by Alishahi et al. in which the latest arrival and departure times of occupants were identified from historical patterns with a 90% confidence [53]. If occupants are not present after their identified latest arrival times for example, the control sequence can assume these occupants will not be present for the rest of the day, and either re-calculate the average comfort setpoint accordingly or trigger a setback if no occupants are present after the pre-calculated latest arrival times. The proposed sequence of operation in Figure *24* is reproducible in other offices as most commercial Building Management Systems offer a scheduling function for temperature setpoints to allow for discovery of thermal sensations at different room temperatures. Further, thermal comfort surveys can be conducted through smartphones thus promoting the proliferation of the algorithm presented in this study.

# 5 Chapter V: Conclusion and future works

This study investigated thermal comfort of respondents in multi-occupant workspaces. Statistical differences were found between respondents thus led to the development of an algorithm to control the room temperature. Further research is required to implement and validate this algorithm. This chapter is presented in three parts: summary of results, limitations, impact, significance, and future research.

## 5.1 Summary of results

The results from this study could help building engineers and operators write sequences of operations to control the HVAC system which are tailored to the individuals that are present in the room. This can create better comfort and reduce energy consumption as less actuation of the damper is needed if there are less setpoint changes by the occupants derived from individual setpoint preferences. There was a statistically significant difference between the 6 respondents in the “no change” thermal preference votes with small (p-value, $2.2 * 10^{-6}$), which highlights the diversity in comfort preferences. It was found that the median temperature of a group of people present in the living lab differed since some of the respondents had a different preferred median room temperature.

The thermal preference and the air movement perception from the diffuser of 6 survey respondents has been analyzed. Temperature ranges for prefer cooler, no change and prefer warmer votes on the Fitbit smartwatch have been analyzed and compared to assess if there were any statistical differences within the survey respondents when they are changing their clothing level from short sleeve shirt (light clothing) and long pants and to long sleeve shirt (heavy clothing) and long pants. No respondents showed statistical differences in their thermal comfort with respect to room temperature or airflow sensing when varying their clothing from light clothing from short sleeve shirt to long sleeve shirt. There were no statistical differences between the 6 respondents in the prefer warmer or prefer cooler temperature votes under a chi squared test of 0.05 level of significance. Statistical differences were also not found when perceiving and not perceiving air movement from the supply air diffuser between respondents.

## 5.2 Limitations

The current study was limited to asking the respondents for 4 levels of clothing such as long sleeve shirt and long sleeve pants for the clothing level. Some occupants were wearing more than one long-sleeve layer on their torso. Thus, a more accurate clothing level questionnaire could be prompted in further studies. Moreover, the relatively small range of temperatures experienced by the respondents may have influenced results, especially on the effect of clothing. The sample sizes were small, but datapoints from each subject was considerably large. This framework was limited to single zone control and did not consider temperature setpoint changes in the two enclosed offices that are adjacent to the co-working space. This study was limited to a small space and sample size. However, this study was meant to be a proof of concept for the proposed workflow. Algorithms to enhance airflow speed have not been investigated as the diffusers dispersed air adequately in the room and not on most occupants during the experiment as only 15% of surveyed votes reported feeling the airflow. The effects of leaving the doors open on the surrounding offices on the temperature setpoint of the 9-person co-working space in the living lab was not investigated and could be investigated in future research as heat transfer through convection is significant in forced air systems.

Further, this study did not verify if the perceptions of thermal comfort and air movement were influenced by the location of the respondents. The air temperature and velocity differ at different locations in the room. The air stream coming out of the supply air diffuser has a different temperature and velocity in different locations in the room according to the thermodynamic laws of conservation of mass, energy, and momentum. Air velocity was not measured with an instrument at each respondent location.

## 5.3 Impact, significance, and future research

This study has an impact on occupant centric control research as it created a foundation for room temperature control algorithms in co-working spaces and addressed several gaps in reviewed literature. Algorithms to satisfy most people in the room with respect to room temperature were developed. Energy savings could potentially be achieved as less thermostat presses will yield a reduction in electric reheat coil usage (for heating mode) since the algorithm will decide a temperature setpoint based on who is in the room and avoid an unnecessary number of thermostat presses. If no algorithms are implemented, there is a possibility that a newly arriving person increases the room temperature to a setpoint that is above what he needs to be comfortable. If this scenario occurs many times in a day with different occupants, the electric reheat coil will be activated for an unnecessary number of times thus resulting in energy wasted.

The reviewed literature identified a small number of papers that introduced algorithms to control room temperature in multi-occupant settings. They require complex mathematical formulas which could prove challenging for building operators and technicians to program in their building management systems.  The algorithm proposed in this study is simple and should be easy to program in the BMS as simple median calculations are involved, and most significantly could result in large energy savings as it entails real-time adjustment of setpoints to established occupant preferences. Most papers in reviewed literature also did not conduct comprehensive statistical analysis in their studies as part of developing occupant centric control algorithms. The study conducted as a part of this research conducted a variety of statistical tests to allow for the building operators to make critical decisions in determining the optimized room temperature setpoints.

Future research could implement and validate the performance of the algorithm presented in section 4.4.

Future works could capture temperature profiles from the survey respondents on their smart devices and adjust the temperature in the B.M.S automatically without human intervention by gaging their thermal preference after the first days of the survey respondent in the office as proposed in the previous chapter. A personal thermal comfort profile could be formulated for each individual that used a smart device. The preferred median temperatures of all respondents could then be found. To let the system, know who is in the room, an identification system tied to the Fitbits and the corresponding comfort profiles would have to be used.

Stochastic modeling would be required to see the effect on group discomfort resulting from changing the setpoints randomly in the enclosed rooms adjacent to the co-working space. Blind position in the enclosed surrounding offices might also affect discomfort in the co-working space as more radiation can penetrate all three rooms and could be investigated in future research.

Further experimentation is needed to implement this framework in large offices (more than 300 $ft^2$) with more than 9 people seated. Integration of electronic devices to the existing data infrastructure such as tablets and smartphones to answer thermal comfort survey questions could open the possibility to large scale thermal survey comfort questionnaire in bigger rooms (20+ occupants) without acquiring new equipment as most occupants readily have access to smartphones [54]. Noise questionnaires could also be asked in future research to ensure quieter HVAC system's operation, which could be added as an optimization parameter when developing and implementing the proposed occupant-centric control algorithms.

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Appendix 1: T-table

| **cum. prob** | **$^{t}$.50** | **$^{t}$.75** | **$^{t}$.80** | **$^{t}$.85** | **$^{t}$.90** | **$^{t}$.95** | **$^{t}$.975** | **$^{t}$.99** | **$^{t}$.995** | **$^{t}$.999** | **$^{t}$.9995** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **one-tail** | **0.50** | **0.25** | **0.20** | **0.15** | **0.10** | **0.05** | **0.025** | **0.01** | **0.005** | **0.001** | **0.0005** |
| **two-tails** | **1.00** | **0.50** | **0.40** | **0.30** | **0.20** | **0.10** | **0.05** | **0.02** | **0.01** | **0.002** | **0.001** |
| **df** | | | | | | | | | | | |
| 1 | 0.000 | 1.000 | 1.376 | 1.963 | 3.078 | 6.314 | 12.71 | 31.82 | 63.66 | 318.31 | 636.62 |
| 2 | 0.000 | 0.816 | 1.061 | 1.386 | 1.886 | 2.920 | 4.303 | 6.965 | 9.925 | 22.327 | 31.599 |
| 3 | 0.000 | 0.765 | 0.978 | 1.250 | 1.638 | 2.353 | 3.182 | 4.541 | 5.841 | 10.215 | 12.924 |
| 4 | 0.000 | 0.741 | 0.941 | 1.190 | 1.533 | 2.132 | 2.776 | 3.747 | 4.604 | 7.173 | 8.610 |
| 5 | 0.000 | 0.727 | 0.920 | 1.156 | 1.476 | 2.015 | 2.571 | 3.365 | 4.032 | 5.893 | 6.869 |
| 6 | 0.000 | 0.718 | 0.906 | 1.134 | 1.440 | 1.943 | 2.447 | 3.143 | 3.707 | 5.208 | 5.959 |
| 7 | 0.000 | 0.711 | 0.896 | 1.119 | 1.415 | 1.895 | 2.365 | 2.998 | 3.499 | 4.785 | 5.408 |
| 8 | 0.000 | 0.706 | 0.889 | 1.108 | 1.397 | 1.860 | 2.306 | 2.896 | 3.355 | 4.501 | 5.041 |
| 9 | 0.000 | 0.703 | 0.883 | 1.100 | 1.383 | 1.833 | 2.262 | 2.821 | 3.250 | 4.297 | 4.781 |
| 10 | 0.000 | 0.700 | 0.879 | 1.093 | 1.372 | 1.812 | 2.228 | 2.764 | 3.169 | 4.144 | 4.587 |
| 11 | 0.000 | 0.697 | 0.876 | 1.088 | 1.363 | 1.796 | 2.201 | 2.718 | 3.106 | 4.025 | 4.437 |
| 12 | 0.000 | 0.695 | 0.873 | 1.083 | 1.356 | 1.782 | 2.179 | 2.681 | 3.055 | 3.930 | 4.318 |
| 13 | 0.000 | 0.694 | 0.870 | 1.079 | 1.350 | 1.771 | 2.160 | 2.650 | 3.012 | 3.852 | 4.221 |
| 14 | 0.000 | 0.692 | 0.868 | 1.076 | 1.345 | 1.761 | 2.145 | 2.624 | 2.977 | 3.787 | 4.140 |
| 15 | 0.000 | 0.691 | 0.866 | 1.074 | 1.341 | 1.753 | 2.131 | 2.602 | 2.947 | 3.733 | 4.073 |
| 16 | 0.000 | 0.690 | 0.865 | 1.071 | 1.337 | 1.746 | 2.120 | 2.583 | 2.921 | 3.686 | 4.015 |
| 17 | 0.000 | 0.689 | 0.863 | 1.069 | 1.333 | 1.740 | 2.110 | 2.567 | 2.898 | 3.646 | 3.965 |
| 18 | 0.000 | 0.688 | 0.862 | 1.067 | 1.330 | 1.734 | 2.101 | 2.552 | 2.878 | 3.610 | 3.922 |
| 19 | 0.000 | 0.688 | 0.861 | 1.066 | 1.328 | 1.729 | 2.093 | 2.539 | 2.861 | 3.579 | 3.883 |
| 20 | 0.000 | 0.687 | 0.860 | 1.064 | 1.325 | 1.725 | 2.086 | 2.528 | 2.845 | 3.552 | 3.850 |
| 21 | 0.000 | 0.686 | 0.859 | 1.063 | 1.323 | 1.721 | 2.080 | 2.518 | 2.831 | 3.527 | 3.819 |
| 22 | 0.000 | 0.686 | 0.858 | 1.061 | 1.321 | 1.717 | 2.074 | 2.508 | 2.819 | 3.505 | 3.792 |
| 23 | 0.000 | 0.685 | 0.858 | 1.060 | 1.319 | 1.714 | 2.069 | 2.500 | 2.807 | 3.485 | 3.768 |

|  |  |  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 24 | 0.000 | 0.685 | 0.857 | 1.059 | 1.318 | 1.711 | 2.064 | 2.492 | 2.797 | 3.467 | 3.745 |
| 25 | 0.000 | 0.684 | 0.856 | 1.058 | 1.316 | 1.708 | 2.060 | 2.485 | 2.787 | 3.450 | 3.725 |
| 26 | 0.000 | 0.684 | 0.856 | 1.058 | 1.315 | 1.706 | 2.056 | 2.479 | 2.779 | 3.435 | 3.707 |
| 27 | 0.000 | 0.684 | 0.855 | 1.057 | 1.314 | 1.703 | 2.052 | 2.473 | 2.771 | 3.421 | 3.690 |
| 28 | 0.000 | 0.683 | 0.855 | 1.056 | 1.313 | 1.701 | 2.048 | 2.467 | 2.763 | 3.408 | 3.674 |
| 29 | 0.000 | 0.683 | 0.854 | 1.055 | 1.311 | 1.699 | 2.045 | 2.462 | 2.756 | 3.396 | 3.659 |
| 30 | 0.000 | 0.683 | 0.854 | 1.055 | 1.310 | 1.697 | 2.042 | 2.457 | 2.750 | 3.385 | 3.646 |
| 40 | 0.000 | 0.681 | 0.851 | 1.050 | 1.303 | 1.684 | 2.021 | 2.423 | 2.704 | 3.307 | 3.551 |
| 60 | 0.000 | 0.679 | 0.848 | 1.045 | 1.296 | 1.671 | 2.000 | 2.390 | 2.660 | 3.232 | 3.460 |
| 80 | 0.000 | 0.678 | 0.846 | 1.043 | 1.292 | 1.664 | 1.990 | 2.374 | 2.639 | 3.195 | 3.416 |
| 100 | 0.000 | 0.677 | 0.845 | 1.042 | 1.290 | 1.660 | 1.984 | 2.364 | 2.626 | 3.174 | 3.390 |
| 1000 | 0.000 | 0.675 | 0.842 | 1.037 | 1.282 | 1.646 | 1.962 | 2.330 | 2.581 | 3.098 | 3.300 |
| **z** | 0.000 | 0.674 | 0.842 | 1.036 | 1.282 | 1.645 | 1.960 | 2.326 | 2.576 | 3.090 | 3.291 |
|  | 0% | 50% | 60% | 70% | 80% | 90% | 95% | 98% | 99% | 99.8% | 99.9% |
|  | **Confidence Level** |  |  |  |  |  |  |  |  |  |  |

[55]

# Appendix 2: Chi-square table

Critical values of chi-square (right tail)

| Degrees of freedom (df) | Significance level (α) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 0.99 | 0.975 | 0.95 | 0.9 | 0.1 | 0.05 | 0.025 | 0.01 |
| 1 | ------- | 0.001 | 0.004 | 0.016 | 2.706 | 3.841 | 5.024 | 6.635 |
| 2 | 0.020 | 0.051 | 0.103 | 0.211 | 4.605 | 5.991 | 7.378 | 9.210 |
| 3 | 0.115 | 0.216 | 0.352 | 0.584 | 6.251 | 7.815 | 9.348 | 11.345 |
| 4 | 0.297 | 0.484 | 0.711 | 1.064 | 7.779 | 9.488 | 11.143 | 13.277 |
| 5 | 0.554 | 0.831 | 1.145 | 1.610 | 9.236 | 11.070 | 12.833 | 15.086 |
| 6 | 0.872 | 1.237 | 1.635 | 2.204 | 10.645 | 12.592 | 14.449 | 16.812 |
| 7 | 1.239 | 1.690 | 2.167 | 2.833 | 12.017 | 14.067 | 16.013 | 18.475 |
| 8 | 1.646 | 2.180 | 2.733 | 3.490 | 13.362 | 15.507 | 17.535 | 20.090 |
| 9 | 2.088 | 2.700 | 3.325 | 4.168 | 14.684 | 16.919 | 19.023 | 21.666 |
| 10 | 2.558 | 3.247 | 3.940 | 4.865 | 15.987 | 18.307 | 20.483 | 23.209 |
| 11 | 3.053 | 3.816 | 4.575 | 5.578 | 17.275 | 19.675 | 21.920 | 24.725 |
| 12 | 3.571 | 4.404 | 5.226 | 6.304 | 18.549 | 21.026 | 23.337 | 26.217 |
| 13 | 4.107 | 5.009 | 5.892 | 7.042 | 19.812 | 22.362 | 24.736 | 27.688 |
| 14 | 4.660 | 5.629 | 6.571 | 7.790 | 21.064 | 23.685 | 26.119 | 29.141 |
| 15 | 5.229 | 6.262 | 7.261 | 8.547 | 22.307 | 24.996 | 27.488 | 30.578 |
| 16 | 5.812 | 6.908 | 7.962 | 9.312 | 23.542 | 26.296 | 28.845 | 32.000 |
| 17 | 6.408 | 7.564 | 8.672 | 10.085 | 24.769 | 27.587 | 30.191 | 33.409 |
| 18 | 7.015 | 8.231 | 9.390 | 10.865 | 25.989 | 28.869 | 31.526 | 34.805 |
| 19 | 7.633 | 8.907 | 10.117 | 11.651 | 27.204 | 30.144 | 32.852 | 36.191 |
| 20 | 8.260 | 9.591 | 10.851 | 12.443 | 28.412 | 31.410 | 34.170 | 37.566 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 21 | 8.897 | 10.283 | 11.591 | 13.240 | 29.615 | 32.671 | 35.479 | 38.932 |
| 22 | 9.542 | 10.982 | 12.338 | 14.041 | 30.813 | 33.924 | 36.781 | 40.289 |
| 23 | 10.196 | 11.689 | 13.091 | 14.848 | 32.007 | 35.172 | 38.076 | 41.638 |
| 24 | 10.856 | 12.401 | 13.848 | 15.659 | 33.196 | 36.415 | 39.364 | 42.980 |
| 25 | 11.524 | 13.120 | 14.611 | 16.473 | 34.382 | 37.652 | 40.646 | 44.314 |
| 26 | 12.198 | 13.844 | 15.379 | 17.292 | 35.563 | 38.885 | 41.923 | 45.642 |
| 27 | 12.879 | 14.573 | 16.151 | 18.114 | 36.741 | 40.113 | 43.195 | 46.963 |
| 28 | 13.565 | 15.308 | 16.928 | 18.939 | 37.916 | 41.337 | 44.461 | 48.278 |
| 29 | 14.256 | 16.047 | 17.708 | 19.768 | 39.087 | 42.557 | 45.722 | 49.588 |
| 30 | 14.953 | 16.791 | 18.493 | 20.599 | 40.256 | 43.773 | 46.979 | 50.892 |
| 40 | 22.164 | 24.433 | 26.509 | 29.051 | 51.805 | 55.758 | 59.342 | 63.691 |
| 50 | 29.707 | 32.357 | 34.764 | 37.689 | 63.167 | 67.505 | 71.420 | 76.154 |
| 60 | 37.485 | 40.482 | 43.188 | 46.459 | 74.397 | 79.082 | 83.298 | 88.379 |
| 70 | 45.442 | 48.758 | 51.739 | 55.329 | 85.527 | 90.531 | 95.023 | 100.425 |
| 80 | 53.540 | 57.153 | 60.391 | 64.278 | 96.578 | 101.879 | 106.629 | 112.329 |
| 100 | 61.754 | 65.647 | 69.126 | 73.291 | 107.565 | 113.145 | 118.136 | 124.116 |
| 1000 | 70.065 | 74.222 | 77.929 | 82.358 | 118.498 | 124.342 | 129.561 | 135.807 |

[56]

# Appendix 3: Mann-Whitney U table

## Two tail test

| $n_2$ | α | $n_1$ | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | | | | | | |
| 3 | .05 | -- | 0 | 0 | 1 | 1 | 2 | 2 | 3 | 3 | 4 | 4 | 5 | 5 | 6 | 6 | 7 | 7 | 8 |
| | .01 | -- | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 3 | 3 |
| 4 | .05 | -- | 0 | 1 | 2 | 3 | 4 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 11 | 12 | 13 | 14 |
| | .01 | -- | -- | 0 | 0 | 0 | 1 | 1 | 2 | 2 | 3 | 3 | 4 | 5 | 5 | 6 | 6 | 7 | 8 |
| 5 | .05 | 0 | 1 | 2 | 3 | 5 | 6 | 7 | 8 | 9 | 11 | 12 | 13 | 14 | 15 | 17 | 18 | 19 | 20 |
| | .01 | -- | -- | 0 | 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
| 6 | .05 | 1 | 2 | 3 | 5 | 6 | 8 | 10 | 11 | 13 | 14 | 16 | 17 | 19 | 21 | 22 | 24 | 25 | 27 |
| | .01 | -- | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 17 | 18 |
| 7 | .05 | 1 | 3 | 5 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | 20 | 22 | 24 | 26 | 28 | 30 | 32 | 34 |
| | .01 | -- | 0 | 1 | 3 | 4 | 6 | 7 | 9 | 10 | 12 | 13 | 15 | 16 | 18 | 19 | 21 | 22 | 24 |
| 8 | .05 | 2 | 4 | 6 | 8 | 10 | 13 | 15 | 17 | 19 | 22 | 24 | 26 | 29 | 31 | 34 | 36 | 38 | 41 |
| | .01 | -- | 1 | 2 | 4 | 6 | 7 | 9 | 11 | 13 | 15 | 17 | 18 | 20 | 22 | 24 | 26 | 28 | 30 |
| 9 | .05 | 2 | 4 | 7 | 10 | 12 | 15 | 17 | 20 | 23 | 26 | 28 | 31 | 34 | 37 | 39 | 42 | 45 | 48 |
| | .01 | 0 | 1 | 3 | 5 | 7 | 9 | 11 | 13 | 16 | 18 | 20 | 22 | 24 | 27 | 29 | 31 | 33 | 36 |
| 10 | .05 | 3 | 5 | 8 | 11 | 14 | 17 | 20 | 23 | 26 | 29 | 33 | 36 | 39 | 42 | 45 | 48 | 52 | 55 |

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | .01 | 0 | 2 | 4 | 6 | 9 | 11 | 13 | 16 | 18 | 21 | 24 | 26 | 29 | 31 | 34 | 37 | 39 | 42 |
| 11 | .05 | 3 | 6 | 9 | 13 | 16 | 19 | 23 | 26 | 30 | 33 | 37 | 40 | 44 | 47 | 51 | 55 | 58 | 62 |
|  | .01 | 0 | 2 | 5 | 7 | 10 | 13 | 16 | 18 | 21 | 24 | 27 | 30 | 33 | 36 | 39 | 42 | 45 | 48 |
| 12 | .05 | 4 | 7 | 11 | 14 | 18 | 22 | 26 | 29 | 33 | 37 | 41 | 45 | 49 | 53 | 57 | 61 | 65 | 69 |
|  | .01 | 1 | 3 | 6 | 9 | 12 | 15 | 18 | 21 | 24 | 27 | 31 | 34 | 37 | 41 | 44 | 47 | 51 | 54 |
| 13 | .05 | 4 | 8 | 12 | 16 | 20 | 24 | 28 | 33 | 37 | 41 | 45 | 50 | 54 | 59 | 63 | 67 | 72 | 76 |
|  | .01 | 1 | 3 | 7 | 10 | 13 | 17 | 20 | 24 | 27 | 31 | 34 | 38 | 42 | 45 | 49 | 53 | 56 | 60 |
| 14 | .05 | 5 | 9 | 13 | 17 | 22 | 26 | 31 | 36 | 40 | 45 | 50 | 55 | 59 | 64 | 67 | 74 | 78 | 83 |
|  | .01 | 1 | 4 | 7 | 11 | 15 | 18 | 22 | 26 | 30 | 34 | 38 | 42 | 46 | 50 | 54 | 58 | 63 | 67 |
| 15 | .05 | 5 | 10 | 14 | 19 | 24 | 29 | 34 | 39 | 44 | 49 | 54 | 59 | 64 | 70 | 75 | 80 | 85 | 90 |
|  | .01 | 2 | 5 | 8 | 12 | 16 | 20 | 24 | 29 | 33 | 37 | 42 | 46 | 51 | 55 | 60 | 64 | 69 | 73 |
| 16 | .05 | 6 | 11 | 15 | 21 | 26 | 31 | 37 | 42 | 47 | 53 | 59 | 64 | 70 | 75 | 81 | 86 | 92 | 98 |
|  | .01 | 2 | 5 | 9 | 13 | 18 | 22 | 27 | 31 | 36 | 41 | 45 | 50 | 55 | 60 | 65 | 70 | 74 | 79 |
| 17 | .05 | 6 | 11 | 17 | 22 | 28 | 34 | 39 | 45 | 51 | 57 | 63 | 67 | 75 | 81 | 87 | 93 | 99 | 105 |
|  | .01 | 2 | 6 | 10 | 15 | 19 | 24 | 29 | 34 | 39 | 44 | 49 | 54 | 60 | 65 | 70 | 75 | 81 | 86 |
| 18 | .05 | 7 | 12 | 18 | 24 | 30 | 36 | 42 | 48 | 55 | 61 | 67 | 74 | 80 | 86 | 93 | 99 | 106 | 112 |
|  | .01 | 2 | 6 | 11 | 16 | 21 | 26 | 31 | 37 | 42 | 47 | 53 | 58 | 64 | 70 | 75 | 81 | 87 | 92 |
| 19 | .05 | 7 | 13 | 19 | 25 | 32 | 38 | 45 | 52 | 58 | 65 | 72 | 78 | 85 | 92 | 99 | 106 | 113 | 119 |
|  | .01 | 3 | 7 | 12 | 17 | 22 | 28 | 33 | 39 | 45 | 51 | 56 | 63 | 69 | 74 | 81 | 87 | 93 | 99 |
| 20 | .05 | 8 | 14 | 20 | 27 | 34 | 41 | 48 | 55 | 62 | 69 | 76 | 83 | 90 | 98 | 105 | 112 | 119 | 127 |
|  | .01 | 3 | 8 | 13 | 18 | 24 | 30 | 36 | 42 | 48 | 54 | 60 | 67 | 73 | 79 | 86 | 92 | 99 | 105 |

## One tail test

| $n_2$ | $\alpha$ | $n_1$ | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | | | | | | |
| 3 | .05 | 0 | 0 | 1 | 2 | 2 | 3 | 4 | 4 | 5 | 5 | 6 | 7 | 7 | 8 | 9 | 9 | 10 | 11 |
| | .01 | -- | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 2 | 2 | 2 | 3 | 3 | 4 | 4 | 4 | 5 |
| 4 | .05 | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 14 | 15 | 16 | 17 | 18 |
| | .01 | -- | -- | 0 | 1 | 1 | 2 | 3 | 3 | 4 | 5 | 5 | 6 | 7 | 7 | 8 | 9 | 9 | 10 |
| 5 | .05 | 1 | 2 | 4 | 5 | 6 | 8 | 9 | 11 | 12 | 13 | 15 | 16 | 18 | 19 | 20 | 22 | 23 | 25 |
| | .01 | -- | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
| 6 | .05 | 2 | 3 | 5 | 7 | 8 | 10 | 12 | 14 | 16 | 17 | 19 | 21 | 23 | 25 | 26 | 28 | 30 | 32 |
| | .01 | -- | 1 | 2 | 3 | 4 | 6 | 7 | 8 | 9 | 11 | 12 | 13 | 15 | 16 | 18 | 19 | 20 | 22 |
| 7 | .05 | 2 | 4 | 6 | 8 | 11 | 13 | 15 | 17 | 19 | 21 | 24 | 26 | 28 | 30 | 33 | 35 | 37 | 39 |
| | .01 | 0 | 1 | 3 | 4 | 6 | 7 | 9 | 11 | 12 | 14 | 16 | 17 | 19 | 21 | 23 | 24 | 26 | 28 |
| 8 | .05 | 3 | 5 | 8 | 10 | 13 | 15 | 18 | 20 | 23 | 26 | 28 | 31 | 33 | 36 | 39 | 41 | 44 | 47 |
| | .01 | 0 | 2 | 4 | 6 | 7 | 9 | 11 | 13 | 15 | 17 | 20 | 22 | 24 | 26 | 28 | 30 | 32 | 34 |
| 9 | .05 | 4 | 6 | 9 | 12 | 15 | 18 | 21 | 24 | 27 | 30 | 33 | 36 | 39 | 42 | 45 | 48 | 51 | 54 |
| | .01 | 1 | 3 | 5 | 7 | 9 | 11 | 14 | 16 | 18 | 21 | 23 | 26 | 28 | 31 | 33 | 36 | 38 | 40 |
| 10 | .05 | 4 | 7 | 11 | 14 | 17 | 20 | 24 | 27 | 31 | 34 | 37 | 41 | 44 | 48 | 51 | 55 | 58 | 62 |
| | .01 | 1 | 3 | 6 | 8 | 11 | 13 | 16 | 19 | 22 | 24 | 27 | 30 | 33 | 36 | 38 | 41 | 44 | 47 |
| 11 | .05 | 5 | 8 | 12 | 16 | 19 | 23 | 27 | 31 | 34 | 38 | 42 | 46 | 50 | 54 | 57 | 61 | 65 | 69 |
| | .01 | 1 | 4 | 7 | 9 | 12 | 15 | 18 | 22 | 25 | 28 | 31 | 34 | 37 | 41 | 44 | 47 | 50 | 53 |
| | .0 | 5 | 9 | 13 | 1 | 21 | 2 | 3 | 34 | 38 | 42 | 47 | 51 | 55 | 60 | 64 | 68 | 72 | 77 |

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | 5 |  |  |  | 7 |  | 6 | 0 |  |  |  |  |  |  |  |  |  |  |  |
| 12 | .01 | 2 | 5 | 8 | 11 | 14 | 17 | 21 | 24 | 28 | 31 | 35 | 38 | 42 | 46 | 49 | 53 | 56 | 60 |
| 13 | .05 | 6 | 10 | 15 | 19 | 24 | 28 | 33 | 37 | 42 | 47 | 51 | 56 | 61 | 65 | 70 | 75 | 80 | 84 |
|  | .01 | 2 | 5 | 9 | 12 | 16 | 20 | 23 | 27 | 31 | 35 | 39 | 43 | 47 | 51 | 55 | 59 | 63 | 67 |
| 14 | .05 | 7 | 11 | 16 | 21 | 26 | 31 | 36 | 41 | 46 | 51 | 56 | 61 | 66 | 71 | 77 | 82 | 87 | 92 |
|  | .01 | 2 | 6 | 10 | 13 | 17 | 22 | 26 | 30 | 34 | 38 | 43 | 47 | 51 | 56 | 60 | 65 | 69 | 73 |
| 15 | .05 | 7 | 12 | 18 | 23 | 28 | 33 | 39 | 44 | 50 | 55 | 61 | 66 | 72 | 77 | 83 | 88 | 94 | 100 |
|  | .01 | 3 | 7 | 11 | 15 | 19 | 24 | 28 | 33 | 37 | 42 | 47 | 51 | 56 | 61 | 66 | 70 | 75 | 80 |
| 16 | .05 | 8 | 14 | 19 | 25 | 30 | 36 | 42 | 48 | 54 | 60 | 65 | 71 | 77 | 83 | 89 | 95 | 101 | 107 |
|  | .01 | 3 | 7 | 12 | 16 | 21 | 26 | 31 | 36 | 41 | 46 | 51 | 56 | 61 | 66 | 71 | 76 | 82 | 87 |
| 17 | .05 | 9 | 15 | 20 | 26 | 33 | 39 | 45 | 51 | 57 | 64 | 70 | 77 | 83 | 89 | 96 | 102 | 109 | 115 |
|  | .01 | 4 | 8 | 13 | 18 | 23 | 28 | 33 | 38 | 44 | 49 | 55 | 60 | 66 | 71 | 77 | 82 | 88 | 93 |
| 18 | .05 | 9 | 16 | 22 | 28 | 35 | 41 | 48 | 55 | 61 | 68 | 75 | 82 | 88 | 95 | 102 | 109 | 116 | 123 |
|  | .01 | 4 | 9 | 14 | 19 | 24 | 30 | 36 | 41 | 47 | 53 | 59 | 65 | 70 | 76 | 82 | 88 | 94 | 100 |
| 19 | .05 | 10 | 17 | 23 | 30 | 37 | 44 | 51 | 58 | 65 | 72 | 80 | 87 | 94 | 101 | 109 | 116 | 123 | 130 |
|  | .01 | 4 | 9 | 15 | 20 | 26 | 32 | 38 | 44 | 50 | 56 | 63 | 69 | 75 | 82 | 88 | 94 | 101 | 107 |
| 20 | .05 | 11 | 18 | 25 | 32 | 39 | 47 | 54 | 62 | 69 | 77 | 84 | 92 | 100 | 107 | 115 | 123 | 130 | 138 |
|  | .01 | 5 | 10 | 16 | 22 | 28 | 34 | 40 | 47 | 53 | 60 | 67 | 73 | 80 | 87 | 93 | 100 | 107 | 114 |

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