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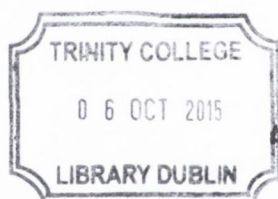
INFRARED IMAGING ANALYSIS OF HAND SKIN TEMPERATURE FOR THERMAL COMFORT ASSESSMENT



Simeon Walsh

A thesis submitted for the degree of Doctor of Philosophy to the
University of Dublin, Trinity College.

2015

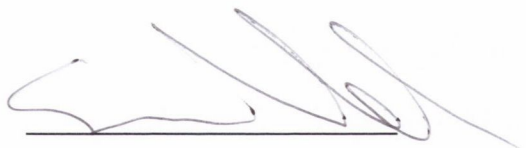


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II. Abstract

Thermal comfort is a subjective sensation of the mind and body which expresses a level of satisfaction with the thermal environment. For years thermal comfort has been studied and external variables such as air temperature and relative humidity have been monitored to find the optimum conditions. Predicted mean vote (PMV) is one of the most accepted measures of thermal comfort. However, PMV is a measure of the average response of a large group, satisfying 95% of occupants at best [1]–[4]. This research aims to relate hand skin temperature to perceived thermal comfort in order to individualise the measurement of thermal comfort.

Tests were performed on participants in a field study in Dublin, Ireland in an environment which was not controlled and the participant was normally seated at a computer. Tests were carried out at the participant's desk where an infrared camera's field of view was on the computer mouse area in order to measure hand skin temperature. Thermal sensation surveys were recorded by the participant and environmental measurements were made.

Automatic processing of infrared images became problematic when skin temperatures were low and near that of the surroundings. In these cases the cold areas of the hands were not recognised by the program. Analysis of the infrared images showed when hand temperature was similar to the temperature of the surroundings, it was not distinguishable from the surroundings. Automatic recognition was abandoned as full hand location data was not available. Low cost infrared cameras have low accuracy ($\pm 2^{\circ}\text{C}$) and hand skin temperatures were found to range broadly (20°C – 37°C). However, the difference in hand skin temperature between a warm and cool thermal sensation was found to be a little as 1°C which is not suitable for use with low cost infrared cameras.

Hand skin temperatures were found to be a better measure of thermal sensation than the environmental variables and the use of these variables in calculations of thermal comfort. Overall Index fingernail temperature showed the highest correlation to thermal sensation with a factor of 0.64 for all participants. Of the environmental variables, operative temperature had a best correlation to thermal sensation with a factor of 0.34.

The results from the study found that the participants could be split into groups based on the hand skin temperature measured and thermal sensation recorded. The data was further split by season as there was significant difference in the hand skin temperature for the same vote of 'neutral' thermal sensation between warm and cool months of the year. Approximate thresholds were found in the entire data set in which recordings of hand skin temperature below 29°C were more likely to have a corresponding thermal sensation of 'slightly cool' or lower. Hand skin temperatures above 34°C were more likely to have a corresponding thermal sensation of 'slightly warm' and warmer. It was found that average hand skin temperature varied between warm and cool months of the year in this study. Average hand skin temperatures in the warm months of the year were found to be higher for each participant than in the cool months of the year for the same recording of thermal sensation. The differences in hand skin temperature were further assessed based on the physiology of the participant. It was noted in the pilot study that participants with higher estimated basal metabolic rate (BMR) were found to have higher hand skin temperature than those with lower BMR.

The infrared camera used in this research is accurate to $\pm 2^{\circ}\text{C}$. In order to assess the hand skin temperature of individuals and reference this to a thermal comfort experienced, an increased accuracy would be necessary given the narrow bands of hand skin temperature to thermal comfort scale. An accuracy of $\pm 0.1^{\circ}\text{C}$ would give a more reliable reading to reference thermal comfort. This research notes some interesting results relating to an individual response of hand skin temperature to seasons and basal metabolic rate. However, further study into these results should consider the inaccuracies of the infrared camera used and concentrate on a more accurate measure of skin temperature. Skin surface sensors on the fingernail area would provide increased accuracy while also providing increased correlation to thermal comfort compared with environmental variables.

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"A good head and good heart are always a formidable combination. But when you add to that a literate tongue or pen, then you have something very special."

— Nelson Mandela

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1. Introduction

Low energy is becoming the norm in society and society is leaning towards a cleaner, greener way of life. With the cost of energy rising both in economic and social cost, offices are being targeted as high energy use environments. High energy use in a modern building is no longer acceptable and offices will need to reduce their consumption of energy.

Occupant comfort becomes less important in reducing energy usage in a building through reduced prioritisation of comfort [5]. Occupants display adaptive behaviour to free running buildings [6]. Economic group has been shown to have an impact on acceptable comfort ranges [7]. Occupants show quick adaptation to climate in climate chamber experiments [8]. Thermal comfort being subjective is difficult to quantify in a way which can satisfy all occupants. Predicted mean vote (PMV) has a component called Predicted Percentage Dissatisfied (PPD) in which the best result is 5% of occupants dissatisfied with their environment [1].

If one could directly measure and not predict, like many of the models used today [1], [3], [9]–[11], the thermal comfort of occupants in an indoor environment then the thermal environment could be adjusted to suit the occupants. Direct measurement would involve intrusive measurement devices, surveys, temperature probes on skin or nonintrusive methods such as measurement of facial temperatures using infrared [12] or the method described in this thesis using infrared cameras to measure hand skin temperature.

Current building management software has taken great steps to improve energy efficiency and adjust to allow for occupant centred control [9], [13]–[15]. However, these systems predict based on models the thermal comfort of occupants.

This research aims to directly measure comfort of individuals in an office environment using infrared imaging of skin temperature. By measuring hand skin temperature this research will be able to determine occupant comfort and effect a change in the building management system.

When the thermal comfort of each occupant in a known space is assessed then building management software can make informed energy saving decisions. For those outside of a mean comfort grouping direct heating/cooling options can be explored.

1.1.Research Objectives

The objectives of this PhD research thesis are as follows:

1. To investigate alternative options of measuring thermal comfort and comparing them to existing measurements.
2. To use infrared cameras to determine the position of hands in the field of view and automatically determine the temperature of each part of the hand.
3. To establish a relationship between hand skin temperature and thermal comfort.
4. Examine the differences between participants in a study and differences in thermal sensation and hand skin temperature recorded.
5. To investigate any changes in hand skin temperature throughout a calendar year which participants may present to the same conditions of thermal sensation.

2. Literature Review

2.1. Indoor Environment Quality

Indoor environmental quality (IEQ) is the quality of a building's environment in relation to health and wellbeing of those who occupy the space. IEQ is determined by many factors including lighting, air quality, air and radiant temperature and damp conditions. Indoor environments are highly complex and occupants can be exposed to a number of contaminants such as gases or particles from the normal operation of the building. Buildings can accrue dust, mould, spores and other particles which would be swept away by wind in a space that wasn't closed off from the outside environment. Factors such as air temperature, relative humidity, ventilation, radiant temperature, lighting, building material, heating and cooling systems have been shown to impact on the occupants response to the indoor environment [16].

The thermal environment of indoor spaces has long been altered by occupants, going as far back as the discovery of fire used to warm the early humans. Humans have come a long way since then and Humans have attempted to control the thermal environment of indoor spaces ever since in an attempt to improve the occupants' reception of the environment. The thermal environment can be linked to productivity [17], [18] and has been shown to have health implications [19], [20]. A number of ISO documents have been written in order to control, assess and describe the thermal environment [1], [21], [22]. Thermal comfort has changed over the years in terms of how important it is, the most recent iteration of thermal comfort was brought on in 1967 by Fanger [23].

2.1.1. Indoor Air Temperature

Indoor air temperature (T_{air}) determines convective heat dissipation. Air movement increases convection heat transfer and increases evaporation from the skin. When a simple system of environment control is used T_{air} is the sole variable which is measured in order to maintain an environment. In most offices and domestic dwellings, air temperature is the only variable measured as it is generally the easiest to measure. Niemelä et al in 2002 investigated the labour productivity in a call centre and the effect air temperature had on productivity [17]. Niemelä et al found that productivity fell by 5-7% with increased indoor air temperature. Lan et al investigated further the impact of T_{air} on wellbeing,

workload and productivity. It was found that high or low indoor air temperatures led to a negative effect on productivity [18].

2.1.2. Mean Radiant temperature (MRT)

The mean radiant temperature, MRT, is the uniform temperature of imaginary enclosure in which radiant transfer from the human body is equal to the radiant heat transfer in the actual non-uniform enclosure. The net amount of radiant heat exchanged by a body is the algebraic sum of all the radiant fluxes exchanged by exposed parts to the body [21].

MRT cannot be measured directly but can be measured by using a globe thermometer. A globe thermometer is simply a temperature probe inside a matt black sphere. When air velocity is zero the globe temperature, T_{globe} , is equal to MRT. When air velocity has to be considered an equation for use with air velocity has been found to calculate MRT [21].

On warm sunny days the effect of MRT is more pronounced while on cool days the influence of MRT is reduced. This is due to clothing insulation factor changes depending on seasons [16]. On a sunny day or in a warm climate, humans wear lighter clothing and less clothing generally. The effect of MRT is greater since the clothing insulation is lower and more radiant energy from the environment can impact more on the skin. MRT and air temperature are coincident in a normal operating environment. Humphreys et al in 2002 investigated large datasets of thermal comfort from around the world. MRT and air temperature was found to have a very small difference of mean absolute difference 0.5 K [2]. Simone et al in 2009 researched the link of air temperature and MRT to see if a person prefers a certain combination of MRT and air temperature. A correlation between thermal sensation vote (TSV) and thermal preference on combinations of MRT and air temperature could not be found. The PMV index was shown to be a good estimation of TSV when the air temperature and MRT were the same but showed an error of up to 1 scale TSV unit when air temperature and MRT were different [24]. The further MRT is from the measured air temperature the more PMV becomes erroneous. The measurement of MRT is important in the environment as otherwise it must be assumed that MRT and air temperature are the same.

2.1.2.1. Black Globe Thermometer

A black globe thermometer is a black conductive sphere into which is placed a temperature sensor. The temperature sensor can be of any type and logging this data electronically is possible. The globe should be made of a highly conductive material in order to avoid losses in the transfer of external radiation to the internal surface. The thickness of the globe surface should be as thin as possible to increase radiation transfer.

The external surface is designed to absorb the radiation from the walls of the enclosure it is placed in. In order to avoid radiation dispersal of the globe it should be painted black with a matt finish.

Black globe thermometers can be used to calculate mean radiant temperature, MRT, by placing the globe in the environment to be measured. The globe approaches a thermal balance under the effect of the radiation exchanges of the globe surface and the external surfaces of the environment. This thermal balance allows MRT to be calculated from the temperature given by the sensor within the globe. Temperature within the globe and temperature of the inner surface are approximately equal.

ISO 7726;2001 details the measurement of globe temperature and the balance equation becomes [21]

$$q_r + q_c = 0$$

where

q_r is the heat exchange by radiation between the walls of the enclosure and the globe, W/m^2

q_c is the heat exchange by convection between air and globe, W/m^2

The heat transfer by radiation between the walls of the enclosure and the globe is a given as the difference in radiations of each,

$$q_r = \varepsilon_g \sigma (\overline{T_r}^4 - T_g^4)$$

where

ε_g is the emissivity of the black globe (no dimension, values between 0 and 1)

σ is the Stefan-Boltzmann constant, $\text{W/m}^2 \text{K}^4$ ($5.67 \times 10^{-8} \text{ W/m}^2 \text{K}^4$)

$\overline{T_r}$ is mean radiant temperature, K

T_g is temperature of black globe, K.

The heat transfer by convection equation is given by

$$q_c = h_{cg}(T_a - T_g)$$

where

h_{cg} is the coefficient of heat transfer by convection, $\text{W/m}^2 \text{K}$

For natural convection

$$h_{cg} = 1.4 \left(\frac{\Delta T}{D} \right)^{\frac{1}{4}}$$

where

D is the diameter of the globe

The thermal balance equation becomes

$$\varepsilon_g \sigma (\overline{T}_r^4 - T_g^4) + 1.4 \left(\frac{\Delta T}{D} \right)^{\frac{1}{4}} (T_a - T_g) \quad (2-1)$$

By natural convection in the case of a standard globe $D=0.15\text{m}$, $\varepsilon_g = 0.95$ (matt black paint) then

$$\overline{T}_r = \left[T_g^4 + 0.4 \times 10^8 |T_g - T_a|^{1/4} \cdot (T_g - T_a) \right]^{1/4} \quad (2-2)$$

By forced convection in the case of a standard globe $D=0.15\text{m}$, $\varepsilon_g = 0.95$ (matt black paint) then

$$\overline{T}_r = \left[T_g^4 + 2.5 \times 10^8 \times V_a^{0.6} \times (T_g - T_a) \right]^{1/4}$$

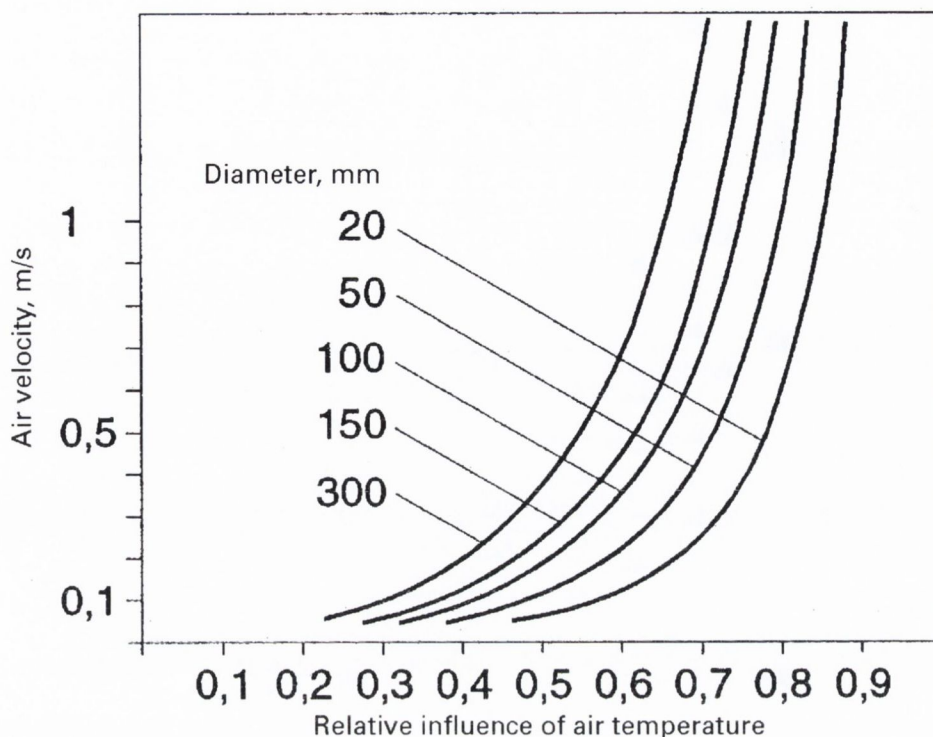


Fig. 2-1 Relative influence of air temperature on mean radiant temperature for various sizes of globe diameter [21]

2.1.3. Relative Humidity

Relative humidity (RH) may be defined as the ratio of the water vapour density (mass per unit volume) to the saturation water vapour density, usually expressed in percent. It is the ratio of current absolute humidity to the maximum absolute humidity which depends on air temperature. The warmer air is the more water vapour the air can hold. When humidity is at 100% the air is totally saturated with water vapour and if cooled from the current temperature water would condense. Humans are sensitive to humidity as skin relies on evaporation of moisture to cool the body. With increased humidity comes decreased evaporation as the air is laden with more water vapour as higher relative humidity. In 1993, Palonen et al investigated the effects of air temperature and relative humidity on thermal comfort of sedentary office workers [25]. It was found that in the normal range of RH in an office environment 30-60%, the effect of RH was minimal. For an increase of 10% of RH was found to be equivalent to a 0.4°C increase in air temperature.

2.1.4. Air Speed

Air speed or relative air velocity affects the rate of convective heat transfer and evaporative losses through sweat of occupants in a thermal environment. Increased relative air velocity leads to increased heat transfer and evaporation.

Predicted mean vote (PMV) has been shown to only be accurate for relative air velocities between 0 m/s and 1 m/s [1].

<0.1 m/s	Stuffy
To 0.2	Unnoticed
To 0.5	Pleasant
To 1	Awareness
To 1.5	Draughty
>1.5	Annoying

Fig. 2-2 Subjective reaction to air movement [16]

Air movement creates subjective reactions as shown in Fig. 2-2. Increased air movement starts to distract the occupant and cause decreased comfort while hardly any air movement creates a 'stuffy' environment where supply of fresh air is negligible. Air movement or ventilation is used to supply fresh air, remove smells, CO₂ and other contaminants, and remove heat from a building and to promote heat dissipation of the skin. The human body needs heat dissipation to operate correctly as metabolic processes occur within the human body which generate heat.

2.2.Control of the Environment

Control of the thermal environment is a desirable feature of most office buildings. The last several decades have shown that control of the indoor environment has become an important industry. Control of the indoor environment has been around for centuries. Mahdavi et al, 1996, note that this development is under two basic assumptions the total environmental control is possible and maintaining a predefined set of environmental conditions assures comfort of the occupants of the environment [26].

Mahdavi et al note that attempts to control the environment are mostly developed from measuring an environmental variable and correlating said variable with people's perception and evaluation of thermal comfort. The other trend is development of the thermal comfort model which involves identification of an increasing number of comfort relevant indices and their refinement.

Using these control indices of thermal comfort no allowance is made for situations when a person feels pleasantly warm or cool and doesn't require change. Mahdavi et al notes that all indices and control mechanisms try to achieve thermal neutrality, a one dimensional state. Mahdavi admits that pleasantness is difficult to define let alone measure. The author concludes that HVAC technology is 'rather unsatisfactory'. Uniform thermal conditions throughout a building are inherently problematic. HVAC technology relies on thermal comfort science which is still limited. A centrally controlled building has in many instances not provided an environment which satisfies the narrow set of predefined figures that thermal comfort science defines. HVAC wastes energy and is a 'brute force' solution [26].

2.2.1. Thermal Comfort System developed by Fanger (1970)

In 1970 P.O. Fanger developed an equation used to determine the thermal comfort of a large group of people based on a heat transfer balance equation [4]. Fanger took the view that it is the combined thermal effect of all physical factors which is of prime importance in determining the thermal state of a human. Fanger developed, by means of a comfort equation, all combinations of variables which will create thermal comfort. The comfort equation, known as predicted mean vote (PMV), uses air temperature, mean radiant temperatures, relative humidity, air velocity, clothing insulation and activity to determine the thermal comfort of an occupant in an environment.

Evaluation of thermal comfort has been studied in depth [4][3][2][27]. The accuracy of PMV has often been questioned and has been shown to be erroneous in certain situations [2]. There are many standards such as ASHRAE scale, preference scale, PMV, PPD and

others including many international standards including ISO 7730 and ASHRAE standard 55, some of which use the comfort equation developed by Fanger. Predicted Mean Vote (PMV) has been adopted by many [3][2][27] was developed by Fanger [4]. PMV predicts the response of occupants based on the conditions and is a derivative from heat transfer physics and fit to human sensation, see equation (2-3):

$$PMV = [0.303e^{\{-0.036M\}} + 0.028]E_{st} \quad (2-3)$$

where

E_{st} is the rate of increase of energy stored within the body

M is the metabolic rate, in watts per square metre (W/m^2)

and

$E_{st} =$ Metabolic rate – mechanical power – skin difference loss – sweat loss – latent respiration loss – dry respiration loss – radiative heat loss – convective heat loss.

$$\begin{aligned} E_{st} = \{ & (M - W) - 3.05 \cdot 10^{-3} \cdot [5733 - 6.99 \cdot (M - W) - P_a] - 0.42 \\ & \cdot [(M - W) - 58.15] - 1.7 \cdot 10^{-5} \cdot M \cdot (5867 - P_a) \\ & - 0.0014 \cdot M \cdot (34 - T_a) - 3.96 \cdot 10^{-8} \cdot f_{cl} \\ & \cdot [(t_{cl} + 273)^4 - (\bar{t}_r + 273)^4] - f_{cl} \cdot h_c \cdot (t_{cl} - t_a) \} \end{aligned} \quad (2-4)$$

$$\begin{aligned} t_{cl} = & 35.7 - 0.028 \cdot (M - W) - I_{cl} \cdot \{3.96 \cdot 10^{-8} \cdot f_{cl} \\ & \cdot [(t_{cl} + 273)^4 - (\bar{t}_r + 273)^4] + f_{cl} \cdot h_c \cdot (t_{cl} - t_a) \} \\ h_c & \end{aligned} \quad (2-5)$$

$$= \begin{cases} 2.38 \cdot |t_{cl} - t_a|^{0.25} \\ 12.1\sqrt{v_{ar}} \end{cases} \quad for \quad \begin{cases} 2.38 \cdot |t_{cl} - t_a|^{0.25} > 12.1\sqrt{v_{ar}} \\ 2.38 \cdot |t_{cl} - t_a|^{0.25} < 12.1\sqrt{v_{ar}} \end{cases}$$

$$f_{cl} = \begin{cases} 1.00 + 1.290I_{cl} \\ 1.05 + 0.645I_{cl} \end{cases} \quad for \quad \begin{cases} I_{cl} \leq 0.078 \, m^2 \cdot K/W \\ I_{cl} > 0.078 \, m^2 \cdot K/W \end{cases} \quad (2-6)$$

where

W is the effective mechanical power, in Watts per square metre (W/m^2);

I_{cl} is the clothing insulation, in square metres Kelvin per Watt ($m^2 \cdot K/W$);

f_{cl} is the clothing surface area factor;

- t_a is the air temperature, in degrees Celsius ($^{\circ}\text{C}$);
- $\bar{t}_r$ is the mean radiant temperature, in degrees Celsius ($^{\circ}\text{C}$);
- v_{ar} is the relative air velocity, in metres per second (m/s);
- p_a is the water vapour partial pressure, in Pascal (Pa);
- h_c is the convective heat transfer coefficient, in watts per square metre Kelvin
[W/($\text{m}^2 \cdot \text{K}$)];
- t_{cl} is the clothing surface temperature, in degrees Celsius ($^{\circ}\text{C}$), determined iteratively by estimating initially.

Research into the PMV equation, as given in ISO 7730;2005 [1], shows that the accuracy of PMV breaks down outside of normal parameters. The following constraints on the variables should be considered in the application of PMV

- M 46W/ m^2 to 232 W/ m^2 (0.8 to 4 met);
- I_{cl} 0 $\text{m}^2 \cdot \text{K/W}$ to 0.310 $\text{m}^2 \cdot \text{K/W}$;
- t_a 10 $^{\circ}\text{C}$ to 30 $^{\circ}\text{C}$;
- $\bar{t}_r$ 10 $^{\circ}\text{C}$ to 40 $^{\circ}\text{C}$;
- v_{ar} 0 m/s to 1m/s;
- p_a 0 Pa to 2,700 Pa;

The equations for t_{cl} and h_c can be solved by iteration and is usually carried out by a computer program. The iteration is used since the equations for t_{cl} and h_c are interdependent. Iteration to find h_c finishes once the answers for the current iteration and the previous iteration approach the same value, convergence. Then t_{cl} can be found using the value for h_c

The result of the equation of PMV predicts the mean response of a large group of people according to the thermal sensation scale:

- +3 hot
- +2 warm
- +1 slightly warm

0	neutral
-1	slightly cool
-2	cool
-3	cold

Values for the PMV scale vary between +3 and -3 and calculation of PMV usually gives a decimal number within the scale. It should be noted that values approaching -3, +3 and beyond are not accurate and PMV is not suited to these environments indicated by previous research [2].

Predicted percentage dissatisfied, PPD, was developed alongside the PMV equation to show the expected dissatisfaction of occupants with the environment. PPD predicts a percentage of dissatisfaction based on the PMV calculated in order to predict the number of occupants which will express discomfort in a given environment [1].

$$PPD = 100 - 95 e^{-(0.03353 PMV^4 + 0.2179 PMV^2)}$$

The PMV and PPD for predicting thermal comfort are well established and used extensively [3], [28], [29]. However, all equations and systems only predict the thermal comfort and do not actually measure it. In order to measure thermal comfort the occupant is interrogated as to feelings of thermal comfort which is intrusive. If office workers were to complete comfort surveys every 5 minutes, productivity might suffer. PMV and PPD use a number of variables in which the measurement of these variables have inherent errors.

A system that could measure thermal comfort of individual occupants without input from the individual and present to the building management system could adjust its settings according to a mean comfort rating. Direct heating/cooling options could be employed for those occupants outside of reasonable comfort.

PMV assigns a number based on a mean vote which describes the environment as between -3 (cool) to 0 (neutral) to 3 (hot). Discrepancies have been reported in PMV [2] illustrating that it is misleading in mean comfort votes of groups of people in buildings. A practical consequence of the discrepancy is in warm environments. In this scenario PMV has been shown to overestimate the mean vote of occupants, which can lead to increased cooling in buildings.

2.2.2. ASHRAE Scale and Preference Scale

The ASHRAE scale was developed by the American Society of Heating Refrigeration and Air-conditioning Engineers. It is a simple scale which interrogates an occupant of an environment by asking the occupant how they feel. Occupants respond by marking the sensation closest to what they most likely feel. Wang et al, 2007 [30], used a modified version of the ASHRAE scale which included 'very hot' and 'very cold'. Each participant in the study was allowed to mark sensation on an analogue scale in which the participant was allowed to give a thermal sensation between two feelings on the ASHRAE scale. Preference scale is much like ASHRAE scale in simplicity and interrogates the subject further in preference of the thermal environment. Preference scale indicates the thermal environment which the occupant would prefer.

How do you feel at this time?		I would prefer to be:	
Hot	7	Much cooler	5
Warm	6	A bit cooler	4
Slightly warm	5	No change	3
Neutral	4	A bit warmer	2
Slightly Cool	3	Much warmer	1
Cool	2		
Cold	1		

Table 2-1 ASHRAE scale and thermal preference scale

The ASHRAE scale and thermal preference scale is another device for measuring thermal comfort by direct interrogation of the subject (Table 2-1). While useful in the research environment, it is impractical to interrupt a worker in the office environment.

2.2.3. Thermal Comfort Measurement in Buildings

Baker et al, 1996 investigated thermal comfort in free running buildings [6]. With growing demand for air-conditioned buildings and electrical energy, Baker aimed to develop comfort criteria appropriate to free-running buildings where environmental conditions are likely to vary more than in mechanically controlled buildings. Baker attempted to debate the differences between observed responses from field studies and predicted comfort responses based on comfort theory.

Two campaigns in 1993 and 1994 were carried out in Athens, Greece where surveys and data were collected summing in 1500 hours of data. PASCOOL comfort surveys were gathered along with environmental variables. The surveys showed that personal differences in room temperature could be as low as 1.5°C below the average room

temperature. Baker found that clothing adjustments were made in a number of cases in order to improve thermal comfort. Baker noted that cold drinks were used as a method of thermal balance in the hot environment [6].

Baker noted that adaptive opportunities existed for the subjects in the study which the predicted mean vote (PMV) does not take into account such as taking of a cold or hot drink and opening closing of windows. In this case PMV and other comfort equations would need to take account of the adaptive opportunities. Since PMV is a heat balance equation it would need adaptation to account for drinks consumed, which Baker considers a cold drink can (330ml) to be worth 12W of cooling (10% reduction in metabolic rate). Baker considered the adaptive responses of subject in the studies and recommended that buildings be designed to provide adaptive opportunity as it will increase overall thermal comfort.

Vrecko et al, 2009 developed an algorithm for calculating the optimal reference temperature in buildings [13]. The algorithm was developed to reduce energy use in unoccupied rooms and recover the temperature of the room back to a defined value by the time the room is occupied again. The algorithm was utilised on six rooms in a simulated hotel. TRNSYS software was used to design the building which was simulated in the town of Portoroz, Slovenia. The weather data was input into the model for a period of one year. When rooms were vacant the room environment is not controlled. When the occupancy is known the room is adjusted to the defined temperature. The algorithm proposed was tested in TRNSYS for various levels of occupancy and knowledge of occupancy. 22°C was the reference temperature to be reached on a heating cycle and 25°C was for the cooling cycle.

The results of the simulation indicate that the algorithm was successful in reduction of energy use by up to 10% where the occupancy is known in advance. When the occupancy is not known in advance the energy saving was found to be 5%.

Vrecko et al utilise a successful algorithm in the simulation. Energy savings are made but the main energy saving (10%) is only made on known occupancy of the rooms. This simulation was made in a hotel type situation. In an office type building the same savings might be negligible based on known advance occupancy as an office is often open plan. The simulation only used weather data for Slovenia. Such savings in energy may not transfer to other locations. The research carried out by Vrecko is solely concerned with simulation and no real field study has taken place. It is difficult to confirm the real world energy savings which could be made [13].

Paul et al, 2007 investigated the hypothesis that 'green' buildings have a better indoor environment quality than conventional buildings [5]. Comfort and satisfaction tests of university buildings were carried out on two conventional and one 'green' building in south-east Australia.

The 'green' building was constructed from rammed earth and recycled materials, the building was naturally ventilated. The conventional buildings were temperature controlled by heating ventilation and air conditioning (HVAC) systems.

The climates of all buildings in the study were a Mediterranean type climate with cool wet winters and hot dry summers. The participants in the study were observed via a voluntary questionnaire. The response rate in all buildings was approximately the same. Variables such as temperature, satisfaction with work environment, occupation and age were recorded.

Warren reported the results from the study showed that it was the 'green' building in which participants were more likely to perceive the environment as warm at a time when the outdoor temperature is high. It was later discovered that the 'green' building was not completely operational and retrofitting of insulation to the roof was recommended. Warren compared buildings in a field type study in which the buildings were different in control scheme. No evidence was found to substantiate the claims that green buildings are more comfortable than standard HVAC buildings. However, the study did confirm that thermal comfort influences overall satisfaction with the thermal environment [5].

Indraganti et al, 2010 investigated the effects of age, gender, economic group and tenure on thermal comfort in residential buildings in the hot and dry climate of India [7]. The field study was conducted in 2008 with over 100 subjects and analysed for the different groups.

The surveys were carried out during May, June and July in 2008 in Hyderabad, India. Apartments were used as the test bed for the study. All subjects were Indian nationals. Four environmental variables were measured: air temperature, globe temperature, relative humidity and air velocity. The subject filled in a questionnaire at the same time. Clothing insulation was approximated based on the clothing worn at the time of the test. Insulation of the seat material was also approximated.

The results from this field study found that thermal sensation of older people was slightly lower than that of the young whom Indraganti reasoned was because of lower metabolic rate and sedentary lifestyle of the older people in the study. Gender was not found to be a

significant factor in thermal sensation. However, women were found to have a different perception of the thermal environment as they spent longer hours at 'home'.

Indraganti investigated the comfort of respondents over three months of the year. A more exhaustive study may involve the entire year in order to improve the accuracy of the results noted. Work was also carried out on the indoor air quality sensation which was found to correlate poorly with thermal comfort, despite the number of foul smells in some buildings.

2.2.4. Alternatives to PMV for assessment of thermal comfort

Air temperature is frequently used as a general measure of thermal comfort. It is frequently the only measured variable in the office environment as it is approximately the same as operative temperature and mean radiant temperature in most steady state conditions [31]. Niemelä et al used air temperature to determine comfort of call centre workers and productivity associated with their perceived comfort [17]. Cui et al used air temperature to determine what part it has on thermal comfort motivation and performance [32]. In his experiments Cui found that between 22°C and 26°C was optimum air temperature for carrying out a memory task.

Sekhar et al used air temperature and humidity jointly with ASHRAE charts to determine thermal comfort of people in tropical office buildings [33]. Sekhar found that there was potential saving in energy cost of cooling a tropical building from higher space temperatures. Sekhar used the ASHRAE space temperature charts and comfort diagrams to determine an environment which would produce satisfaction. Rather than concentrate on one variable such as air temperature, operative temperature and humidity was considered in satisfying the acceptable range of the chart.

Fig. 2-3 shows one such chart which shows an acceptable range of operative temperature and humidity for winter and summer based on a set of conditions. Sekhar used higher operative temperatures and lower humidity levels to make the environment more acceptable rather than increasing the cooling load on in a more humid environment.

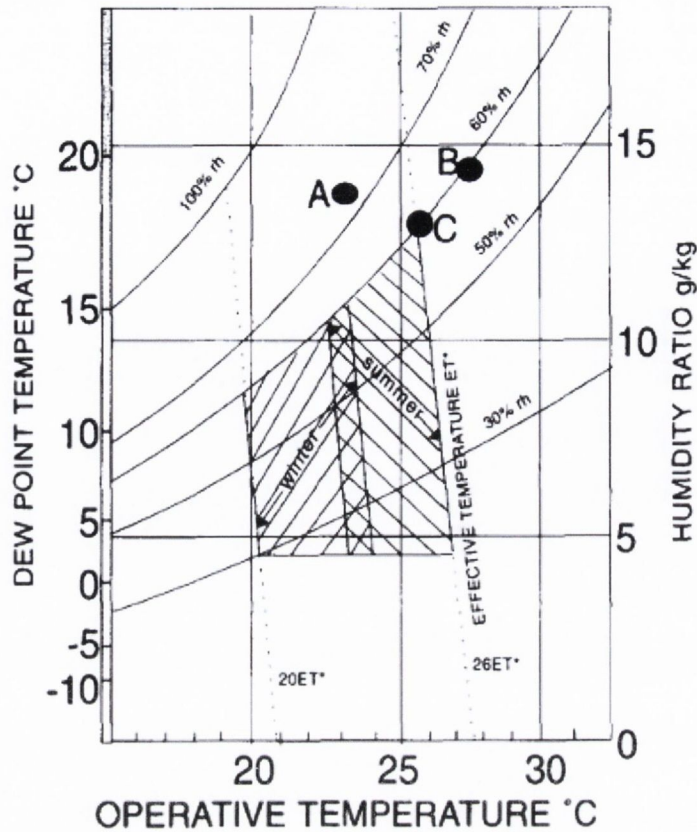


Fig. 2-3 Acceptable ranges of operative temperature and humidity for people in typical summer and winter clothing during light, primarily sedentary activity (1.2 met). The ranges are based on a 10% dis-satisfaction criterion. A: typical space condition found in Singapore -- consequence of tropical climate and conventional coil sections. B: de Dear's thermal acceptability in Singapore -- from climate chamber studies. C: proposed space condition for Singapore -- achievable by an alternative cost effective energy efficient method of coil selection, Sekhar et al [33]

The method Sekhar et al employed, used the ASHRAE charts to work out thermal comfort under a number of assumptions of clothing and assumes there will be 10% dissatisfaction with the environment. The method is for the general populous and becomes inaccurate when used for a single person, as does PMV.

Sherman et al in 1985 developed a simplified model based on the original research by Fanger of PMV [34]. Sherman used a simplified solution to allow calculation of PMV and effective temperature are linear in the air temperature and mean radiant temperature, quadratic in the dew point and avoid iterations necessary in Fanger's method of PMV calculation.

Sherman used simple convection coefficients instead of Fanger's iterative one. Sherman found that the direct calculation of coefficient would give the same results for most indoor environments but not all. Sherman also decided to use dew point in which he says would produce very little extra uncertainty in the prediction of thermal comfort.

In derivation of a simplified model, Sherman has made PMV a far more accessible calculation but has however introduced some uncertainty and error from making assumptions. In certain cases the simplified solutions will not work, which the author admits, but are rare situations.

The Chartered Institution of Building Service Engineers (CIBSE) published Environmental Design: Guide A in 2006, 7th edition [35]. In this document factors affecting thermal comfort are considered to be air temperature, mean radiant temperature, relative air speed humidity and the personal factors being clothing and metabolic rate. In the design document PMV PPD developments in ISO 7730 [1] are discussed. A table of recommended comfort conditions are given for each environment such as Banks, Churches, and Dwellings etc.

For offices, an operative temperature of 21-23°C for winter and 22-24°C in summer is recommended under the assumption that clothing and activity levels are static. The guide also recommends a suggested air supply per person, noise and illumination for the environment.

The basis of these comfort conditions is from the PMV equation in which assumptions of clothing, activity (metabolic rate), air speed and humidity are made. Operative temperature combines air and mean radiant temperatures. The assumptions assume a PMV of ± 0.5 . The proportion of people dissatisfied at this level of accuracy is still 10% at the best of cases. This is assuming that metabolic and clothing assumptions are correct, which may not always be the case. 10% is still a large amount of dissatisfied office occupants.

De Dear et al, 1998 developed an adaptive thermal comfort model in which simple variables were used to predict thermal comfort [8]. De Dear proposed a variable temperature standard based on an adaptive approach. 21,000 sets of data from 160 buildings were collected in order to build this new standard.

De Dear used the raw data collected to conduct a meta-analysis of the human subjective response to indoor climate and how it interacted with the outdoor meteorological factors. Thermal neutrality is the operative temperature that most closely corresponds with a mean thermal sensation vote of zero. Thermal neutrality showed an adaptive relationship with

mean indoor temperatures. This relationship was found to be stronger in free running buildings than in mechanically controlled buildings. De Dear found that people reduced clothing insulation values based on increasing outdoor temperatures and vice versa. De Dear found that in winter 90% of thermal acceptance was given as $22.5^{\circ}\text{C} \pm 1.2^{\circ}\text{C}$ while in summer the figure was $23.5^{\circ}\text{C} \pm 1.2^{\circ}\text{C}$. For naturally ventilated buildings, general acceptability was found to have a wider range for 90% acceptance.

De Dear noted that there were discrepancies in the calculation of PMV leading to high levels of error. In development of the optimum temperatures for both free running and ventilated buildings a simpler measure was developed. Thermal acceptability was still only considered to be 90% at the highest value. This acceptance excluded local discomforts, which ASHRAE standard 55 has detailed as being another 10% of occupants [31]. De Dear leaves 20% of occupants outside thermal acceptance criteria. PMV and Operative temperature offer the same level of error in calculation of overall thermal comfort. Individual measurement of thermal sensation has yet to employed in thermal acceptance of the environment [1], [31].

There are a number of indices for measurement of thermal comfort. Carlucci et al [36] describe some known indices for thermal comfort in Table 2-2, from 1905 to 2010. Individual references are listed in Appendix 9.3. Each index uses a measure of temperature, humidity or other environment or personal variable, such as clothing, to determine a measure of thermal comfort. In each index a prediction of comfort is made. There is no direct measure of a person's thermal comfort save for the direct interpretation of the individual.

Year	Index name	Author(s)
1905	Wet-bulb temperature (WBT)	Haldane [A.1]
1916	Katathermometer	Hill et al. [A.2]
1923	Effective temperature (ET)	Houghton and Yaglou [A.3]
1929	Equivalent temperature (T_{eq})	Dufton [A.4]
1930	Globe-thermometer temperature (GtT)	Vernon [A.5]
1932	Corrected effective temperature (CET)	Vernon and Warner [A.6]
1935	Thermo integrator	Winslow et al. [A.7]
1937	Operative temperature (OpT)	Winslow et al. [A.8]
1937	Humiture	Hevener [A.9]
1941	Standard operative temperature ($SOptT$)	Gagge [A.10]
1945	Thermal acceptance ratio (TAR)	Ionides et al. [A.11]
1945	Index of physiological effect (Ep)	Robinson et al. [A.12]
1945	Wind chill index (WCI)	Siple and Passel [A.13]

Year	Index name	Author(s)
1946	Corrected effective temperature (CET)	Bedford [A.14]
1947	Predicted 4-hour sweat rate (P4SR)	McArdel et al. [A.15]
1948	Resultant temperature (RT)	Missenard et al. [A.16]
1950	Craig index (I)	Craig [A.17]
1955	Heat stress index (HSI)	Belding and Hatch [A.18]
1957	Wet-bulb globe temperature (WBGT)	Yaglou and Minard [A.19]
1957	Oxford index (WD)	Lind and Hallon [A.20]
1958	Thermal strain index (TSI)	Lee [A.21]
1959	Temperature-humidity index (THI)	Thom [A.22]
1959	Equatorial comfort index	Webb [A.23]
1960	Index of physiological strain (Is)	Hall and Polte [A.24]
1960	Humiture revisited	Lally and Watson [A.25]
1961	Cumulative discomfort index (Cum DI)	Tennenbaum et al. [A.26]
1962	Cumulative effective temperature (Cum ET)	Sohar et al. [A.27]
1962	Index of thermal stress (ITS)	Givoni [A.28]
1966	Heat strain index (corrected) (HSI)	McKarns and Brief [A.29]
1966	Prediction of heart rate (HR)	Fuller and Brouha [A.30]
1967	Effective radiant field (ERF)	Gagge et al. [A.31]
1970	Predicted mean vote (PMV)	Fanger [A.32]
1970	Prescriptive zone	Lind [A.33]
1971	New effective temperature (ET*)	Gagge et al. [A.34]
1971	Wet globe temperature (WGT)	Botsford [A.35]
1971	Humid operative temperature	Nishi and Gagge [A.36]
1971	Apparent temperature (AT)	Steadman [A.37]
1972	Predicted body core temperature	Givoni and Goldman [A.38]
1972	Skin wettedness	Kerslake [A.39]
1973	Predicted heart rate	Givoni and Pandolf [A.40]
1974	Standard effective temperature (SET)	Gonzales et al. [A.41]
1978	Skin wettedness	Gonzales et al. [A.42]
1979	Fighter index of thermal stress (FITS)	Nunneley and Stribley [A.43]
1979	Humidex	Masterton and Richardson [A.44]
1979	Apparent temperature (AT)	Steadman [A.45]
1980	Equivalent uniform temperature (EUT)	Wray [A.46]
1981	Effective heat strain index (EHSI)	Kamon and Ryan [A.47]
1982	Predicted sweat loss (msw)	Shapiro et al. [A.48]
1982	Humisery	Weiss [A.49]
1982	Humiditure	Weiss [A.49]
1984	Munich energy balance model for individuals (MEMI)	Höppe [A.50]
1985	Skin temperature energy balance index (STEBIDEX)	De Freitas [A.51]
1985	Heat budget index (HEBIDEX)	De Freitas [A.51]
1986	Predicted mean vote (modified) (PMV*)	Gagge et al. [A.52]
1987	Survival time outdoors in extreme cold (STOEC)	De Freitas and Symon [A.53]
1987	Tropical summer index (TSI)	Bureau of Indian Standards [A.54]

Year	Index name	Author(s)
1987	Summer simmer index (SSI)	Pepi [A.55]
1988	Wind chill-equivalent temperature (WET)	Beshir and Ramsey [A.56]
1989	Required sweating (SWreq)	ISO 7933 [A.57]
1994	Man–environment heat exchange model (MENEX)	Blazejczyk [A.58]
1996	Cumulative heat strain index (CHSI)	Frank et al. [A.59]
1998	Physiological strain index (PSI)	Moran et al. [A.60]
1998	Modified discomfort index (MDI)	Moran et al. [A.61]
2000	New summer simmer index (new SSI)	Pepi [A.62]
2001	Environmental stress index (ESI)	Moran et al. [A.63]
2002	CIBSE Guide J criterion	CIBSE [A.64]
2005	Wet-bulb dry temperature (WBTD)	Wallace et al. [A.65]
2005	Relative humidity dry temperature (RHDT)	Wallace et al. [A.65]
2005	Percentage outside range	ISO 7730 [A.66]
2005	Degree-hour criterion	ISO 7730 [A.66]
2005	PPD-weighted criterion	ISO 7730 [A.66]
2005	Average PPD	ISO 7730 [A.66]
2005	Cumulative PPD	ISO 7730 [A.66]
2006	CIBSE Guide A criterion	CIBSE [A.67]
2007	Degree-hour criterion (modified)	EN 15251 [A.68]
2008	Overheating risk	Robinson and Haldi [A.69]
2008	Overheating risk	Nicol et al. [A.70]
2010	Exceedance _M	Borgeson and Brager [A.71]

Table 2-2 Indices for Thermal Comfort, Carlucci et al [36]

2.2.5. Personalised Thermal Comfort

Jazizadeh et al, 2013 developed a thermal preference scale for personalised comfort profile identification [37]. The author proposes integrating thermal preference data from a building user into a HVAC system in real time. A field experiment was developed and a proposed sensation scale was found to outperform the five level ASHRAE thermal sensation scale.

Jazizadeh et al used a feedback system which the building user input information on location and thermal preference into a mobile device or computer. The user would vote on the thermal preference using a scale on temperature, lighting and air flow. The HVAC system aggregated these votes per location and adjusted the environment according to the preference. The authors utilised new technology in gathering data via mobile device application. However, the user of the building needs to be motivated to input this data and on a regular basis. The author admits that on a long term basis motivation to participate in this data collection is the main challenge.

The goal of personalised comfort in an environment which reflects the occupant's wishes is a respectable one. Other systems such as PMV or Operative temperature rely on a mean assessment. Personalised comfort is an achievable goal but it should not come at the cost of interrupting the user. Jazizadeh et al found that the system developed showed high correlation between user's votes and the HVAC induced temperature compared to the other variables meaning temperature is the most important comfort variable [37].

Melikov et al 2012 assessed the performance of seat headrest incorporated personalised ventilation for thermal comfort and air quality purposes [38]. The application of personalised ventilation was for the automobile industry or the theatre where subjects would be seated for long periods of time.

Melikov et al placed participants on a chair which provided personalised ventilation to the neck and head area from behind. The response of the participants was assessed on the ASHRAE seven point thermal sensation scale at different exposure times. The participants were allowed to change their clothing during the tests. Tests were performed at staged air temperature levels, 20/22°C, 23/23°C and 26/26°C. The neck was found to be the coldest reported region as no clothing was present here. In generating increased air flow for air quality purposes to the head and neck area the ventilation inadvertently cools the skin of the participant causing discomfort. A large proportion of the test subjects reported 'slightly cool' on the neck region and some reported 'slightly cool' at the head region. At the highest temperature of the test 26/26°C very few of the subjects felt air movement and reported cool sensation [38].

Melikov et al note that personalised ventilation is a good way of improving the air quality of the occupants. However, this research has indicated that increasing the room air temperature to 26°C can overcome the discomfort felt by air flow over the neck, ears and head. Increasing room temperature to this value would require a lot more input of energy and heating flow to achieve this in a heating season. Where cooling seasons are employed in hotter countries personalised ventilation could be employed to cool the occupant without cooling the entire room.

Zhang et al, 2010, investigated using air motion to improve the comfort of individuals in a hot environment [39]. Zhang reports that when air motion was introduced to tests perceived air quality was significantly improved.

Zhang performed tests in a controlled environment chamber using local cooling and heating devices. The subjects filled in thermal sensation and preference surveys throughout the tests while subjected to various air temperatures and ventilation flows and

local heating/cooling of feet, arms and hands. The subjects performed mental tests as well and typing tests. Mental performance was at its best in cold conditions while logical thinking was best in warmer conditions. Typing was not subject to change for change in temperature of the chamber.

Zhang's research found that air movement increases perceived air quality. Air movement can be used to increase comfort in warm conditions. Zhang also measured finger temperature and found that finger temperature below 30°C indicated cool discomfort and when the finger temperature is between 30.6°C and 32.0°C the body experienced the highest comfort. Zhang reports that the three most influential local parts of the body, the head, hands and feet, and proposed that conditioning these parts to a tight band while conditioning the room to a less tight band could be done very efficiently. An annual energy saving of 40% when widening the acceptable thermal limits in a building to 18-30°C with local heating and cooling employed based on three test cities in a simulation.

2.2.6. Adaptive Control Models

Work has progressed on more and more complicated thermal comfort theories. Adapting current known equations or measures or utilising completely new approaches to thermal comfort. Adaptive models are the state of the art theories in which more complex parameters are assessed to determine comfort.

Yao et al, 2009 investigated using a 'black box' type theory into which factors such as culture, climate, social, psychological and behavioural adaptations were used to detect thermal comfort [3]. A model set up to account for these factors was called the Adaptive Predicted Mean Vote (aPMV) model. Yao examined the theory that these factors could have an impact on thermal sensation felt by the human body.

Yao used the 'thermal environment survey' in ASHRAE Standard 55; 2004 with some modifications to examine the subject's physiological, cultural and thermal sensation. Subjective thermal sensation, humidity sensation and air flow sensation were recorded by the subjects. Environmental variables were measured at the time of the survey. Yao found that in warm conditions where PMV is greater than zero, aPMV was less than PMV. Whereas in cool conditions, where PMV is less than zero aPMV was greater than PMV. This means in warm conditions the subject may not feel as warm as the predicted sensation according to PMV and vice versa for cool conditions. Yao proposed an equation for warm and cool conditions separately for aPMV.

Yao et al separated the conditions into warm and cool groups. For the warm conditions an indoor air temperature of 22°C – 40°C was investigated while for the cool conditions it was 8°C – 16°C. Yao did not at any point present the results of the conditions between 16°C and 22°C, which would be considered normal operating temperatures for most offices in Europe. It is unclear why these results were left out the author does not mention the omission. This range of temperature is the most likely range to be present in an office environment with a possible increase of the upper limit to 25°C. Yao used a 'black box' method in which the processes impacting on the thermal sensation of the subjects were not examined. Yao aims to incorporate the physiological, psychological and behavioural attributes of subjects into a whole thermal comfort equation which adapts the existing PMV equation. In using PMV for the adaptive process all errors in PMV are brought into this new model and more variables are added. PMV has a large number of variables already and Yao adds more to the aPMV model. Yao does not mention in the article where subjects for the tests were from. However, the results and equations relate only to Chongqing, China by the authors own admission. The research in this article can therefore only be applied to the area in which the test were carried out and further tests

would be required in other areas of the world to confirm that the adaptive PMV model could be applied worldwide.

Humphreys et al, 2002 examined the use of ISO 7730 predicted mean vote (PMV) as a device to predict the thermal sensation of people in buildings [2]. Data from many sources was gathered to investigate the validity of PMV. Humphreys freely admits that PMV cannot be expected to be precise given an individual, rather it predicts the mean comfort vote of a large group of people.

The data set was analysed to find discrepancies between calculated PMV and the ASHRAE scale thermal sensation recorded. Over 17,000 cases of PMV were included in the dataset. When data points were outside the normal scale of operations in a building the data was discarded. 16,762 data points were then available. Humphreys used operative temperature instead of the measured air and mean radiant temperatures as they were found to co-vary with a variance of 0.96.

Humphreys found that PMV can be seriously misleading when used to predict the mean comfort votes of people in everyday conditions in buildings especially in warm environments. Humphreys noted that modification of the PMV equation can be used to improve accuracy of prediction. PMV, in various forms, has been used since Fanger developed the equation in 1972 [4]. However, PMV has been shown to be misleading especially in the case of individual comfort. No allowance is made in the equation for local discomfort or for discomfort of the minority in a large group of people.

During the investigation into the validity of PMV, Humphreys et al developed a new PMV equation

$$PMV_{new} = 0.8(PMV - D_{PMV-ASHRAE}) \quad (2-7)$$

where

$$\begin{aligned} D_{PMV-ASHRAEnew} &= -4.03 + 0.0949T_{op} + 0.00584(RH\%) \\ &+ 1.201(met * clo) + 0.000838T_{out}^2 \end{aligned} \quad (2-8)$$

T_{op} is operative temperature (°C)

$RH\%$ is relative humidity (%)

met is metabolic rate

c_{lo} is clothing insulation

T_{out} is outside temperature ($^{\circ}\text{C}$)

The revised PMV was shown not to be biased in the middle of the scale but some bias was displayed in the colder end of the scale in values of -1.5 or below. Humphreys notes that use of a steady state equation for a dynamic situation is an approximation. The comfort condition is a dynamic equilibrium between heat transfer of the body with the environment [2].

In 2013, Simone et al examined the influence of clothing distribution and local discomfort on the assessment of global thermal comfort [40]. Simone carried out a field type study in a hypermarket in Italy. Employees of the hypermarkets were asked to fill out questionnaires while physical measurements were carried out.

Questionnaires used the seven point ASHRAE scale of 'very cold' to 'very hot'. Data collection points were fixed so there was no discrepancy in the movement of the subject. Globe temperature, air velocity, radiometric asymmetry, dry bulb temperature and relative humidity were gathered to compare with the questionnaire filled out by subjects.

Simone et al found that PMV had a prediction error in some job types analysed. In some cases the 'comfort temperature' reached by questionnaires was found to be 4°C higher than that which PMV predicted. Simone suggested that clothing insulation be appropriately modified to reduce requests for increases in temperatures which was considered less expensive than increasing the air temperature. Radial asymmetry showed that the low temperature of the floor area resulted in cold sensation in the lower limbs which contributed to the overall cold thermal sensation recorded by the questionnaires. Local thermal discomfort was displayed in some cases of the research. Simone suggests that the PMV index is not always correct in prediction particularly in cases of local discomfort.

Niemelä et al, 2002 investigated the effects of changing air temperature on labour productivity in call centres in Finland [17]. In two call centres the productivity was compared between rooms of different air temperatures. Intervention, in the form of cooling units to lower air temperature in summer, was added and effects were monitored. Productivity was monitored before and after intervention. Most employees in the call centres were female. Productivity was measured by number of calls, total work time, and active work time of each employee in every shift.

Results from the tests showed that mean air temperature in the building in which intervention was not made was 23.6°C. The building in which intervention was made was found to have a mean air temperature of 25.1°C before intervention and 22.6°C after. Each employee acted as their own reference between the months of July and October. The employees were found to be most productive in October while least productive in July. July was set up as a reference month while the other months involved the intervention on cooling.

The findings by Niemelä show an increase in productivity by 7% in the call centres. Labour productivity decreased by 5-7% when air temperatures were above 25°C. Thermal comfort is shown not only to be a subjective response of satisfaction in the environment but also impacts on work productivity. It is therefore essential, from an employer's perspective, to maintain thermal comfort of all employees to ensure that work productivity is high. Lighting and acoustical conditions were not found to be a factor in levels of productivity in this research but solely air temperature differences.

2.2.7. Other State of the Art Control Systems

Current building thermal comfort control technology is based on algorithms to control the HVAC equipment with a number of predictive strategies. Algorithms for Building Management Systems (BMS) have been at the forefront of control strategies in buildings. Energy savings can be made based on changing the control strategies and algorithms are a powerful way of applying this. As such, a lot of research has revealed newer and better algorithms based on the state of the art of the time [14][41][15][42]. Curtiss et al [41] studied using neural networks to control the set point of a HVAC system. He et al [15] used a multiple model predictive control strategy based on fuzzy models to control Air handling units.

2.2.7.1. Genetic Algorithms for control

Huang et al [14] used genetic algorithms to tune the PID controller for a HVAC system. The controller aims to satisfy the conditions which the above methods such as PMV or operative temperature ranges would set out in a normal environment. The genetic algorithm is used to achieve the set environment as quick as possible.

The genetic algorithm is a search algorithm combining a randomised search pattern with a Darwinian natural selection process. The algorithm searches within a search space for the best fit solution to the problem presented. In this case it is the HVAC controller. Based on the information given to the algorithm a function with a view to energy savings or occupant

comfort can be set up and the algorithm will adjust the PID controller settings based on the best fit solution. Within the genetic algorithm process, batches of solutions are produced and the best 2 'chromosomes' are chosen and these are mutated and bits from each used to populate a new 'generation' in which the process happens again. Elitism preserves the chromosome with the best-fit and the search is limited to a time scale. The most elite chromosome is used to control the HVAC system.

The author used HVACSIM+ to determine the effectiveness of the simulation. Huang proved genetic algorithms work better than the Ziegler-Nichols method for controller tuning. However, genetic algorithms used a large amount of processing time for each loop which could limit the applications of this method.

2.2.7.2. Kalman Filters

Kalman filters have been used in model adaptation for HVAC systems [9]. Kalman filtering predicts a system's state based on the previous states and has been proven to work well with dynamic systems. Kalman filtering allows systems with a large amount of lag to foresee the change in environment and correct the lag which may have otherwise occurred in the system should there have been no predictive model. Platt et al [9] used Kalman filtering and genetic algorithms for HVAC zone modelling. Results show that shorter prediction periods resulted in a better fit of the model to the real environment. Zone status was accurately modelled and predicted so the HVAC system could, in advance, effect change in energy resource consumption.

Genetic algorithms and Kalman filters are allowing buildings reach the predefined environmental conditions which are suitable for increased levels of comfort. They aid the speed of application of the predefined conditions. However, if the predefined conditions are not acceptable to the occupants these new systems cannot respond to create an environment that is acceptable.

2.2.8. Personal Factors affecting thermal comfort

In order to centre the control of buildings on occupants the individual factors must be understood in how each variable effects a change in thermal comfort. Many personal factors which affect thermal comfort are used in the calculation of predicted mean vote (PMV). When PMV is calculated, it is calculated for all the occupants in a room which

means the personal variance of, for example, clothing or metabolic rate creates a discrepancy in the measure of PMV and thus the level of comfort occupants are experiencing in the environment.

2.2.8.1. Metabolic Rate

Metabolism is defined as the sum total of all the chemical reactions in the body that are necessary in order to maintain homeostasis. Metabolism involves catabolic reactions and anabolic reactions [43]. Metabolic rate describes the speed at which the heat from these reactions is being produced.

Basal metabolic rate (BMR) is amount of daily energy expended by humans at rest. The basal metabolic rate is sufficient for functioning of the vital organs. BMR gives the minimum working metabolic rate for continued survival and can be estimated using the Harris-Benedict equation [44] and later revised [45].

For men,
$$\text{BMR} = 88.362 + 4.799 \cdot \text{Height} + 13.397 \cdot \text{Weight} - 5.677 \cdot \text{Age} \tag{2-9}$$

For women,
$$\text{BMR} = 447.593 + 3.098 \cdot \text{Height} + 9.247 \cdot \text{Weight} - 4.737 \cdot \text{Age} \tag{2-10}$$

The primary control for metabolic rate is the hypothalamus. The hypothalamus also is responsible for the regulation of food intake. Metabolic rate is raised in a human who has recently consumed food.

BMR differs between individuals. The difference has been shown to be linked to fat free mass of the individual. Higher fat free mass should indicate a higher BMR and conversely lower fat free mass should indicate a lower BMR. Johnstone et al, 2005, showed fat free mass accounted for 63% of difference in basal metabolic rate, however 26% of the test subjects had a BMR that could not be explained by either fat free mass, fat mass, sex, or age [46]. Comparing two subjects of the same physiological data, mass, height age, sex, fat mass and fat free mass will not yield the same result in basal metabolic rate. If basal metabolic rate is different than normal metabolic rate for working at a computer will be different as BMR is the base rate upon which other processes such as muscle contraction and increased brain activity are added to.

Metabolic rate used to calculate PMV is expressed in the units W/m^2 or met. It is assumed to be equal to the rate of heat production. Measurement of metabolic rate is intrusive and

requires measurement of oxygen consumption. As metabolic rate is difficult to measure ISO 8996:2004 details the metabolic rate for typical activities. Error is high and accuracy is $\pm 20\%$ when basing metabolic rate on type of activity. Using an expert method of calculation the accuracy increases to $\pm 5\%$ but these methods would not be possible in an office environment. Heart rate has been shown to relate to metabolic rate and can increase the accuracy of the metabolic rate to $\pm 10\%$. Resting heart rate and basal metabolic rate or resting metabolic rate should be estimated along with maximum heart rate. Loss of accuracy comes from these estimations. ISO 8996; 2004 uses a table to show metabolic rate for certain occupations. This research is concerned with office workers doing sedentary to clerical work sitting at a desk. Sedentary work describes a metabolic rate of 55 to 65 W/m^2 and clerical work is described as 65 to 100 W/m^2 .

Body segment		Work intensity		
		Light	Medium	Heavy
Both hands	Mean	70	85	95
	Range	<75	75 to 90	>90
One arm	Mean	90	110	130
	Range	<100	100 to 120	>120
Both arms	Mean	120	140	160
	Range	<130	130 to 150	>150
The body	Mean	180	245	335
	Range	<210	210 to 285	>285

Table 2-3 Metabolic rate (W/m^2) for a seated subject as a function of work intensity and body segment involved [22]

Body posture	Metabolic rate ($\text{W}\cdot\text{m}^{-2}$)
Sitting	0
Kneeling	10
Crouching	10
Standing	15
Standing stooped	20

Table 2-4 Supplement to metabolic rate for body postures [22]

Table 2-3 and Table 2-4, taken from ISO 8996, describe the expected metabolic rate for various conditions of work intensity and body posture [22]. The second table describes the addendum of metabolic rate taken from the first table based on body posture. For an

office worker seated at a desk operating a mouse and keyboard of a computer, considered to be light work intensity, the metabolic rate would be estimated at 70 W/m^2 and the range expected would be less than 75 W/m^2 . If kneeling, the metabolic rate would be increased by 10 W/m^2 as given in the table.

Using the table for metabolic rate for a seated subject using both hands in a light work intensity the range is up to 75 W/m^2 and the mean is 70 W/m^2 [22]. Using these tables the metabolic rate for a subject at a desk working at a computer can be in the range 55 to 100 W/m^2 . ISO 7730:2005 goes further to estimate metabolic rate of sedentary activity in office as 70 W/m^2 . ANSI ASHRAE standard 55 describes metabolic rate for a seated person typing as 65 W/m^2 in the appendix of activity levels [31]. Accuracy of metabolic rate and PMV decreases has been shown to decrease as activity increases [2]. Using a metabolic rate of less than 80 W/m^2 has been shown to be free from bias however once the metabolic rate is higher than that the sensation of warmth is overestimated. For the purposes of this research metabolic rate will be assumed to be 70 W/m^2 based on the tables in the two international standards and other research using the same tables [47].

Increased metabolic rate means increased heat production. The PMV equation uses the rate of heat generation against the heat loss through different process, convective, radiative etc. in an energy balance equation. As has been shown metabolic rate differences between individuals can create more heat to be lost to the surrounding environment in order to balance the energy equation. If the energy cannot be lost the cutaneous blood flow increases to cope with the impending temperature increases. Increased skin temperature will lose more heat to the environment in the energy exchange as the ΔT , temperature difference, has increased.

2.2.8.2. Clothing insulation

The difference between skin temperature and air temperature, delta T (ΔT), of the human body to the surrounding environment can be reduced using clothing. Clothing insulation provides a reduced surface temperature and therefore a reduced ΔT with the environment. Therefore decreasing the surface temperature of clothing decreases the amount of heat lost through convective and radiative processes for the skin that is shaded by the clothing. The same applies conversely to high radiative sources, such as the sun, where surface temperature of the clothing may be higher the skin temperature can remain cooler.

Insulation of clothing is defined in thermal resistance 1 clo is $0.155 \text{ m}^2 \text{ K/W}$. Change in insulation level has been shown to be seasonal and males usually have a higher clo value in both summer and winter seasons [19]. This seasonality has been used to save money

in offices as lower indoor air temperatures are acceptable considering the increased clothing insulation in winter as are higher indoor air temperatures in summer.

Direct measurement of clothing insulation is impractical and time consuming. A set of typical values of combinations of clothing is set out in Table 2-5.

Work clothing	I_{cl}		Daily wear clothing	I_{cl}	
	clo	$m^2 \cdot K/W$		clo	$m^2 \cdot K/W$
Underpants, boiler suit, socks, shoes	0,70	0,110	Panties, T-shirt, shorts, light socks, sandals	0,30	0,050
Underpants, shirt, boiler suit, socks, shoes	0,80	0,125	Underpants, shirt with short sleeves, light trousers, light socks, shoes	0,50	0,080
Underpants, shirt, trousers, smock, socks, shoes	0,90	0,140	Panties, petticoat, stockings, dress, shoes	0,70	0,105
Underwear with short sleeves and legs, shirt, trousers, jacket, socks, shoes	1,00	0,155	Underwear, shirt, trousers, socks, shoes	0,70	0,110
Underwear with long legs and sleeves, thermo-jacket, socks, shoes	1,20	0,185	Panties, shirt, trousers, jacket, socks, shoes	1,00	0,155
Underwear with short sleeves and legs, shirt, trousers, jacket, heavy quilted outer jacket and overalls, socks, shoes, cap, gloves	1,40	0,220	Panties, stockings, blouse, long skirt, jacket, shoes	1,10	0,170
Underwear with short sleeves and legs, shirt, trousers, jacket, heavy quilted outer jacket and overalls, socks, shoes	2,00	0,310	Underwear with long sleeves and legs, shirt, trousers, V-neck sweater, jacket, socks, shoes	1,30	0,200
Underwear with long sleeves and legs, thermo-jacket and trousers, Parka with heavy quilting, overalls with heave quilting, socks, shoes, cap, gloves	2,55	0,395	Underwear with short sleeves and legs, shirt, trousers, vest, jacket, coat, socks, shoes	1,50	0,230

Table 2-5 Thermal Insulation for typical combinations of clothing, ISO 7730:2003 [1]

A more detailed table of clothing insulations is given in Table 2-6, each piece of typical clothing insulation value can be added up to give the total clothing insulation value. Thermal insulation of the surrounding environment should be considered too. If the subject is sitting on a chair, the chair has a thermal insulation value. This is also given in ISO 7730:2005 [1]. For the purposes of this research a standard office chair of thermal insulation value of 0.1 clo is assumed to be the best fit.

Garment	I_{clu}		Change of optimum operative temperature, °C
	clo	m ² · K/W	
Underwear			
Panties	0,03	0,005	0,2
Underpants with long legs	0,10	0,016	0,6
Singlet	0,04	0,006	0,3
T-shirt	0,09	0,014	0,6
Shirt with long sleeves	0,12	0,019	0,8
Panties and bra	0,03	0,005	0,2
Shirts/Blouses			
Short sleeves	0,15	0,023	0,9
Light-weight, long sleeves	0,20	0,031	1,3
Normal, long sleeves	0,25	0,039	1,6
Flannel shirt, long sleeves	0,30	0,047	1,9
Light-weight blouse, long sleeves	0,15	0,023	0,9
Trousers			
Shorts	0,06	0,009	0,4
Light-weight	0,20	0,031	1,3
Normal	0,25	0,039	1,6
Flannel	0,28	0,043	1,7
Dresses/Skirts			
Light skirts (summer)	0,15	0,023	0,9
Heavy skirt (winter)	0,25	0,039	1,6
Light dress, short sleeves	0,20	0,031	1,3
Winter dress, long sleeves	0,40	0,062	2,5
Boiler suit	0,55	0,085	3,4
Sweaters			
Sleeveless vest	0,12	0,019	0,8
Thin sweater	0,20	0,031	1,3
Sweater	0,28	0,043	1,7
Thick sweater	0,35	0,054	2,2
Jackets			
Light, summer jacket	0,25	0,039	1,6
Jacket	0,35	0,054	2,2
Smock	0,30	0,047	1,9
High-insulative, fibre-pelt			
Boiler suit	0,90	0,140	5,6
Trousers	0,35	0,054	2,2
Jacket	0,40	0,062	2,5
Vest	0,20	0,031	1,3
Outdoor clothing			
Coat	0,60	0,093	3,7
Down jacket	0,55	0,085	3,4
Parka	0,70	0,109	4,3
Fibre-pelt overalls	0,55	0,085	3,4
Sundries			
Socks	0,02	0,003	0,1
Thick, ankle socks	0,05	0,008	0,3
Thick, long socks	0,10	0,016	0,6
Nylon stockings	0,03	0,005	0,2
Shoes (thin soled)	0,02	0,003	0,1
Shoes (thick soled)	0,04	0,006	0,3
Boots	0,10	0,016	0,6
Gloves	0,05	0,008	0,3

Table 2-6 Thermal insulation for pieces of clothing with changes in optimum operative temperature, ISO 7730; 2003 [1]

2.2.8.3. Gender Differences

Research has shown that gender difference is not a significant factor in preferred thermal environment. In Fanger's experiment in 1972, American males preferred a slightly cooler environment while Danish males preferred a slightly warmer environment compared to their female counterparts [4]. Gender difference doesn't have a marked effect on thermal preference however mean male heights are higher than female [48] in Ireland which

means weight is also higher as has been shown around the world [49][50]. The inequality leads to different mean basal metabolic rates (BMR) and mean surface areas. Different BMR leads to increased dissipation of heat from the body.

Clothing insulation has been shown to be different between genders. Female subjects generally chose clothing with a lower total clo value.

2.3.Human Response to the Environment

2.3.1. Thermoregulation within the human body

Thermoregulation is the ability of an organism to maintain its internal temperature within certain limits. It is a part of homeostasis where the dynamic state of stability between the internal environment and external environment can maintain the internal environment at a constant temperature. Internal environment can be maintained and controlled through a number of mechanisms. In humans, core temperature is maintained by cutaneous blood flow, shivering, sweating, metabolic changes, piloerection/arrectorpili and mitochondria fat conversion.

2.3.2. Hypothalamus

When studying how the human body regulates temperature and comfort it is important to recognise that blood flow is one of the primary regulators in the human body to maintain core temperature, it is one of the first mechanisms to be employed by the body. The main controller for this mechanism is the hypothalamus gland, based in the endocrine system, it is a hormonal system. The hypothalamus is the so called 'thermostat' of the body, which in turn controls the heat dissipation mechanisms and heat recovery, such as sweating, shivering and cutaneous blood flow regulation. It is a portion of the brain which contains nuclei with several functions, located in the brain stem and responsible for body temperature, hunger, thirst, fatigue, sleep and circadian cycles. The preoptic/anterior hypothalamus (PO/AH) controls thermoregulation in the brain [51].

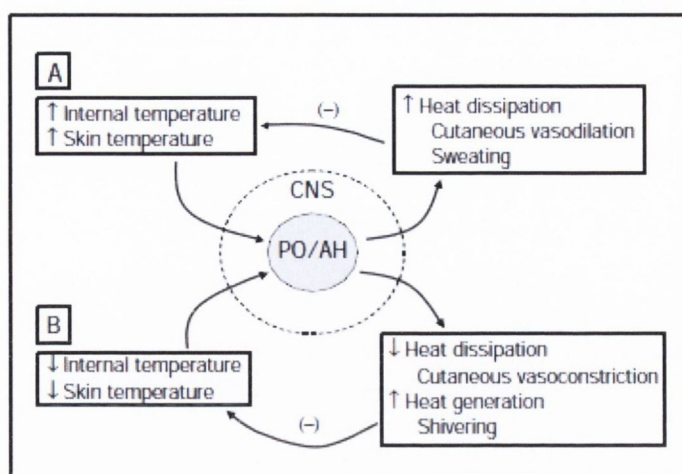


Fig. 2-4 Physiologic thermoregulation in humans [52]

2.3.3. Cutaneous Blood Flow

Cutaneous blood flow (skin blood flow) is a mechanism used to regulate body temperature. The hypothalamus tries to achieve thermal homeostasis through skin blood flow regulation. Sympathetic neural control of vasoconstrictor and vasodilator systems allow for substantial changes in the blood flow to the skin. During vasodilation cutaneous blood flow has been found to reach 6 to 8 l/min during hyperthermia [52]. Resting skin blood flow was found to be approximately 250 ml/min, which results in heat dissipation equivalent to the level of resting metabolic rate. During exercise heat exposure causes sweating and vasodilation, however during sedentary activities such as office work, sweating is negligible as is shivering. The main thermoregulation mechanism then becomes skin blood flow. Cutaneous blood flow has been shown to increase skin temperature through heat dissipation from the arterioles and capillaries in the skin through which the blood flows [43].

2.3.3.1. Arterio-venous anatomoses (AVAs)

The skin acts as a large heat sink when the body has too much heat energy and acts as an insulator when the body has the correct amount of heat energy. Arterio-venous anatomoses (AVAs) are controlled by the hypothalamus and regulate cutaneous blood flow. These 'valves' either allow blood flow to the capillary loops in skin when the body is hot or cut off flow to the loops when the body is cold [51]. There are more AVAs in the skin of the hands and fingers than in the rest of the body surface [30]. With increased AVAs comes increased control in blood flow in the hand and fingers.

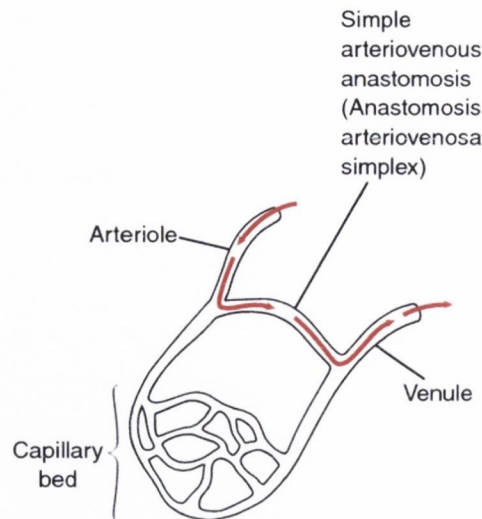


Fig. 2-5 Simple Arterio-venous anastomosis (AVA)[53]

When temperature experienced by a body is low the sympathetic nerve is stimulated and cutaneous vasoconstriction is stimulated leading to reduced blood flow to the capillary loops in the skin. This in turn reduces the temperature of the skin since there is no source of heat and heat is dissipated to the surroundings by convection and radiation. Conversely, when a body experiences a high temperature the sympathetic nerve activity decreases and the AVAs dilate (vasodilation) and allow blood flow to the capillary loops.

A low blood flow in cold weather is tolerated by skin as the metabolic rate is lowered. Shivering is employed as a mechanism of heating the body by using muscle contractions to burn energy. High blood flow in warm conditions means the sympathetic nerve activity is low and the body does not lose enough heat the sweat gland is activated which also secretes bradykinin, which stimulates more vasodilation [51].

2.4. Infrared Imaging

2.4.1. Black body radiation

The term 'black body' indicates a material that absorbs all the light and heat that hits the material. The material gets warm because of this. This is in contrast to a material like glass which appears to let light through and a material like a shiny metal which reflects most of the light hitting its surface [54].

A black body absorbs light with no transmission or reflection. Unattached electrons are free to move within the whole material, they crash into things and energy is lost in the vibrations created. The kinetic energy is converted to heat energy by this process. Therefore a black body is very good at converting energy from light into heat.

The converse is also true, black bodies radiate light when heated. The exact frequency of light at a given temperature can be accurately calculated. This can often be in the infrared spectrum for low temperature bodies.

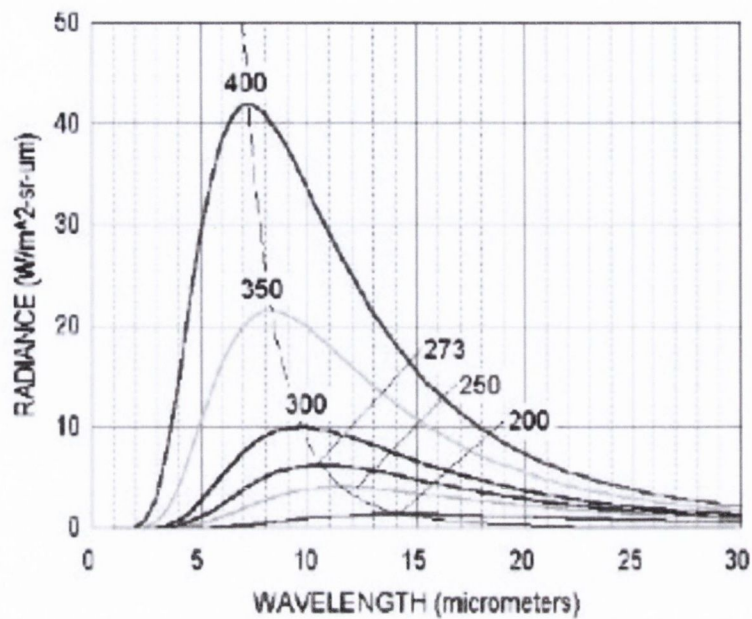


Fig. 2-6 Radiance and wavelength of light emitted by a black body for given temperatures [55]

Every body above 0K emits electromagnetic radiation on some scale. The human body at 300K emits radiation in the form of infrared light. Black bodies at c.3500K or more emit visible light as can be seen from Fig. 2-6. Analysis of infrared radiation can therefore be used to assess the temperature of a body based on maximum wavelength of light emitted. Skin has a very high emissivity close to that of a black body therefore temperature can be more accurately measured based on the black body laws.

In 1893, Wien deduced that as temperature changes so does the frequency of the most intense emitted radiation. Wien found that frequency is directly proportional to absolute temperature.

$$f_{max} \propto T \tag{2-11}$$

where f_{max} is maximum frequency.

Human skin is regarded as grey body which has an emissivity close to that of a black body (0.98) [56]. The fingernail which is measured in this research has an emissivity different to that of the skin. However, Savastano et al remarked that the convex shape of the human nail and texture of the nail plate make the differences in emissivity negligible in the mid-infrared wavelength range [57]. In addition colour of skin has no bearing on emissivity value. In measurement of skin temperature the important thing is to note the infrared camera is capable of setting the emissivity to 0.98 otherwise errors in measurement will occur.

Law of Stefan-Boltzmann

$$W = \varepsilon \sigma T^4 \quad (2-12)$$

where W is the radiation (W/m^2), ε is emissivity, σ is the constant of Stefan-Boltzmann (5.68×10^{-8}) and T is the temperature of the surface of the object.

Wien's Displacement Law is obtained from Planck's law. It states that the wavelength distribution of radiated heat energy from a black body at any temperature has essentially the same shape as the distribution at any other temperature, except that each wavelength is displaced on the graph. When assessing the average thermal energy, the peak wavelength is shown to be inversely proportional to temperature

$$\lambda_{max} T = b \quad (2-13)$$

where b is the Wien's displacement constant, $2.8977685 \times 10^{-3} \text{ m}\cdot\text{K}$

T is the absolute temperature.

The maximum temperature of a human is approximately 38°C , when applying Wien's Law this gives maximum wavelength of skin to be $9.4\mu\text{m}$. So an infrared camera can be configured to measure in the range around $9.4\mu\text{m}$ [12]. Since the electromagnetic

radiation emitted from the skin can be measured by an infrared camera, skin temperature can then be calculated from this emission.

2.4.2. Infrared Thermography

In the last twenty years infrared thermography has grown into an important tool in heat transfer, thermo fluid dynamics, heat fluxes, medical, automotive and many other applications [58][59][60]. Infrared thermography was introduced in the early 1960s and measures the temperature of surfaces, traditionally this is presented in a graphic form where pixel colour and/or brightness represents temperature measured. It is a non-contact technique of temperature measurement.

The infrared spectrum is generally split into four bands: near infrared (0.75-3 μm), middle infrared (3-6 μm), far infrared (6-15 μm) and extreme infrared (15-1000 μm). An infrared detector is usually configured for middle infrared or far infrared [61]. Photon detectors are used to measure infrared as they have a short response time. However, these need cooling with liquid nitrogen to reduce noise and increase speed of measurement. Photon detectors and others were only capable of point measurements and two dimensionality was created by a scanning mechanism. Newer infrared detectors use miniature coolers built into the system. Modern infrared detectors use uncooled microbolometer and focal plane arrays [61].

Eveland et al [62] aimed to use infrared image sequences to recognise human faces for a security, surveillance or robotics application. Infrared light is transmitted regardless of time of day and has a distinct advantage over visible light in this regard. Computer vision algorithms are more suited to infrared imagery as there is little variance in infrared light transmitted based on different lighting conditions, therefore, infrared is a more stable platform for facial recognition.

However, this research is concerned with hand recognition the same algorithms may be applied to recognising the unique characteristics of hands on the infrared image. The CONDENSATION algorithm was employed for tracking faces. The CONDENSATION algorithm tracks contours of objects moving in an environment, the infrared environment is better suited to this algorithm than the visible spectrum as contours are more pronounced in infrared. The contours are more pronounced due to temperature difference rather than colour difference which an ordinary camera relies on. Eveland used region classifying output as the input for the model which set to streamline the process as background classified regions could be ignored from processing. One of the main processes of

Eveland's research was the calibration of the infrared camera to show a calibrated image to give a direct relationship between the intensity of the pixel to the intensity of thermal emission, responsivity.

Radiometric calibration links the pixel intensities of images to physical parameters. This is required considering the losses of atmosphere and instrument. Individual infrared cameras can have their own characteristics of intensities, radiometric calibration removes these. Eveland compared long wave infrared sensor and mid wave infrared sensor. He was concerned with one range of the Planck curve based on an average temperature of the skin (30°C). This research will be concerned with changing Planck curve based on changing skin temperature. Images were classified as one of three distinct groups: background, covered skin and exposed skin. Probabilities of these classes are calculated using Bayesian tracking, then by CONDENSATION algorithm.

Gulyaev et al [63] investigated the use of dynamical thermography in the human body and the application of same to medical assessment. In his basic process, Gulyaev subtracted the background image from each frame of interest in order to produce the dynamic temperature. Experiments were based on time and temperature dependencies to isolate the variables of interest. Infrared radiation is absorbed by water and organic compounds in 3-5 microns and 8-12 microns, because of this radiation from the human body is only seen from a 300 micron depth below the surface of the skin. This layer from surface to a 300 micron depth consists of capillaries and the arterio-venous anatomoses. This means that core temperatures are not radiated from the body and do not conflict with skin temperatures required in this research. Heat from the layer of skin is made up of blood flow to the skin, heat conducted outwards from core sources, thermal production from involved metabolism and water evaporation from the surface. Experiments by the author and others [64] have shown that heat transfer from core and evaporation has a negligible effect on skin temperature at rest.

2.4.3. Car Climate Control

In 1994, Burch et al [60] investigated the application of infrared thermography to automotive climate control. An image radiometer was used with a sensor cooled to 73K, to achieve good resolution. Target temperature was calculated from the resulting image by subtracting the total radiosity and scaling up the result based on the emissivity of the subject. This gives blackbody equivalence and can be referenced to a Planck blackbody radiance distribution to give the final temperature. Images were then digitized by a microprocessor. Infrared proved an effective tool for capturing the temperature distribution in an automotive cabin. Burch suggested that infrared has rapid temperature assessment,

is non-intrusive, portable and convenient. However a screen to gather the air temperatures must be used as air alone does not emit infrared in measurable quantities.

2.4.4. Low Cost Infrared Imager Applications

Al-Habaibeh [65] investigated use of a low cost infrared system for detecting novelties in a manufacturing process. A simple image comparison was employed between images of a normal process and a faulty process. The number of 'heat' pixels in the image was calculated and compared to the normal and faulty states. Temperature of the pixels is not measured and a spread of low temperature pixels could in fact cause a problem in identifying problems. NETLAB software was used to compare the images of normal operation and faulty operation. A threshold value for the difference between faulty and normal operation was set up and this was used to alert the operator to faults created in the system. This system is a low cost system which was sought after in this research to ensure the system can be applied to real world situations. The infrared camera used by Al-Habaibeh was an IRISYS IXS9009 thermal imager which has a low pixel count 16x16 pixels. The cost of this imager was 7% of the cost of a high resolution and is 20% of the size of same.

Automobile technology has also adopted using infrared as a comfort indicator because it is non-invasive and straightforward to gather images [66], [61], [60]. Burch et al [60] used solids placed within the air stream to determine temperatures of air stream at those points based on the infrared signal received. Burch used high-porosity screens and showed that air distribution from the floor vent can be measured with a porous screen using a long wave sensitive camera, FLIR Thermacam S60 which measures in the range 7.5 to 13 μm . De Oliveira [12] and Korukçu et al [61] used a camera with a similar range.

2.5.Hand skin temperature indicating thermal comfort

Liu et al, 2010 evaluated calculation methods of mean skin temperature in order to find appropriate ones for a human thermal comfort study [67]. Skin temperature was monitored at many sites throughout the subject's body. Liu used copper thermocouples to measure temperatures on the body in 21 locations during the test. Tests were conducted in a controlled environment where the air temperature was altered and the response of the subject was monitored. Liu calculated mean skin temperature using a weighted system and an unweighted system and evaluated the techniques.

Liu found that the greatest difference in mean skin temperatures across the cold to hot environments was found to be the feet. Hands, forearms and elbows were found to have a good range of values between cold and hot thermal sensations. Liu found that when the subject responded with a cool or cold sensation, skin blood flow was reduced caused by vasoconstriction to conserve body heat, skin temperature was found to be significantly decreased. When subjects responded with warm thermal sensation, vasodilation occurred and skin temperature was significantly increased. The results presented by Liu corroborated those which Humphreys reported in using finger temperature to assess thermal comfort [68]. In reality using the feet, elbow or forearm as a measure of thermal comfort is difficult as these areas are most likely to be covered up in an office environment. Hands and face are the two parts of the human body which are more than likely to be exposed, measurement of these areas is easier. Liu made temperature measurements on the face and found that the difference in mean skin temperatures to be much lower than the differences presented by the hands. A larger range and difference between conditions is easier to measure based on errors in equipment.

Humphreys et al [68] proposed that skin temperature of the hand can be used alone or in conjunction with ambient room temperature to monitor and predict thermal sensation and comfort. The researchers gathered data from 200 office workers in two locations in the UK once a month over the course of a year. Finger temperature was gathered along with thermal sensation and environmental data such as air and globe temperature. Analysis was carried out on the data gathered and finger temperature was found to match well to thermal sensation meaning finger temperature was a good measure of thermal sensation expected. Across the range of subjects in the test the finger temperature distribution was found to be a bimodal response.

Finger temperature was measured by placing a thermocouple between thumb and forefinger and the temperature measurement was taken when it became stable. This process for measurement allows the heat generated by thumb and forefinger to be insulated by each other and increased temperature may have resulted from the insulation of thumb against forefinger. One single measurement was taken from the subject per month. It would be difficult to distinguish the variance in hand temperature over a short period such as a week or day and to ensure that finger temperature was measured in the same conditions, such as the same time of day. Skin temperature is known to vary based on metabolic rates. Metabolic rates change throughout the day and are especially raised after a meal and much lower after rest. Humphreys et al did not mention how measurements made were controlled to avoid discrepancies such as these.

Thermal preference scale:

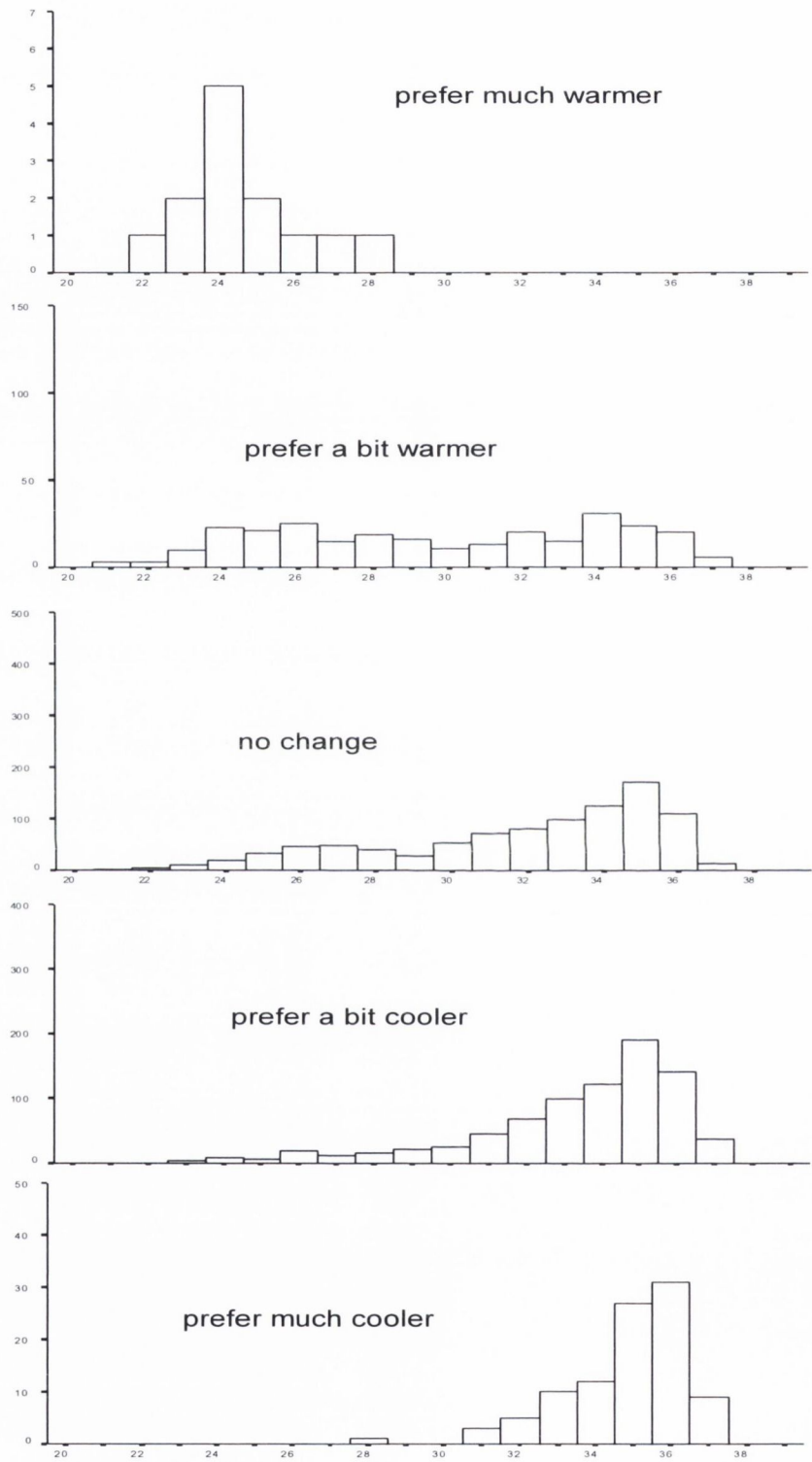


Fig. 2-7 Histogram of finger temperature for each category of ASHRAE scale, Humphreys et al [68]

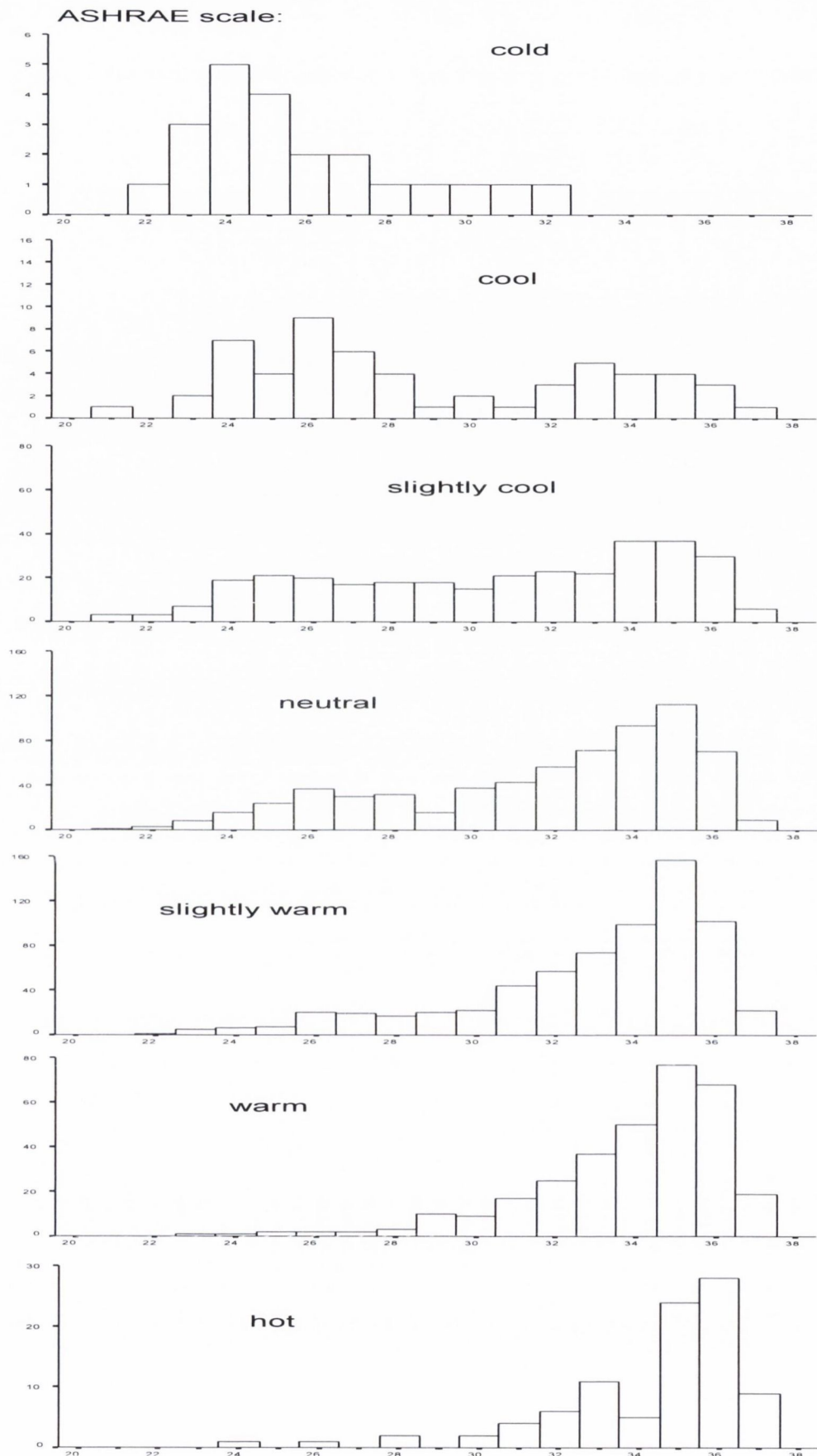


Fig. 2-8 Histogram of finger temperature for each category of preference scale, Humphreys et al [68]

Humphreys found that finger temperature was a better measure of thermal comfort than the measured globe temperature. Finger temperature was found to have a higher correlation factor. Finger temperature to ASHRAE scale vote was found to have a correlation factor of 0.37 while globe temperature was found to correlate to ASHRAE scale with a factor of 0.31. There is some improvement in using finger temperature as a measure of thermal sensation, however the increase was not found to be significant. On looking at the graph of each thermal sensation, presented in Fig. 2-8, it is clear that colder finger temperatures lead to colder ASHRAE and preference scale votes while hotter finger temperatures lead to warmer votes. The data shows there are no definite thresholds between hot and cold thermal sensations but a gradual increase in probability of thermal sensations at certain finger temperatures.

The data gathered included for a large number of office workers. Differences between finger temperatures recorded across course of a day were not investigated. Seasonal differences in skin temperature was available in the data but was not examined.

Wang et al [30] investigated the correlation of overall body thermal sensations and comfort with upper-extremity skin temperature. Thermal physiology tests were carried out by the research team in an environmentally controlled chamber on 19 body segments to determine comfort relationships. 17 subjects participated in these tests and 23 tests were performed. Subjects were sitting at a computer performing work. During testing skin temperatures were measured using thermocouples and thermal sensation was recorded from -4 "very cold" to +4 "very hot", 0 was not given as an option and -0.1 "just uncomfortable" and +0.1 "just comfortable" was given to force a judgement. Local segmenting tests were also carried out in which the left hand was placed in a controlled environment and was subjected to various testing. Conditions used were hot, warm, neutral, cool and cold.

In hot and warm environments finger temperatures averaged 36.7°C, in neutral finger temperature averaged 35.9°C but fluctuated at 2-5 minute intervals, in cool environment the mean finger temperature was 22°C. Finger temperatures were shown to range from approx. 20°C to 37°C within the conditions tested. Finger temperature was shown to be a good indicator of thermal sensation vote by the subject as the threshold of 30°C was established as the general boundary of thermal sensation. When finger temperature is below 30°C thermal sensation was most often in cold comfort and when finger temperature was over 35°C thermal sensation was generally warm comfort. The gradient between finger temperature and forearm temperature was calculated and plotted against the thermal sensation, cool discomfort was generally evident when finger-forearm

temperature was less than 0°C. The gradient of finger temperature and hand temperature was also calculated and both were plotted against thermal sensation. $T_{\text{finger}} - T_{\text{forearm}}$ was shown to be a more accurate measure of thermal sensation giving a larger gradient for both cool and hot environments. The $T_{\text{finger}} - T_{\text{hand}}$ gradient did however show some relation to thermal sensation.

Wang et al stated that prediction of sensation is more accurate to that presented by Humphreys et al (1999) because of the use of a standard environment. Humphreys found that 35°C and 26°C were peaks of hot and cold sensation, in the study conducted here peaks were found at 36-37°C and 20-27°C. Change in clothing was not accounted for in Humphreys' data. Wang et al conducted the research in the University of California, Berkley. Form of measurement by Wang et al is a thermocouple on the skin. Temperature readings were made on one finger and at one point on hand and forearm. The range of temperatures on the skin in these locations was not measured and could be corrupted on subjects with differing vascular systems or local heating/cooling. A subject with arteries or veins closer to the skin surface could skew temperatures measured by hand and forearm thermocouples considerably. Wang hypothesised that using the gradient of finger-forearm instead of just finger temperature alone would improve the prediction of thermal sensation however the improvement was small and insignificant. Wang et al used a thermal chamber on one hand only in his experiments, there is no mention of applying the same test conditions and measurement to the other hand. This approach cannot be recreated in a common real-world situation and is too specific for mentioning in this research.

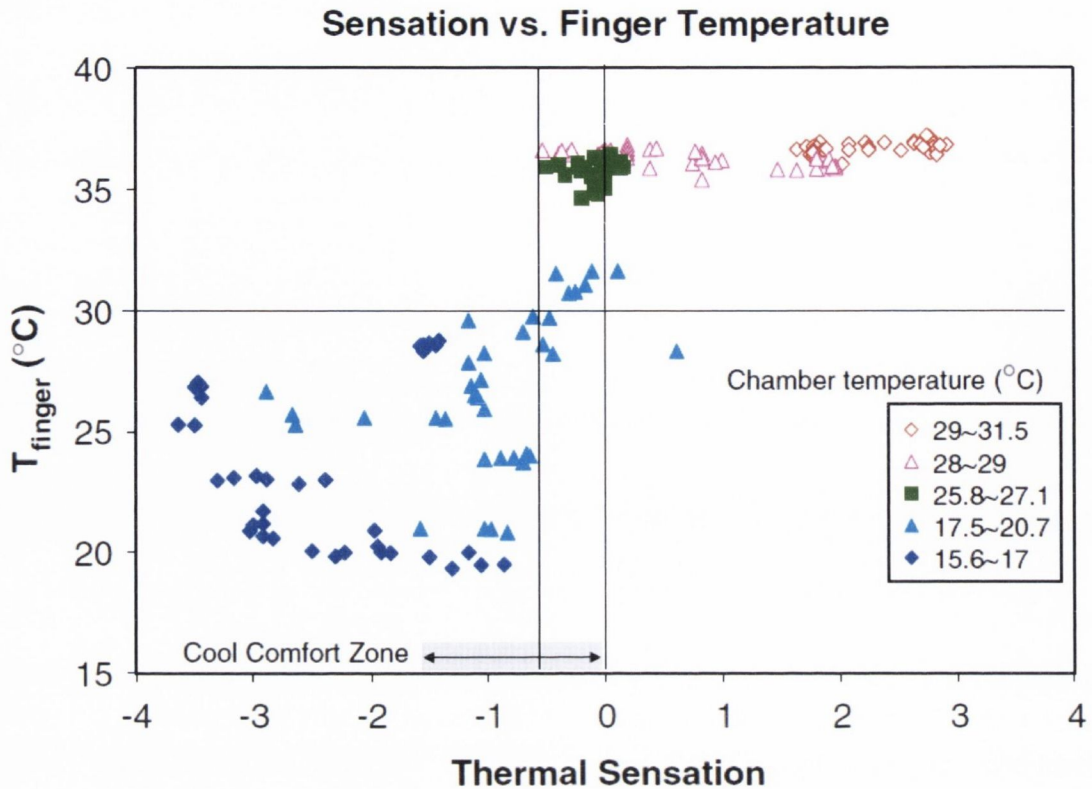


Fig. 2-9 Thermal Sensation and Finger Temperature (Wang et al, 2007) [30]

As can be seen from Fig. 2-9, there is a general boundary between thermal sensations. Thermal sensation of less than -0.5 shows a finger temperature of less than 30°C while thermal sensations of greater than -0.5 show finger temperatures of greater than 30°C .

Wang found that there was a boundary temperature between feeling cold and feeling hot of 30°C . This threshold could be used to measure the onset of cold/cool sensations. When subjects felt thermally warm/hot finger temperatures were seen between 35°C and 37°C . When subjects felt thermally cool/cold, finger temperatures were seen in a wide range between 20°C and 30°C . On subjects feeling thermally neutral finger temperatures were seen to be between 28°C and 35°C .

Research has been carried out on infrared imaging analysis of facial temperature to determine thermal comfort by De Oliveira et al, 2007 [12]. De Oliveira noted that skin temperature at 35°C emits maximum wavelength of infrared light of $9.4\mu\text{m}$. Image processing was performed by segmentation of the image detection of points of interest, then local segmentation of the points of interest. Temperature of the skin was calculated by averaging the area segmented.

Spectral analysis showed that infrared images change when subject is in a cold environment. The power spectrum shows peaks at various frequencies and a significant change in the peaks of the power spectrum to indicate the change between the subject in a comfortable environment and a cold environment. The work carried out by Oliveira et al was in response to a strong societal demand to obtain human measurements without constraints. The paper notes that further work will be carried out to validate the processing and analysis method used in this paper and a contact measurement of physiological parameters.

De Oliveira only developed a system for examining facial temperature and presented the methodology of measurement. Research carried out by Liu et al would suggest that the face is part of the body which does not appear to fluctuate in temperature as much as the extremities [67]. Oliveira et al uses the face to determine thermal comfort and whilst there are changes in the frequencies of the infrared radiation it would appear that applying this to the temperature of the extremities would be more effective in assessing comfort [30], [68].

3. Experimental Equipment, Procedures and Materials

3.1.Introduction

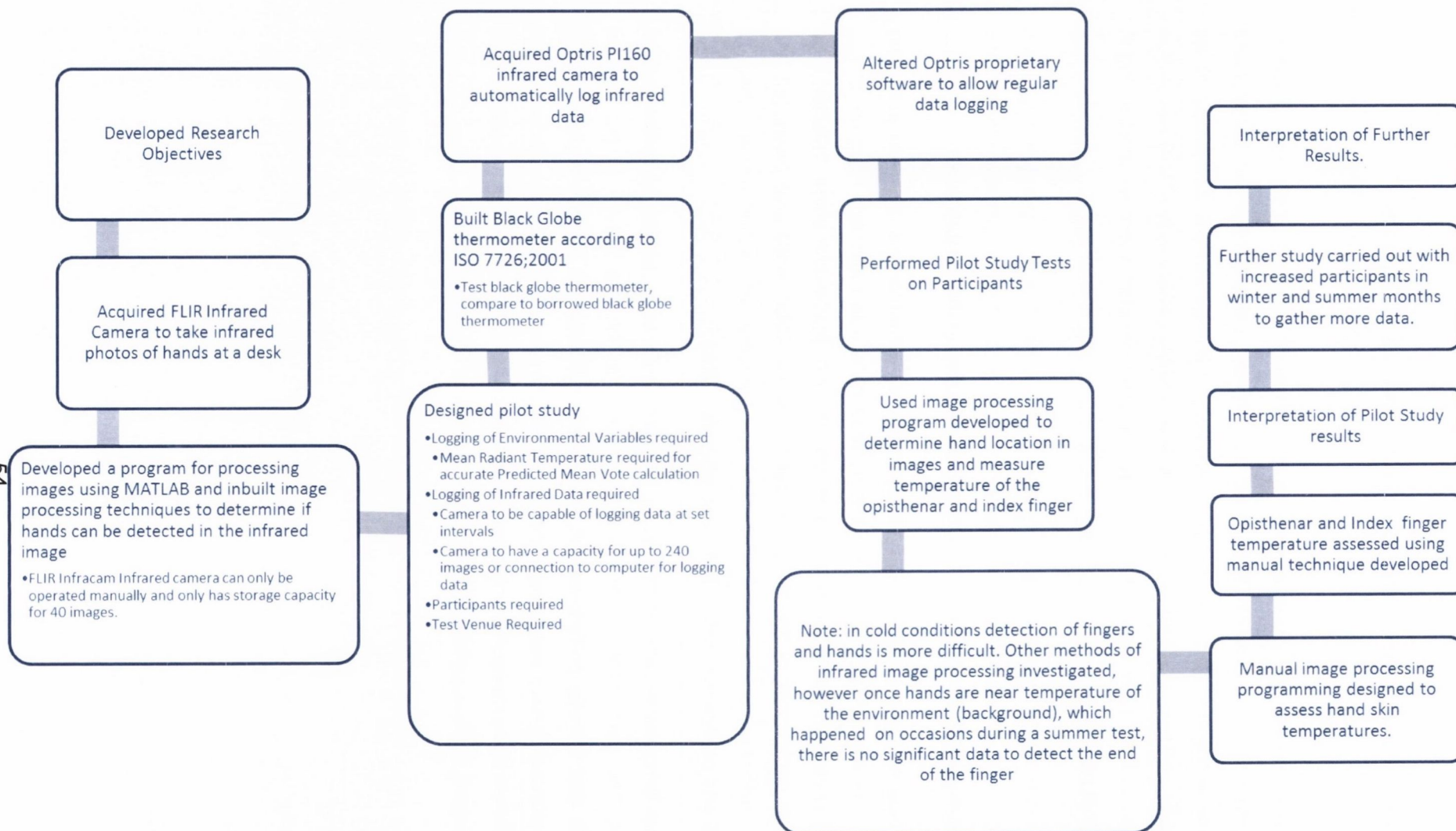
The literature review highlighted an area where increased accuracy of thermal sensation measurement could be achieved in an office environment. Links of hand skin temperature to thermal sensation have shown better accuracy than the current technology of air temperature and mean radiant temperature in the predicted mean vote (PMV) calculation [68]. Errors in PMV have also been highlighted in warm climates where air conditioning is used to cool offices.

An investigation into using an infrared camera to detect hand skin temperature (T_{skin}) was proposed. Firstly a short pilot into automatic image processing of infrared images took place to ensure that hands could be automatically tracked in the images taken.

A pilot study was proposed in which participants were asked to fill in a survey at regular intervals, the environment measured and infrared data was captured. Analysis of T_{skin} would be compared with thermal sensation and thermal preference votes collected from the human participants in the study. Environmental variables were also measured and used to traditionally assess thermal comfort and compare with actual measurement of ASHRAE and preference scales. PMV was also calculated.

Hand skin temperature was monitored at the same time as a number of environmental variables. The participant in each test was asked to fill in a survey of the thermal sensation and thermal preference felt at defined measurement periods throughout the test. An infrared camera was used in measurement. As part of the PMV calculations mean radiant temperature measurements were needed in order to be assured of the accuracy of measurement. A black globe thermometer was required for this purpose.

Fig. 3-1 Work Flow Chart



3.2.Initial Plan for Infrared image processing

Every measurement technique, such as air temperature and globe temperature, for thermal comfort assessment, for example PMV, uses a sensor which automatically measures a parameter. A skin temperature measurement device would be attached to a subject and automatically measure temperature at the skin. An infrared camera is incapable of automatic measurement of skin temperature as the camera measures temperature in the entire field of view of the lens. A program would have to be constructed to automatically find the appropriate hand location and measure the temperature of these areas. This is a key component of applying infrared measurement of hand skin temperature to the real world. In the real world having an operator choose the location of hands in an image is not feasible as the time and money consumed would be significant compared to the savings made in productivity due to correct thermal comfort of occupants [17], [18].

In order to assess the possibility of using infrared images of hands to measure T_{skin} , firstly a set of sample images were taken using an infrared camera. The research department had a FLIR camera available which would normally be used for heat loss in buildings assessment. The FLIR Infracam was used to capture images of hands in a normal office environment and a program was developed to take an image input and find the outline of a hand in the image.

3.2.1. FLIR Infracam

The FLIR infracam, Fig. 3-2, is a tool more generally used for heat loss assessment in buildings. It has very low capacity for storing infrared images and interpolates and image to a double the size for better representation of object in the field of view. The technical data of the FLIR Infracam is presented in Fig. 3-3. It has an uncooled microbolometer detector with a capacity for 120x120 pixels. The camera also has a viewing screen and capacity for storing images on the device. The spectral range of the camera is between 7.5 μm and 13 μm . Skin at 35°C emits infrared light of about 9.4 μm which is in the middle of the range of the camera, so it is suited well to the measurement of the temperatures expected in initial tests.

The FLIR Infracam was used as it was readily available, for more complete tests, capacity of the infrared camera would need to be increased because very few images were able to be stored on the device. For the purposes of trialling a set of hand images it was considered suitable.



Fig. 3-2 FLIR Infracam (SD version shown, non-SD version used in this research)

Imaging performance	Spectral range	7.5–13 μm
	Detector type	Focal Plane Array (FPA), uncooled microbolometer 120 $\times$ 120 pixels
	Image frequency	9 Hz
	Accuracy	$\pm 2.0^{\circ}\text{C}$ ($\pm 3.6^{\circ}\text{F}$) or $\pm 2\%$ of reading
	Thermal sensitivity	■ InfracAM: 0.20°C (0.36°F) ■ InfracAM SD: 0.10°C (0.18°F)
Image presentation	Screen	89 mm (3.5 in.) color LCD, 18-bit colors
	Interpolation	Detector image interpolated to 240 $\times$ 240 pixels
Object temperature ranges	Object temperature ranges	-10 to $+350^{\circ}\text{C}$ ($+14$ to $+662^{\circ}\text{F}$)
Laser pointer	Classification	Class 2
	Type	Semiconductor AlGaInP diode laser, 1 mW, 635 nm (red)

Fig. 3-3 FLIR Infracam Technical Data

3.2.2. Acquiring Infrared Images of Hands

The FLIR Infracam was used to acquire infrared images of hands, such as those shown in Fig. 3-4 and Fig. 3-5.

A suitable participant was selected and the FLIR camera was set up above a person working at a desk and trained on the keyboard area of the computer where the participant's hands were placed. Several infrared images were taken of the positioning of the hands. In a later test, Fig. 3-5, infrared images were taken of a different participant's hand while working at a desk. The images were exported to a computer where image processing took place to identify the temperature of the hands.

Fig. 3-4 shows an infrared image of a pair of hands which are placed on a keyboard. It is difficult to see the keyboard as it is low in temperature compared with the hands which are higher in temperature and are brighter. The brighter the pixel, the higher the temperature as the bar at the bottom of the image shows. The range shown here is between 23°C and 33°C, where a jet black pixel would represent temperatures of 23°C and below and a bright white pixel represents 33°C and above. Inside the range the brightness of the pixel corresponds to a temperature value. An emissivity value of 0.98 has been set as shown in the image and the average temperature also is shown in the top left corner. Both skin and nail have approximately the same emissivity value which is 0.98, [57]. The FLIR logo is shown in the top right of the image.

The hands can clearly be identified in this image. The main palmar part of the hands are both warmer, in general, than the fingers which decrease in pixel brightness toward the tips. The fingernails cannot be distinguished in this image.

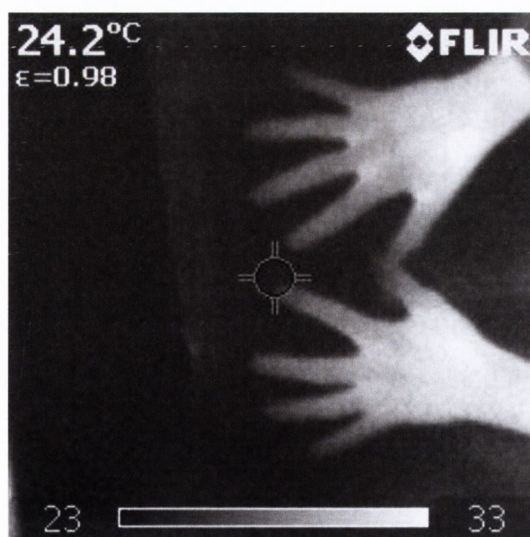


Fig. 3-4 Infrared Images of Hands taken with FLIR Infracam

Fig. 3-5 shows an infrared image of a single hand. The hand is much brighter than the one shown in Fig. 3-4, which means it is warmer. A crosshairs in the image is clearly shown in the middle of the frame. The forearm of the participant is visible and appears to be cooler than the hand. In fact, the opisthenar (back of the hand) appears to be cooler than the fingers, which is contrary to the image shown in Fig. 3-4. The range of temperatures shown in the lower bar is between 20°C and 35°C, which is different to the image above. Cross comparison of the images using the pixel brightness alone would not suffice as the temperature range is different. In order to process the images fully, temperature of the hands was evaluated. The images saved by the FLIR Infracam only contained pixel data and not temperature data. Interpretation of the infrared image data would have to take place in order to evaluate the representation of temperature in the image.

A MATLAB program was written to process the FLIR images acquired in order to assess the suitability for automatic hand recognition.

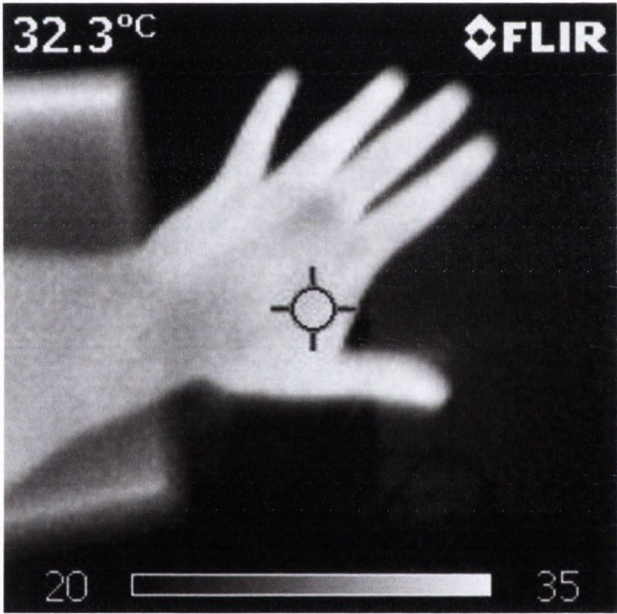


Fig. 3-5 Infrared Image of Hand taken with FLIR Infracam

3.2.3. MATLAB programming to process temperature data and automatically distinguish hands from FLIR Infrared images

The FLIR Infracam saves infrared images as JPEG data, which is a compression type image that includes loss of data. Before any processing takes place there is a loss of data. The memory on the FLIR is small and could not hold a lossless file type such as BMP. Further to this the FLIR data needs to be interpreted to determine the temperature which the pixels are at. The numbers at either end of the bar show the minimum and maximum figures on each image. Character recognition software should be able to find the numbers represented here and determine the minimum and maximum. The crosshairs clearly

shown in Fig. 3-5 will also disturb finding the entire outline/surface of the hand and fingers. This programming will investigate ways of removing the crosshairs from the image using a substitution type routine that replaces pixels in the crosshairs with similar pixels beside the position of the crosshairs.

MATLAB was chosen as the tool for image processing as it already has images processing toolboxes and has the capacity to work with large matrices of data. MATLAB has a large array of functions which can be called upon in scripts and functions can be created to speed up the process of programming for research purposes [69]. The methodology described here assumes a basic knowledge of computer programming techniques. Only complex operations and specific operations written by the author are explained as the reader is expected to understand the basic techniques shown. The extracts of the programming code is shown in this chapter. However, the entire code is presented in the Appendix 9.6.

MATLAB code was written to import an image taken with the FLIR camera and remove the crosshairs by using a substitution algorithm, as described above. The code is described in the Appendix 9.6.1 and the cross hairs removal function in the Appendix 9.6.2. JPEG artefacts were removed using a MATLAB native function 'imopen'. The median values of the levels of grey were found using the 'graythresh' function. The threshold value was used to create a monochrome image where pixels above the threshold level were changed to a white pixel and those below the threshold level were set to black. This monochrome image was then used to find the edge or outline of the objects in the native MATLAB function 'edge' is used to find the outline of the significant data in the monochrome image. The outline is processed further to thicken the line given by the 'edge' function using the native 'imdilate' function. The entire code is presented below with commented explanations of each line of code.

```
% This script uses infrared images generated by the FLIR Thermacam which
% was on loan from the Civil Engineering Department in Trinity College.
It
% was used to process infrared images of hands in an office environment
at
% a desk. The aim of this script is to identify the area which the
hand(s)
% occupies automatically. This is achieved through processing of the
image
% with a threshold type edge detection method in built into MATLAB.
Objects
% are detected from this. The size and area of the objects are determined
% and object of low size or low perimeter to area ratio are discarded as
% not being hands. Other objects which could be detected in the space
could
% be computer mice, cups of hot beverage, residual heat left by the
% arm/finger/hand in the furniture. As hands have a larger perimeter to
```



```

% area ratio than most man made objects, especially when the fingers are
% spread, this can be used to refine the objects in the image.
% The FLIR images evaluated here have the FLIR logo in the top left
corner,
% a temperature bar with min and max temperatures on the bottom row.
Added
% to that in the middle of the image there is a crosshairs. This program
% attempts to detect the min and max temperatures of the images through
an
% OCR (Optical Character Recognition) program. The FLIR logo is blanked
out
% from the images so that it is not detected as an object and the
crosshair
% is removed using a substitution type mechanism of the pixels in the
% area.

```

```

clc, close all, clear all
set(0,'DefaultFigureWindowStyle','docked')
%%imshow('InitialMagnification',100)
iptgetpref('ImshowInitialMagnification')
warning off
%WARNING('off',msgID)

```

```

%% Load Image and convert to Grayscale
I=imread('images/IR_2598.jpg'); % Load the images to be processed

I2=rgb2gray(I); % The image is grayscale anyway, I2 is converted to
                % grayscale.

```

```

cropped = Crosshairs(I); % The crosshairs of the images is attempted to
be
                        % removed by using the Crosshairs function. The
                        % image is also cropped and FLIR logo removed by
                        % this function.

```

```

%% Find significant data within image
for m=4:4
    foreground=imopen(cropped, strel('disk',m));
    % The image is cleaned up, with JPEG artifacts removed and the image
    % is smoothed

    figure,imshow(foreground);
    % The resulting image is displayed
end

```

```

%% Test to see full contrast image
level = graythresh(foreground); % Threshold values for the altered image
% calculated using the graythresh MATLAB native function.
% GRAYTHRESH(I) computes a global threshold (LEVEL) that can be
% used to convert an intensity image to a binary image with IM2BW. LEVEL
% is a normalized intensity value that lies in the range [0, 1].
% GRAYTHRESH uses Otsu's method, which chooses the threshold to minimize
% the intraclass variance of the thresholded black and white pixels.

```

```

fudge2 = 1.3;
% A factor named 'fudge2' is allowed to change the threshold value so
that
% the correct edge can be determined. If the factor is not correct some
of
% the hand/fingers may not be detected properly or furniture could be
% included in the detected area.

```



```

bw = im2bw(foreground,level*fudge2);
% The Image is converted to a Black and White image or logical image
based
% on the threshold value times the value set of fudge2. This means that
% pixels with a value lower than the value of "level*fudge2" will be set
to
% the value 0, and those above set to the value 1. This creates a logical
% matrix in which an edge detection program can be performed on the
logical
% matrix.

% The B&W image is displayed for the user to check
figure,imshow(bw)

%% Find edges within the image

% The native "edge" detection function in MATLAB is called for the B&W
% image created above "bw", the Sobel method is chosen here but others
% were explored during the research, which had very similar edge detection
% for the purposes of finding the outline of the hand.
%
% EDGE takes an intensity or a binary image I as its input, and returns a
% binary image BW of the same size as I, with 1's where the function
% finds edges in I and 0's elsewhere.
%
% EDGE supports six different edge-finding methods:
%
%     The Sobel method finds edges using the Sobel approximation to the
%     derivative. It returns edges at those points where the gradient of
%     I is maximum.
%
% Here the threshold value is found, however development of the code
above
% and conversion to the B&W image makes the thresholding redundant
[junk threshold] = edge (bw,'sobel');

% fudge_factor is set and used to decrease or increase the value of the
% threshold for processing in the 'edge' function
fudge_factor = 0.3;

% Edge function is called and returns a b&w image which contains the
edges
% of objects detected.
bw2=edge(bw,'sobel',threshold*fudge_factor);
figure,imshow(bw2)

% In the folowing script the line created above is not significant enough
% to be processed further so the line is widened using the 'imdilate'
% function
se90 = strel('line',3,90);
se0 = strel('line',3,0);
dilated = imdilate(bw2, [se90 se0]);
%%

% Boundaries are found using the native bwboundaries function which
returns
% a matrix 'L' which contains solid (not outlined) objects detected using
% the edge technique
[B,L] = bwboundaries(bw,'noholes');

```

```

% Display the label matrix and draw each boundary
figure,imshow(label2rgb(L, @jet, [.5 .5 .5]))
hold on

% Each boundary is represented with a different colour
for k = 1:length(B)
    boundary = B{k};
    plot(boundary(:,2), boundary(:,1), 'w', 'LineWidth', 2)
end

% The properties of each region is gained and assigned to stats.
stats = regionprops(bw, 'area', 'perimeter')

%bw3=edge(I2,'prewitt');
%bw4=edge(I2,'roberts');
%bw3=edge(foreground,'sobel');

%figure,imshow(bw2);
figure,imshow(dilated);
title('Dilated image mask');
filled = imfill(dilated, 'holes');
figure, imshow(filled);
title('Binary image with filled holes');

% The original image imported is overlaid with the border created using
the
% above technique
BWnobord = imclearborder(filled, 4);
BWnobord = filled - BWnobord;
figure, imshow(BWnobord), title('Cleared border image');
bw5 = uint8(bw2);
bw5(bw5>0) = 255;
comb1 = imadd(bw5,cropped);

%% Uninteresting space is set to zero.
% All pixels outside of the area in which objects were detected and
deleted
% are blanked, set to zero.
comb2=cropped;
comb2(L<1)=0;

%figure,imshow(comb1);
figure,imshow(comb2);

%% size of image and size of ROI calculated
[x,y]=size(comb2);
i = 0;
p = 0;
for k=1:x
    for l=1:y
        if comb2(k,l)>0
            i=i+1;
        end
    end
end
end

%% Mean is calculated then adjusted to show mean of ROI by
% multiplying by total region then dividing by ROI

% Mean temperature value is calculated here using the Region of interest

```

```

% created 'comb2'. Since the area outside of the ROI is set to zero the
sum
% of it can be calculated for only the ROI area. 'i' is the number of
% nonzero values which the sum is divided by to give the average
% temperature.
m1 = sum(sum(comb2))/i

%% Mean is then compared to the calibrated intensity
% This portion of the programming code is for detection of the
temperature
% max and min which the FLIR infracam displays on all images.

%% Scale of intensity is set up
I3 = rgb2gray(I);
%figure, imshow(I3);
I4 = imcrop(I3, [52 227 137 4]);
%figure, imshow(I4);
m3 = mean(I4);

%% Evaluate Temperature Min and Max from Image

% Min temperature pixels are isolated here.
I5 = imcrop(I3, [14 214 25 21]);
% The image is converted to a B&W image for OCR processing
I5(I5<207)=0;
I5(I5>0)=255;
I6 = im2bw(I5);
% Image presented to OCR program must be in a uint8 format
I7 = uint8(I6);
I7(I7==0) = 255;
I7(I7==1) = 0;

% The image is sent to the OCR program and a set of characters are
returned
% set to 'word3'
[word3] = OCR(I7);
% This character set is converted to a number
tempmin = str2double(word3)

% The same process is completed for Max temperature of the FLIR camera
% image
I51 = imcrop(I3, [204 224 25 11]);
I51(I51<207)=0;
I51(I51>0)=255;
I61 = im2bw(I51);
I71 = uint8(I61);
I71(I71==0) = 255;

[word3] = OCR(I71);
tempmax = str2double(word3)

%% Temperature values given to the calibrated intensity based on
% temperature scale
m4 = double(1:254);
[x1,y1] = size(m4);

% 'dist' is the difference in temperature between units of pixel
intensity
% That is to say, pixel intensity of 100 is 'x Celsius' and a pixel
intensity
% of 101 is 'x + dist Celsius'
dist = ((tempmax-tempmin)/(m4(y1) - m4(1)));

```



```

% The values of temperature of each pixel intensity is set up here in a
% matrix called 'tempvalue'

tempvalue = m4;
g=0;
for g=1:y1
    tempvalue(g) = ((m4(g) - m4(1))*dist) + tempmin;
end

%% Find temperature

% Temperature is found by approximating the pixel intensity to the value
of
% temperature calculated for each pixel intensity value. i.e. 1 to 255
% intensity equals a Celsius temperature value given in tempvalue.
tempvalue(round(m1))

```

It was found that factors were necessary for the interpretation of the images and finding the outlines of the hands in the images. These factors are named 'fudge_factor' and 'fudge2'. These factors would need to be set for each set of images which were largely of the same brightness and hand positioning. Any large differences in image location would need the factors to be reassessed.

As part of the FLIR images there is a minimum and maximum figure for the temperatures given in the bottom left and right, respectively. The code above uses an optical character recognition program (OCR) to determine the values of these figures. The returned values were used to determine the corresponding temperature value of pixel brightness. The minimum temperature value returned corresponds to black, pixel colour is 0, and the maximum temperature corresponds to the pixel value of 255. The matrix 'tempvalue' was set up which holds the temperature value which corresponds to the pixel brightness between 0 and 255. That is to say, 'tempvalue' is a matrix 256x1 in size.

The hand outline, which was found using the edge technique, was then used to find the mean temperature of the pixels in the outline. The shape of the hands was different for each image processed. The outline found was used to black out, or set to zero all other values apart from those which were part of the outline or inside same. By finding the number of non-zero figures and summing the entire matrix of figures the average was found by dividing the first into the second. This average pixel intensity value was then used to find the corresponding temperature on the scale created 'tempvalue'.



Fig. 3-6 Original Image from FLIR Camera for processing



Fig. 3-7 Processing Stage 1: Image cropped, crosshairs, temperature bar, FLIR logo and emissivity value removed



Fig. 3-8 Processing Stage 2: JPEG artefacts removed



Fig. 3-9 Processing Stage 3: Image is converted to monochrome using the grey threshold value

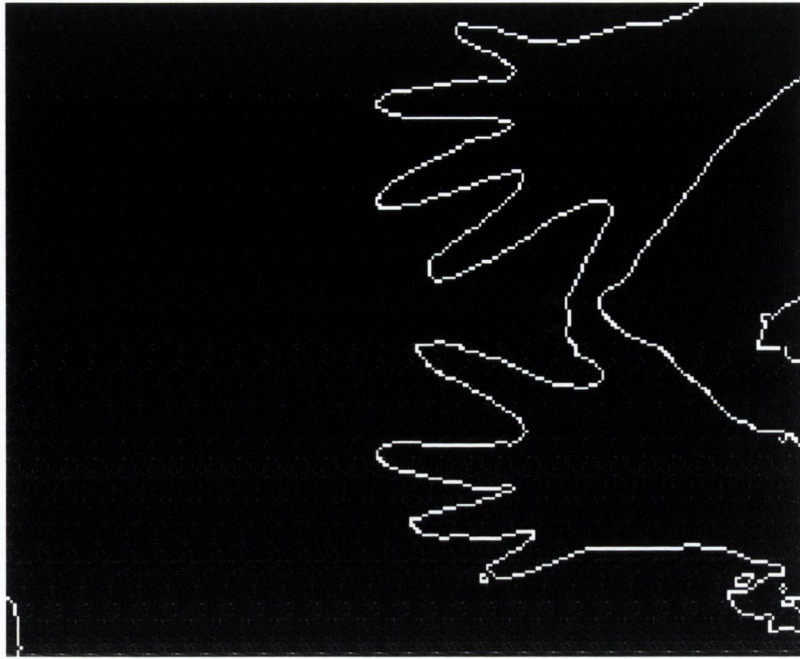


Fig. 3-10 Processing Stage 4: Edges of the monochrome image are found using the EDGE function

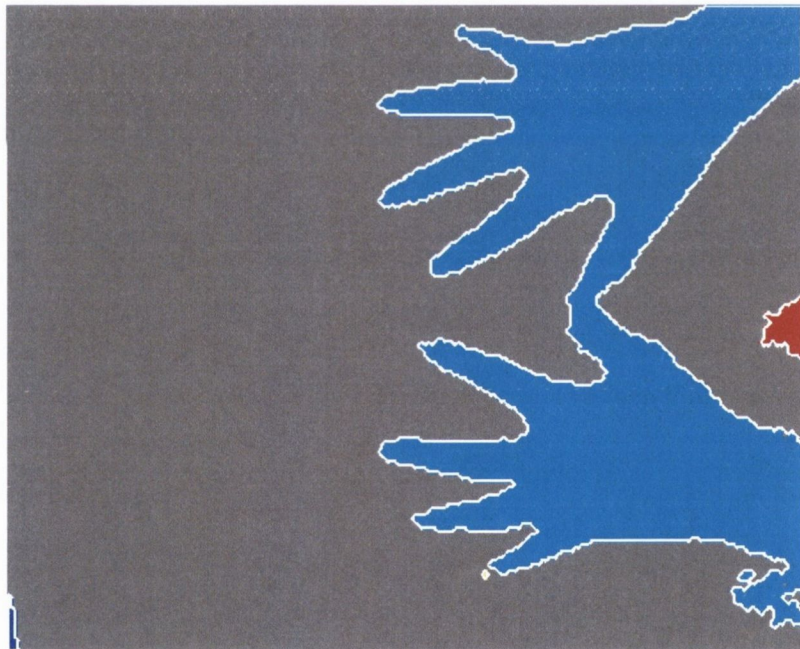


Fig. 3-11 Processing Stage 5: Regions Identified

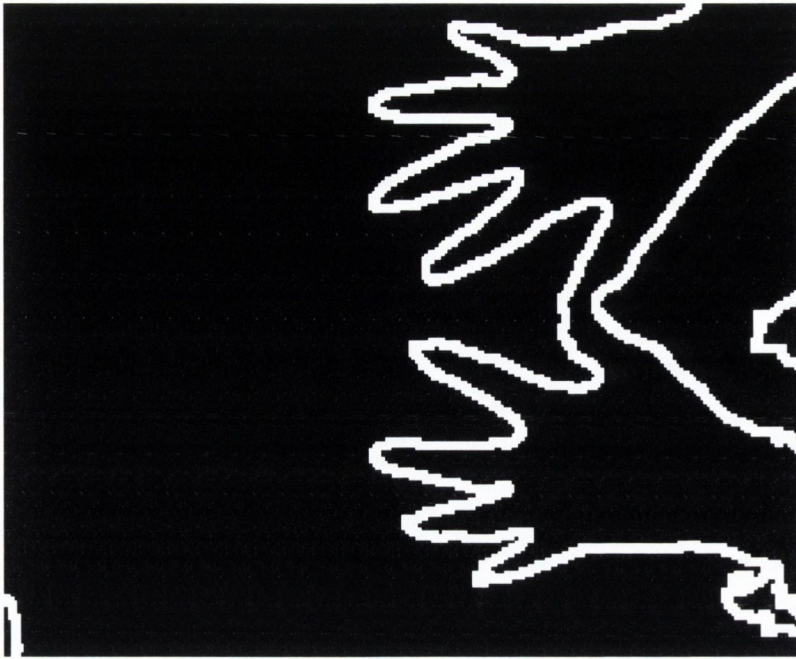


Fig. 3-12 Processing Stage 6: Dilated edge line

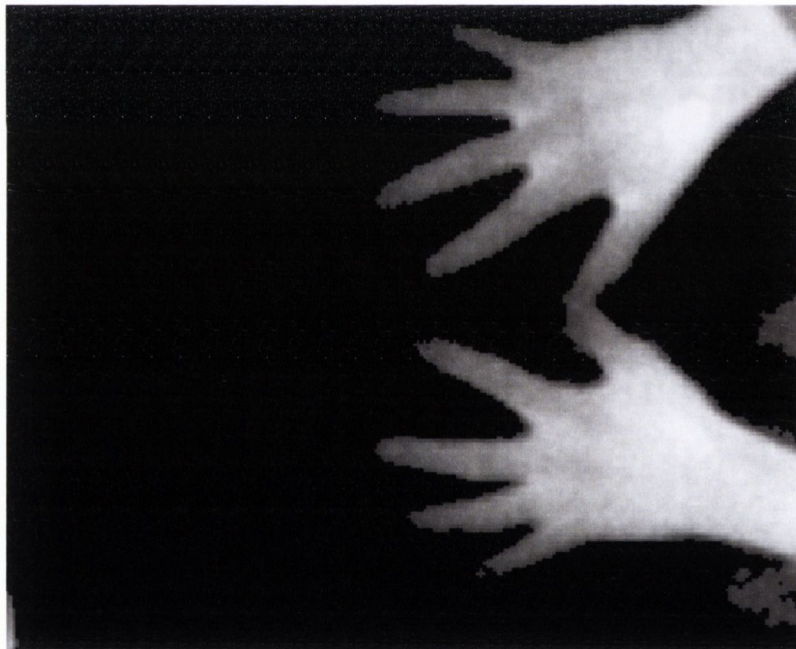


Fig. 3-13 Processing Stage 7: Final image used to find average temperature of the hands

3.2.3.1. *Blanking out regions found of no interest*

The figures drawn by the MATLAB script are shown in Fig. 3-6 to Fig. 3-13. Fig. 3-10 shows the edge of the objects detected using the native 'edge' function in MATLAB. The hands are clearly shown outlined but there are other artefacts found, in the lower left of the image, between the hands and below the left wrist. In the final image, Fig. 3-13, used for measuring the temperature of the hands the artefacts found are shown. In the temperature measurement of the pixels the artefacts were included in this measurement and the average temperature found was of the hands and the artefacts together, in this case 29.3°C was found to be the temperature of the area given in Fig. 3-13.

In order to delete these artefacts from the final image a script was added. The script looked at the "regions" returned from the 'bwboundaries' native MATLAB function. In this script, the regions properties were found and assigned to the variable 'stats'. Region properties perimeter and area were found for each of the regions shown in Fig. 3-11. The area of the hands in every image should be comparatively large. The perimeter should also be large compared to the area, as the fingers and palmar area create a larger perimeter than area relative to a normal shape, circle, rectangle etc. In the following code a radius of a supposed circle is calculated based on the area of each region. The perimeter times the radius divided by the area is queried. If it is less than 1.5 then the region is blanked out. Also if the region has an area less than 1000 pixels the region is blanked. The resulting image is presented in Fig. 3-14. It shows the outline of the regions deleted but the overall region has been deleted. The average temperature of this whole area was calculated again and found to be 29.3°C.

```
stats = regionprops(bw, 'area', 'perimeter');

[s1,s2,s3] = size(stats);

for i = 1:s1
    radius = sqrt(stats(i,1).Area/3.14);
    %stats(i,1).Perimeter*radius/(stats(i,1).Area*2)
    if stats(i,1).Perimeter*radius/(stats(i,1).Area)<1.5
        L(L==i)=0;
    elseif stats(i,1).Area < 1000
        L(L==i)=0;
    end
end
figure,imshow(label2rgb(L, @jet, [.5 .5 .5]))
title('Objects which are not hands are deleted');
hold on
for k = 1:length(B)
    boundary = B{k};
    plot(boundary(:,2), boundary(:,1), 'w', 'LineWidth', 2);
end
```

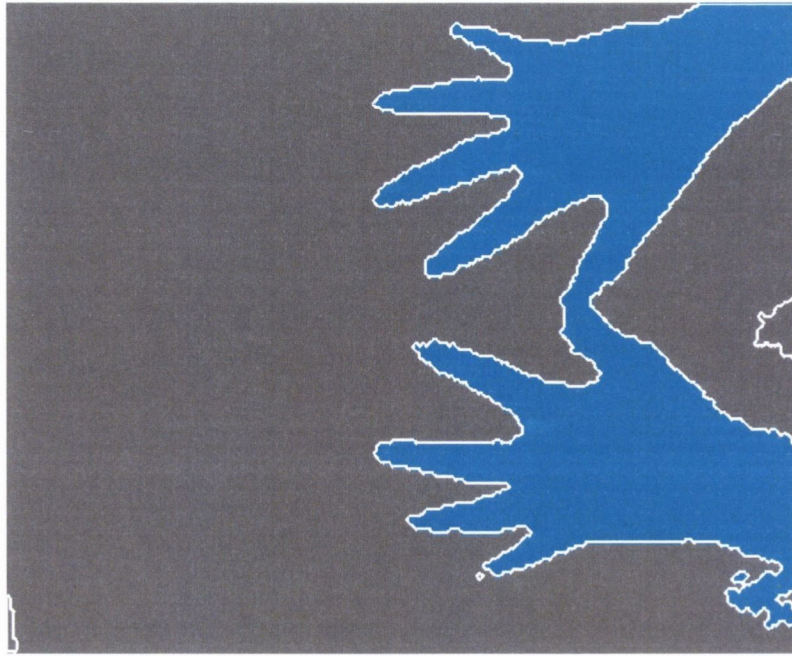



Fig. 3-14 Image Processing: Small regions deleted and low perimeter to area regions deleted

3.2.3.2. Further processing of the Hand Region

Once the region of the hands and fingers was found using the above method, it was decided to split the region up into finger, opisthenar and forearm in order to compare readings of each. Previous research, [30], [59], has shown that the fingers, palmar area and forearm can have distinctly different temperatures which can be linked to thermal sensation.

In order to identify the wrist of the hand for segregating the image into three distinct areas, the forearm, the opisthenar and the fingers, the forearm was designated to come from a side of the image. The distance between each boundary of the forearm, top and bottom, was measured for each image and when the thickness of the arm reached a minimum value before increasing this was marked as the wrist on the image. Forearm and hand were split into distinct areas.

In order to find the line of the knuckles, a centre point of the wrist boundary was found and the furthest pixel within the object from the centre of the wrist on the hand side was found. This was assumed to be the end of the middle finger. The golden ratio was used to calculate the distance the knuckles were from the end of the middle finger. The relationship of the golden ratio to the hand can be seen in Fig. 3-15. The middle finger distal phalange has a ratio of Phi to the intermediate phalange.

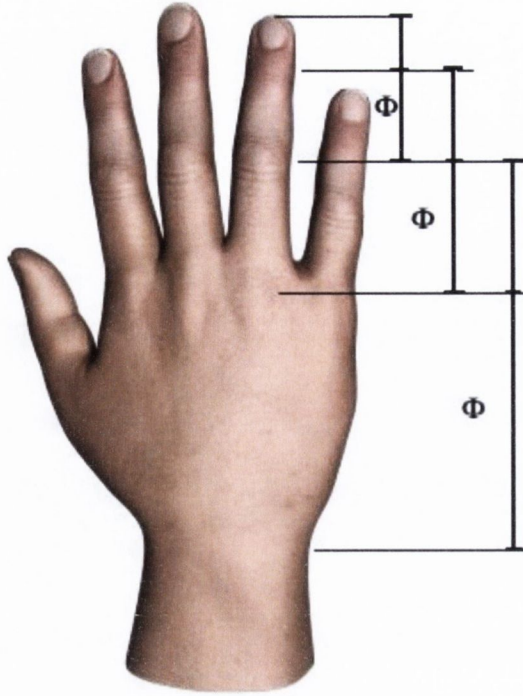


Fig. 3-15 Hand showing the golden ratio Phi relationship of each part of the hand

$$\phi = 1.618$$

$$\phi \cdot d_{\text{dist}} = d_{\text{inter}}$$

$$\phi \cdot d_{\text{inter}} = d_{\text{proximal}}$$

$$\phi \cdot d_{\text{proximal}} = d_{\text{opisthenar}}$$

$$d_{\text{wrists totip}} = d_{\text{dist}} + d_{\text{inter}} + d_{\text{proximal}} + d_{\text{opisthenar}}$$

$$d_{\text{wrists totip}} = \frac{d_{\text{inter}}}{\phi} + \frac{d_{\text{proximal}}}{\phi} + \frac{d_{\text{opisthenar}}}{\phi} + d_{\text{opisthenar}}$$

$$d_{\text{wrists totip}} = 2.236 d_{\text{opisthenar}}$$

where

ϕ is Phi the golden ratio

d_{dist} is the length of the distal phalange of the middle finger

d_{inter} is the length of the intermediate phalange

d_{proximal}	<i>is the length of the proximal phalange of the middle finger</i>
$d_{\text{opisthenar}}$	<i>is the distance from wrist to proximal phalange of the middle finger</i>
$d_{\text{wristtotip}}$	<i>is the distance from wrist to tip of the middle finger</i>

The ratio of opisthenar length to the distance between wrist and tip of the middle finger solved in the equations above was used to calculate the position and angle of the line of the knuckles. This line could be used to split the hand region into two parts, opisthenar and fingers. The thumb if unobscured by the opisthenar is also included in the opisthenar area.

When three distinct areas of the image were identified the three areas were taken in turn to use with the original temperature matrix created by the infrared imager. The area of forearm, opisthenar and fingers were identified within the matrix of temperature and the average temperature of each of these regions was calculated and presented for results analysis. This process was performed on each image captured for each session of the pilot study.

Problems were found with this processing method. While the method worked when a hand was warm it was when the hand was cool or near the temperature of the surroundings that the program could not fully identify the hand and finger area.

3.2.4. Problems encountered with automatic image processing technique

The programming technique above uses the MATLAB native 'edge' function which takes a monochrome image and returns the edge to which it perceives using the algorithm in the function. This edge is perceived on a monochrome image and not a grayscale image which was saved by the infrared camera. By converting the image to a monochrome image, data is lost, the matrix now has values of 0 and 1 rather than values from 0 to 255. In converting the image to monochrome a threshold value for working out what is converted to 1 and what converted to 0 is created which, depending on the image, required adjustment using a scaling factor.

When the threshold value wasn't correctly set the edge detected is problematic. Fig. 3-16 shows the result when the grey threshold value is set to high and portions of the hands are lost in the monochrome conversion process. Fig. 3-17 shows the result when the grey

threshold value is set too low and portions of the furniture, keyboard and background are included in the image for edge detection. The original image is presented in Fig. 3-6.



Fig. 3-16 Grey threshold value scaling factor set too high, portion of fingers lost in monochrome conversion

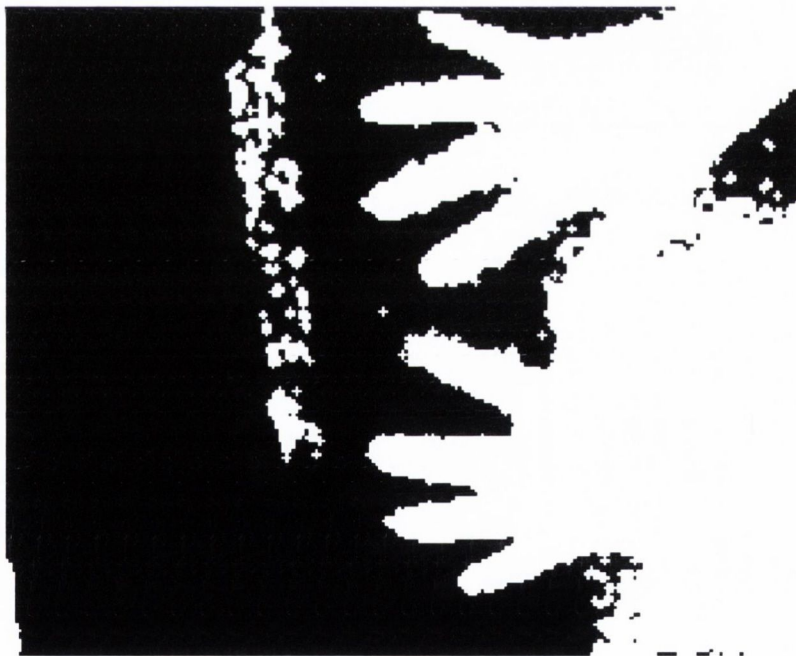


Fig. 3-17 Graythreshold value scaling factor set too low, hands not clearly outlined

Once the grey threshold value was set correctly, the definition of the outline of the hand was not perfect Fig. 3-14 shows the outline of the hands with a large area in the lower right hand corner which the monochrome conversion has included. By adjusting the

scaling factor in small amounts this region can be deleted from the monochrome image, this is time consuming and not an automatic process. Fig. 3-18 shows the result of this and the temperature reported by the program was found to be 29.5°C for this result. The difference from previous measurement was 0.2°C. Changing the scaling factor higher means fewer pixels of the hands are converted to the monochrome image. Therefore measurement of the temperature of the entire hand becomes less accurate as the whole hand was not detected.

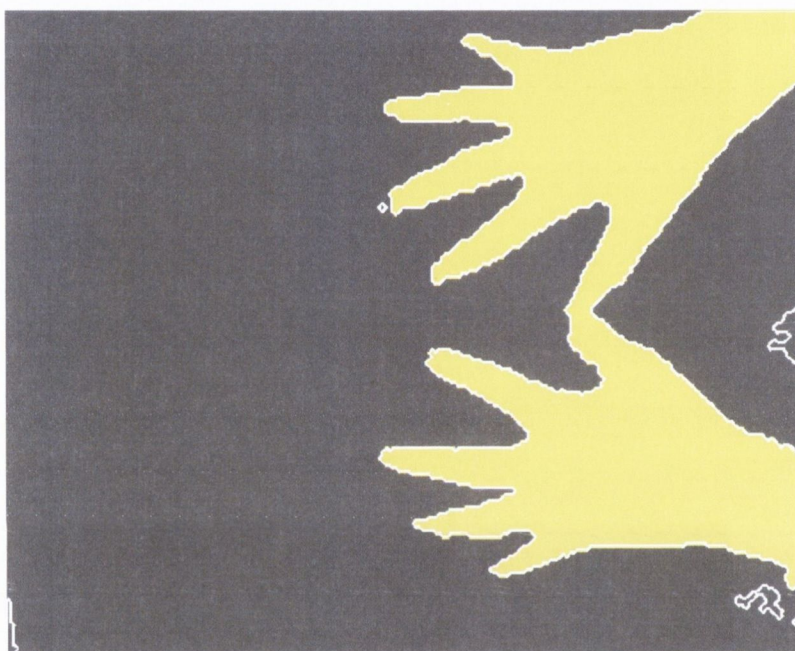


Fig. 3-18 Image processing: grey scaling factor honed

Initially, the infrared image data processed in MATLAB was converted to a bitmap. MATLAB was programmed to take in all the infrared data and return a bitmap image of the temperatures recorded. The program returned a black and white bitmap image in which whiter pixels represented higher temperatures and blacker pixels represented lower temperatures. The minimum temperature and maximum temperature were defined, usually at 25°C and 35°C respectively. The maximum and minimum temperatures were used to define the blackest pixel value 0 and the whitest pixel 255. Any temperatures beyond these values would just have the respective 0 or 255 value. The bitmap was then saved using the same filename with a BMP extension. The user then looked through the images to filter the images and corresponding CSV imager files based on quality of the image, position of the hand and presence of the hand. Once these images were filtered out of the session folder the image processing could begin. MATLAB was programmed to take each image in turn and identify the hand in the image using the Sobel operator edge

technique. Objects other than the hand were filtered out based on area and perimeter of the object. Low area objects and objects with a low perimeter to area ratio were filtered out which left the arm and hand in the image.



Fig. 3-19 Hand identification problems

Fig. 3-19 shows the problems encountered with another processing technique using the golden ratio and Phi relationship of the fingers to the hands. The first image is the infrared image captured by the camera converted to a pixel intensity picture. The hand of the participant is clearly shown in the image. The opisthenar area of the hand is at a much higher temperature to the environment, whereas the fingers are closer to the surrounding environment temperature. The second image displays the results of the Sobel edge detection program when a higher threshold is used. The baby finger of the participant is missing from this detection routine. The third image shows the results when a lower threshold was used for the Sobel edge detection. It is clear that a lot of artefacts have been carried through the processing stage and remain in the image for temperature processing.

In the processed images shown in Fig. 3-19 lines at the wrist and knuckles are shown. The automatic processing of the images first identifies the hand and arm in the image then splits this into the finger, opisthenar and forearm. The split can then be used to measure the average temperature of each segment. For the forearm and opisthenar this mostly worked quite well for average temperature measurement. However, the finger area was very difficult to assess as the 'edge' technique could not properly identify the boundary of the fingers when the fingers were cold.

3.3.Low cost black globe thermometer

A pilot study was proposed in which measurement of environmental variables was necessary for calculating accepted thermal comfort measures, such as predicted mean vote (PMV). PMV requires, among other things, mean radiant temperature, as well as being an important measurement of thermal comfort in itself [68].

A black globe thermometer is essential for calculating mean radiant temperature. In most indoor environments the mean radiant temperature is assumed to be the same as the air temperature, thus negating the requirement of measuring black globe temperature. However, this research requires accurate measurement of PMV. It was decided that a black globe thermometer was necessary for the environmental condition measurement to give an accurate PMV for the occupant location.

Commercially available black globe thermometers are expensive. Due to budgetary constraints, it was necessary to construct a black globe thermometer from low cost parts and compare it to a known manufactured black globe, borrowed from a local university.

3.3.1. Sensors

A PT-100 sensor was proposed as a suitable sensor for placing in the black globe thermometer. A PT-100 sensor is a resistance thermometer which changes resistance with changes in temperature. The PT-100 sensor used in the black globe thermometer (Onset TMC6-HD) uses a copper-plated sensor tip. The PT-100 sensor twinned with the HOBO U12 gives a specified accuracy of $\pm 0.25^{\circ}\text{C}$ from 0°C to 50°C .

The two sensors were connected to an Onset HOBO U12 Temperature/Relative Humidity complete with two external data channels (Fig. 3-20). The Onset unit offered small size, low cost and external channels for sensors of varying type to be connected. Experiments could be easily set up with a large degree of flexibility.

The PT100 sensors are 'off the shelf' sensors and come with a degree of error. No calibration of the sensors took place and therefore larger error will occur from using the values which are logged. As part of a 'real world' test (not climatically controlled), error involved in uncalibrated temperature sensors are considered part of a real world test.



Fig. 3-20 Onset HOBO U12 Data Logger and PT-100 Sensor (www.onset.com, 2012)

3.3.2. Construction of low cost black globe thermometer

Low cost black globe thermometers have been made before using various materials and sizes [70], [71]. ISO 7726:2001 details how to make a black globe thermometer and use calculations given within the standard to estimate the mean radiant temperature [21]. Purswell et al used ISO 7243:1989 to construct a black globe thermometer based on the characteristics given in the standard [72]. Purswell used a copper tank float as the globe, copper offers high conductivity and low thickness, which was then painted black.

A copper float tank with diameter 150mm was used for the black globe thermometer. The black globe was painted in a thin layer of matte black paint as described in ISO 7726:2001

[21]. A hole the size of the sensor was drilled in the globe and the calibrated PT-100 sensor was placed in the black globe and sealed inside using glue. The PT-100 sensor wire was thick and was able to support the end of the sensor in the centre of the globe without further undermining the globe surface with supports. The copper tank float was then mounted on a long screw with a foot to elevate it.

ISO 7243:1989 dictates that temperature sensors used for globe temperature measurement have a measuring range of 20 °C to 120 °C and accuracy of measurement:

Range 20 °C to 50 °C: $\pm 0,5$ °C;

Range 50 °C to 120 °C: ± 1 °C.

The sensor used in this black globe thermometer has a measuring range of -40°C to 100°C in air and accuracy of ± 0.25 °C from 0°C to 50°C. There is no accuracy data outside of this range and the sensor does not comply with the top end of the range specified of 120°C. In this research, globe temperature measured ranged from 15°C to 30°C which is within the allowable range. It should be noted for future research that the black globe thermometer may not have the accuracy needed above 50°C.

3.3.3. Hot plate in cool environment test.

To test the constructed low cost black globe thermometer performance, a commercially available logger and black globe thermometer was borrowed from a local university for the duration of the calibration testing. The low cost globe thermometer was required due to budgetary constraints. A Grant 2020 series logger (Fig. 3-21) was connected to a 40mm diameter manufactured globe thermometer made from plastic, named external globe thermometer. There is a significant difference in size of the black globe thermometers used. ISO 7726:2001 presents equations which are used to calculate globe temperature from the measure temperature. These equations take account of the diameter of the black globe used.



Fig. 3-21 Grant 2020 series data logger

The grant logger and Onset HOBO logger were set up in front of a vertical hot plate in a test chamber.

The low cost globe and external globe were placed in front of the hot plate and connected to the respective loggers. The second PT-100 sensor was connected to the HOBO logger and mounted in the vertical position in line with the globes. The experimental equipment was set up 1 metre from the hot plate in a line as in Fig. 3-22. The equipment was all equidistant from the hot plate and the sensors, both globes and separate PT-100 sensor were placed to the centre of the equipment to ensure the radiant energy from the hot plate fell on the same proportion of each sensor. Both Grant and Onset HOBO loggers were set up to log at one minute intervals. At the beginning of the test the hot plate was turned on. The loggers were started simultaneously to ensure measurement at the same time in every minute of measurement.

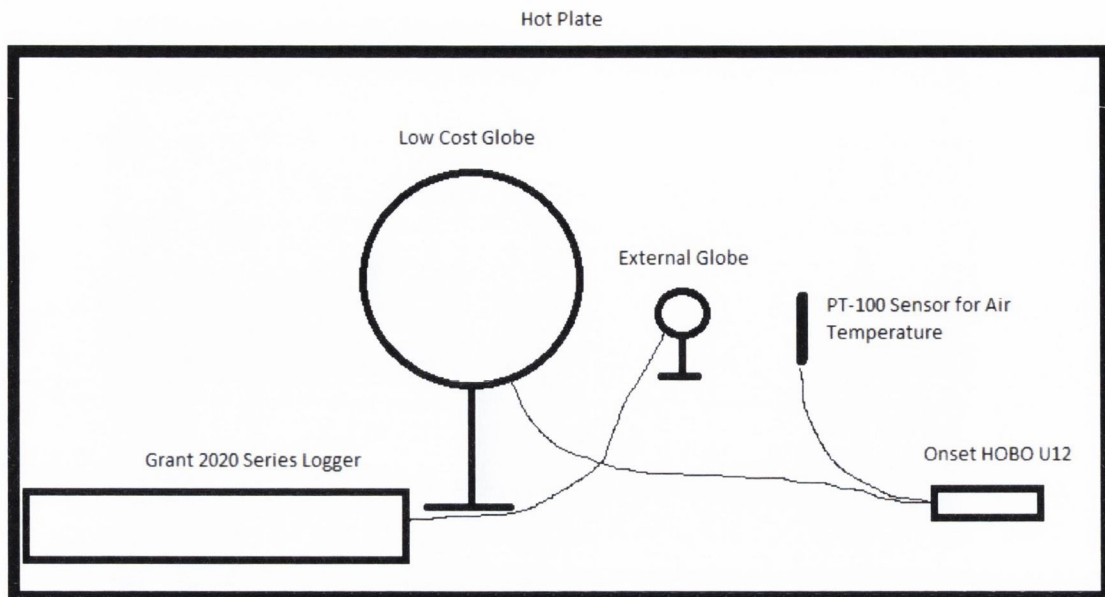


Fig. 3-22 Hot Plate Experiment Equipment Locations

The experiment was conducted over three hours and then the loggers and hot plate were stopped. The logged data was downloaded from each logger. For each minute the mean radiant temperature was calculated based on the Globe temperature and Air temperature, for each globe separately.

The equation used for calculating the mean radiant temperature of low cost globe is given in Equation (2-1). The equation was applied for each minute based on the air temperature and globe temperature recorded. The result was mean radiant temperature (MRT) for each minute of the test.

Mean radiant temperature was calculated again for the smaller external globe. The air temperature recorded was measured by the PT-100 sensor. A graph of the air temperature and mean radiant temperatures of both big and small globes calculated over time was drawn. The data is presented in Fig. 3-23. Error bands were drawn for each calculation of MRT. As can be seen from the graph at all times, the two MRT measurements are within the errors bars of the other. MRT is distinct from air temperature. MRT measured by the low cost thermometer was found to be within the error range of the borrowed smaller globe. The low cost globe was used for the rest of the experiments.

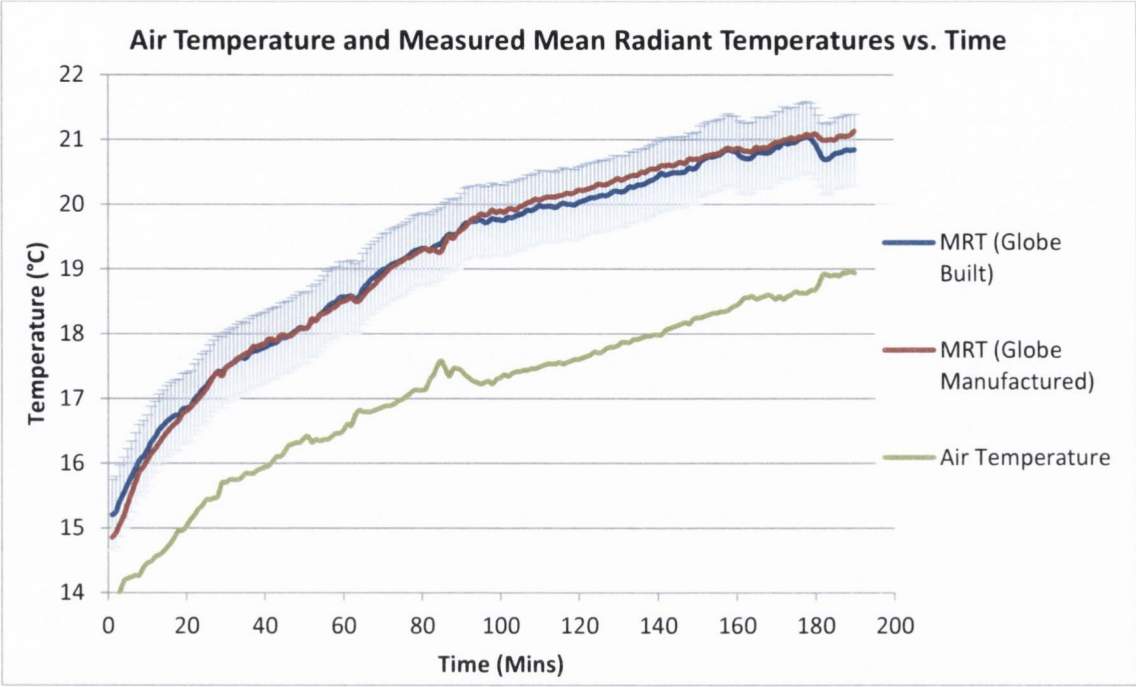
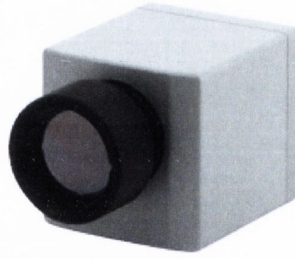


Fig. 3-23 Air and Mean Radiant temperatures compared with air temperature recorded during the hot plate test

3.4.Infrared Imager

An infrared camera was acquired through funding, an Optris PI160 with a 48°x37° lens. This infrared camera offers a small form size, ease of connection to and control by computer and offers the best value based on the needs of this research. The PI160 records infrared imagery in the spectral range 7.5 - 13 μm , which is the range of infrared light given off by skin at normal temperatures. The detector is a FPA, uncooled type offering 160x120 pixel resolution.

Optris PI160 IR Camera



Detector:	FPA, uncooled (25 μm x 25 μm)
Optical resolution:	160 x 120 pixel
Spectral range:	7.5 - 13 μm
Temperature range (scalable via programming keys or software):	-20°C...100°C 0°C...250°C 150°C...900°C, additional range: 200°C...1500°C (option) ¹⁾
Frame rate:	120 Hz
Optics:	23° x 17° FOV / f = 10 mm or 6° x 5° FOV / f = 35.5 mm or 41° x 31° FOV / f = 5.7 mm or 72° x 52° FOV / f = 3.3 mm
Thermal sensitivity (NETD):	0.08 K with 23° x 17° FOV / F = 0,8 0.3 K with 6° x 5° FOV / F = 1,6 0.1 K with 41° x 31° FOV and 72° x 52° FOV / F = 1
Accuracy:	$\pm 2^\circ\text{C}$ or $\pm 2\%$
PC interface:	USB 2.0
Process interface (PIF):	0-10 V input, digital input (max. 24V), 0-10 V output
Standard PIF:	2x 0-10 V inputs, digital input (max. 24 V), 3x 0-10V outputs, 3x relay (0-30 V/ 400 mA), fail safe relay
Industrial PIF:	
Ambient temperature (T_{Amb}):	0°C...50°C
Storage temperature:	-40°C...70°C
Relative humidity:	20 - 80%, non condensing
Enclosure (size / rating):	45 mm x 45 mm x 62 mm / IP 67 (NEMA 4)
Weight:	195 g, incl. lens
Shock / vibration:	25G, IEC 68-2-29 / 2G, IEC 68-2-6
Tripod mount:	1/4-20 UNC
Power supply:	USB powered

Fig. 3-24 Technical Specifications for Optris PI160

While the accuracy of the imager is low the thermal sensitivity is high for the lens used in this research, as can be seen in Fig. 3-24. The Optris PI160 comes with plug-ins ready for

use with LabVIEW and can be programmed using C++ programming language. The accuracy of the Infrared imager was $\pm 2^{\circ}\text{C}$ or $\pm 2\%$. All measurements in this research were between 20°C and 40°C . 2% of that is a max figure of 0.8°C which means that $\pm 2^{\circ}\text{C}$ is the larger accuracy and the one which should be used.

The precision of the imager is very high with the lens fitted of 0.1°C . A low accuracy and high precision means that measurements carried out in the same conditions will yield a high precision but low accuracy. It is assumed that the environmental conditions of each test carried out would not adversely affect the precision and accuracy of the infrared imager. Given that the environmental conditions were the same, the experiments should show a large degree of repeatability. However, should the variance of the temperature of the hands be slight then infrared technology as it stands would not be suitable for this application.

Calibration of the imager was completed in the factory and the calibration files were used in the operation of the camera. The factory recommends re-calibration every year. All tests completed were conducted within a year of delivery from the factory.

All tests were conducted using the same infrared camera. Any discrepancy in measurement would be repeated in each test.

3.5.Pilot Study

A pilot study was designed to assess the response of hand skin temperature to varying environmental conditions. The pilot study was setup in an office environment which the participant occupied. The study was a field type study in which the environment was not controlled. The infrared camera needed reprogramming to log images at defined intervals.

3.5.1. Reprogramming of proprietary software

The software and files which came bundled with the Optris imager contained controlling software, calibration files for the specific imager bundled, LabVIEW program examples and C++ example software.

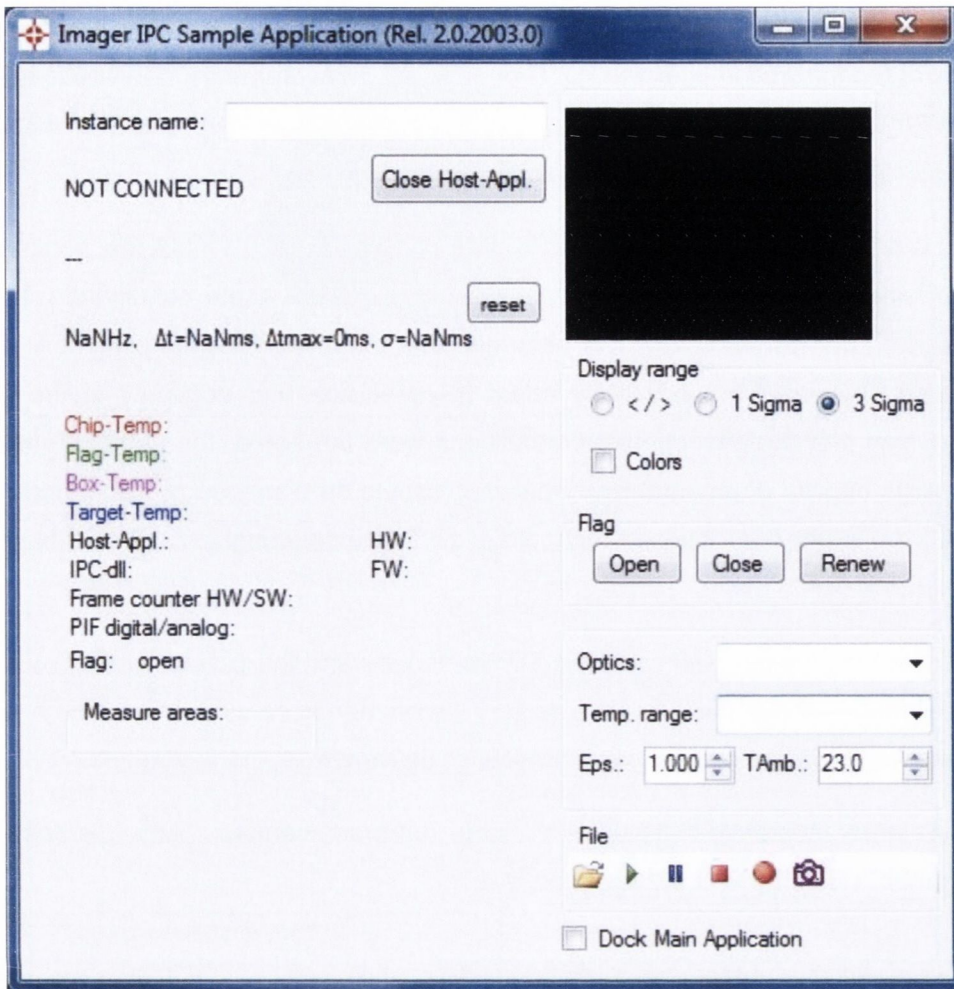


Fig. 3-25 Imager IPC Sample Application C++ Programmed Communicating with PI Control

C++ programs for total control in real-time of the Optris PI160 came with the imager. The C++ software communicates with the PI Control. PI Control is the proprietary software which controls the infrared camera. The PI Control software communicates directly with the imager and all communication is through the PI Control program. The C++ program provided detailed information about the imager and shows an infrared image in the black box, Fig. 3-25. The infrared image itself is not sent through the C++ program and actually points to the image provided by the PI Control program. Therefore, capturing of the imagery provided by the PI Control program would have to be done through the PI Control program. A solution to this was to set up the C++ program to tell PI Control to take a snapshot. A snapshot was then timed using the C++ program to every 30 seconds once the signal was sent to PI Control takes a snapshot and saves it in a designated folder and format as given in the preferences.

The code, an extract of which is shown in Fig. 3-26, utilised an existing 100ms timer in the code for which an integer was defined in the header files called 'takeSnap'. takeSnap

increased in value every 100ms cycle until it equals 300 when the functions calls 'ipc->FileSnapshot(0);' which takes a snapshot of the current image on the infrared camera. The snapshot is saved to the default directory and under the folder settings of the infrared PI control program. The infrared imager data file is then used later on during image processing. The full C++ coding is included in Appendix 9.5 C++ Programming Code.

```
HRESULT FormMain::MainTimer100ms(void)
{
    Painted = false;
    if(Connected && progressBarInit->Visible)
    {
        int i = ipc->GetInitCounter(0);
        progressBarInit->Value = progressBarInit->Maximum - i;
        progressBarInit->Visible = (i != 0);
    }
    if(takeSnap < 300) {

        takeSnap += 1;

    }
    if(takeSnap == 300) {
        ipc->FileSnapshot(0);

        takeSnap = 0;
    }
    return S_OK;
}
```

Fig. 3-26 C++ Code inserted into proprietary Optris software

3.5.2. Thermal Sensation Survey

The thermal sensation survey was an integral part of the pilot study as this recorded the thermal response of the participant. Thermal sensation was then compared to other predictive measures of thermal comfort such as PMV and operative temperature, it was also compared to hand skin temperature in order to investigate correlation. Previous research has used the ASHRAE thermal sensation scale and thermal preference scale given in Table 2-1 [68], [67]. The survey created asked the participant "How do you feel at this time?". Participants scored their thermal sensation based on the ASHRAE scale by circling a number. The survey also asked "I would prefer to be:" and participants similarly answered based on the ASHRAE thermal preference scale. The participant was asked to fill out the survey every 5 minutes while seated at their desk. Timing of the survey was achieved using a repeating countdown timer which would beep when the participant was to record a measurement. Coordination of measurement was essential to ensuring every measurement was taken at the same measurement time in each minute or five minute

measurement cycle. Fig. 3-27 shows a sample survey given to the participants. Humphries et al have used the same survey type in his research into accuracy of PMV and finger temperature [2], [68]. The participant was asked to indicate ‘How do you feel at this time?’ based on a scale of 1 to 7, as shown. The participant circled the number which most represented his or her feeling. At times the participant indicated being between feelings by indicating a response between the numbers presented. The participant was asked to fill out preference, ‘I would prefer to be:’ based on thermal preference scale.

Name:								Session:						
	How do you feel at this time?							I would prefer to be:						
Time	Cold	Cool	Slightly Cool	Neutral	Slightly warm	Warm	Hot	Much cooler	Abit cooler	No change	Abit warmer	Much warmer		
	1	2	3	4	5	6	7	5	4	3	2	1		
	1	2	3	4	5	6	7	5	4	3	2	1		
	1	2	3	4	5	6	7	5	4	3	2	1		
	1	2	3	4	5	6	7	5	4	3	2	1		
	1	2	3	4	5	6	7	5	4	3	2	1		
	1	2	3	4	5	6	7	5	4	3	2	1		
	1	2	3	4	5	6	7	5	4	3	2	1		
	1	2	3	4	5	6	7	5	4	3	2	1		
	1	2	3	4	5	6	7	5	4	3	2	1		
	1	2	3	4	5	6	7	5	4	3	2	1		
	1	2	3	4	5	6	7	5	4	3	2	1		
	1	2	3	4	5	6	7	5	4	3	2	1		
	1	2	3	4	5	6	7	5	4	3	2	1		
	1	2	3	4	5	6	7	5	4	3	2	1		

Fig. 3-27 Sample Thermal Sensation and Preference Survey

The ASHRAE scale of thermal sensation has been used in other research concerned with thermal comfort [3], [8], [10], [30], [68]. It is used in this research as a direct comparison between participants in the study. Comparison of thermal sensation scale has been used extensively to investigate the response of humans to environmental stimulus [8], [68]. This research used the ASHRAE scale and preference scale to compare the responses of individuals. An assumption was made that the thermal sensation scale as recorded by the participant is directly comparable. That is, when two participants felt ‘neutral’ they were experiencing the same psychological effect of satisfaction with the environment. It was also assumed that when participants recorded the same thermal sensation in different tests at different times of the year that the participant is feeling the same sensation. The ASHRAE scale was developed to allow this assumption to be made for direct comparison of sensations [31].

3.5.3. Infrared Imaging of Hands

It was proposed that hand skin temperature through infrared could be used to measure thermal sensation of a subject. Previous research, by Wang and Humphreys, has shown a link of hand skin temperature to thermal sensation [30], [68]. The purpose of this pilot study is to corroborate the previous research into the area and produce data from a field study in which multiple measurements are made during a short period to track the changes in hand skin temperature.

Humphreys et al used finger temperature measured using a thermistor held between thumb and forefinger to link to the measured value of globe temperature in a field study. Humphreys showed that finger temperature was a better variable to use than globe temperature in predicting the thermal sensation of subjects. During the test a single measure of finger temperature and thermal sensation was made. Wang et al used finger, hand and forearm temperature in a controlled environment to link to thermal sensation. Subjects were placed in a climatically controlled chamber and temperatures of the arm and hand skin were measured over time and compared to thermal sensation data recorded.

The aim of this pilot study was to investigate the links of opisthenar and index fingernail temperatures to ASHRAE scale and preference scale thermal comfort surveys. Tests were performed on participants over a period of time in an uncontrolled field environment. The link of hand skin temperature was compared against the existing accepted measurements of thermal comfort. The results of these tests are presented in *Chapter 4 Pilot Study: In-depth test results* and *Chapter 5 Pilot study: Other participant results*.

3.5.4. Participant acquisition and information

Potential participants from within the research centre were canvassed based on gender, time spent at a computer desk and body mass. Four participants were identified who would spend long periods of time sitting at a computer. Sitting at a computer doing 'light sedentary work' has been approximated as having a metabolic rate of 70 W/m^2 , as per Table 2-3.

Participant no.	Gender	Age	Build	Weight	Usual Clothing
M1	Male	29	Broad	99kg	Thick Jumper, Jeans
M2	Male	25	Broad	92kg	Thick Jumper, Jeans
F1	Female	25	Slight	58kg	Thin Jumper, Jeans
M3	Male	30	Slight	60kg	Very Thin Jumper, Jeans

Table 3-1 List of participants and characteristics for pilot study

All participants were in the 25-30 age range, two had a similar weight, 92kg and 99kg, and the other two also had a similar weight, 58kg and 60kg. There was only one female in the pilot study. The two males of similar weight, M1 and M2, also had similar height. Comparison of these two participants was performed to assess the similarity of thermal preferences for persons of similar physiology. Other research into the relationship of hand skin temperatures and thermal sensation have not investigated the difference of physiology of subjects [30], [68]. A thermal sensation questionnaire, as shown in Fig. 3-27, was given to the participants at the start of each test to fill out thermal sensation and thermal preference. The questionnaire was explained to the participant using the same language in each case. Using the same language was to ensure that each participant recorded sensation and preference data in the same manner. Comparison of the data could be carried out between participants. The response of the participants was measured according to the physical attributes presented. At this early stage 4 participants were selected to investigate the relationship of hand skin temperature to thermal comfort. The pilot study collected a lot of data in just 8 tests on 4 participants. A number of variables were logged in minute or half minute intervals which for a two hour test produced 120 to 240 data points. Each infrared capture contained 19,200 data points of information. A way of efficiently processing the data was needed. Increasing the sample size to 10 or 20 people would have tripled or quadrupled the data collected and need for processing. In further research, by this author or by others the capacity to increase the sample size should be considered.

3.5.5. Pilot Study Method

The literature review showed previous experiments in which thermistors were used to measure temperature on subjects. In this research an infrared camera was used mounted on a tripod and trained on the area in which the hand would normally be. The environmental variables measured, were measured locally, on the desk of the participant in order to have the most accurate readings. Syncing the recording of the environmental variables and infrared data was achieved by starting the two loggers at the same time. An alarm was set up to repeat every five minutes synced with the two loggers. The alarm was

used to tell the participant who was working on a computer to record thermal sensation and preference data.

The participants identified in 3.5.4 were tested in morning sessions and afternoon sessions. The participants were asked to be normally seated at their desk and perform the same movements and processes they would normally do during the day. The experimental equipment consisted of the Optris PI160, Tripod, Hobo U12 Logger, Low cost globe thermometer, cables and laptop.

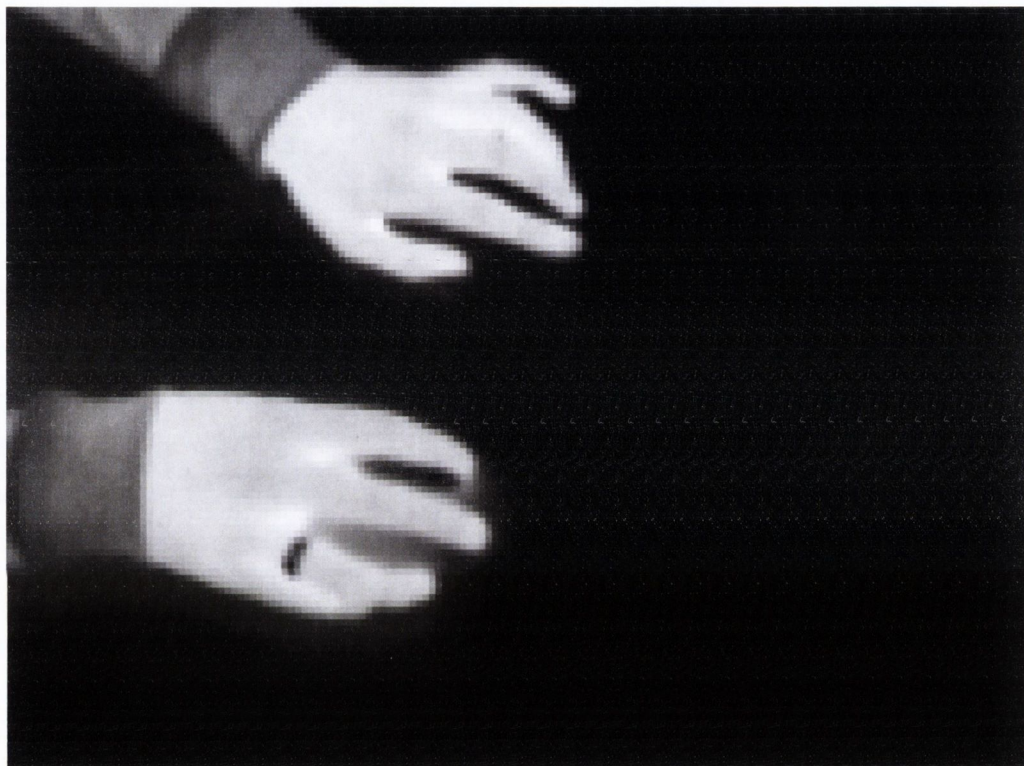


Fig. 3-28 Typical infrared image captured using the Optris Camera

The equipment was set up on the participant's desk. Optris camera was secured to the tripod and tripod was extended to allow the camera a viewing area which would contain the movements of the hand during the test. The tripod was placed on the desk and the camera was pointed downwards toward the mouse and keyboard area of the desk. The laptop was set up next to the camera and the PI Connect software was run and the C++ software was run to record the images produced every 30 seconds. The PI Connect software was set up to record a CSV file of temperature rather than a Bitmap file. The CSV file actually recorded the temperature value rather than pixel brightness and was easier to use in data processing. Each pixel was recorded as a temperature in degrees Celsius. The Hobo U12 logger was started and the low cost globe thermometer was connected and logged. The Hobo U12 recorded air temperature, relative humidity and globe temperature.

At the start of the test the participant was given a thermal sensation survey. The survey was explained using the same language for each participant. Once the alarm signalled the participant recorded thermal sensation and thermal preference data while they were at their desk. Alarms were triggered every 5 minutes and synced to the other loggers and infrared camera recording times.

The HOBO U12 logger was used to measure air temperature, globe temperature and relative humidity at one minute intervals. Accuracy in measurement of temperatures was specified by the logger as $\pm 0.35^{\circ}\text{C}$, for conditions of 0°C to 50°C . Relative humidity was specified to be accurate to $\pm 2.5\%$, between 10% and 90% relative humidity. For all tests temperatures and relative humidity measured was found to be within these ranges hence the error range specified could be used. Measurement of these environmental variables was conducted at a level of 1 metre from the floor level near the participant to account for any local variance in environment. This was done to ensure repeatability and validity between tests and participants.

ASHRAE Standard 55 suggests acceptable thermal environments for the purposes of thermal comfort [31]. The standard suggested operative temperature and relative humidity combinations which offer the most thermal comfort. These ranges in operative temperature are accurate to the nearest unit of degrees Celsius. Since the measurement of air and globe temperature was accurate to $\pm 0.35^{\circ}\text{C}$ which by calculation of operative temperature means the accuracy was decreased to $\pm 0.5^{\circ}\text{C}$. The HOBO U12 was deemed to be accurate enough to determine the effect of the thermal environment on the participant. The HOBO logger has been tested by the manufacturer and was found to have a drift in logging temperature of 0.1°C per year. The HOBO U12 purchased for this research was less than a year old for most of the tests carried out in this research.

The infrared camera was programmed with the ambient air temperature and emissivity of human skin (0.98) to increase the accuracy of measurement. The camera was mounted away from other sources of infrared light such as sunlight and hot objects like radiators to ensure accuracy of measurement. If a radiant source is in the field of view of the camera particularly on the participant's hands the results could be skewed by local heating of the hands. The temperatures recorded by the infrared imager produced a matrix of temperatures. Average temperatures were calculated to avoid any discrepancy in the measurement of a single pixel and increase accuracy of the measurement.

3.5.6. Pilot Study Tests carried out

Participant	Study	Test Type	Date	Start Time	End Time
M1	Pilot Study	Afternoon	23/07/2012	15:20	16:16
M1	Pilot Study	Morning	24/07/2012	11:18	12:15
M2	Pilot Study	Afternoon	24/07/2012	15:18	15:41
M2	Pilot Study	Morning	25/07/2012	11:34	13:28
M3	Pilot Study	Morning	26/07/2012	11:25	12:28
M3	Pilot Study	Afternoon	26/07/2012	14:46	16:14
F1	Pilot Study	Morning	01/08/2012	11:13	12:49
F1	Pilot Study	Afternoon	01/08/2012	14:06	15:08

Table 3-2 presents a summary of the pilot study tests carried out for each participant. Each participant was subject to an afternoon and morning test. Some were on the same day others were on different days but each test on each participant was within one day of the other test and all test carried out were within two weeks of each other.

The number of participants was low at this point in the pilot study in order to ensure the method was correct for processing the images and measuring temperature of the hand. Further study could include for more people. However, the concept of using infrared cameras to detect hands and measure skin temperature needed to be proven before the experiment can be expanded to include to more people. The amount of data collected was very large and processing of the data from additional participants would be cumbersome. The data collected is not considered representative but rather to analyse possibilities of using infrared cameras to determine skin temperature and relate this to thermal comfort.

Participant	Study	Test Type	Date	Start Time	End Time
M1	Pilot Study	Afternoon	23/07/2012	15:20	16:16
M1	Pilot Study	Morning	24/07/2012	11:18	12:15
M2	Pilot Study	Afternoon	24/07/2012	15:18	15:41
M2	Pilot Study	Morning	25/07/2012	11:34	13:28
M3	Pilot Study	Morning	26/07/2012	11:25	12:28
M3	Pilot Study	Afternoon	26/07/2012	14:46	16:14
F1	Pilot Study	Morning	01/08/2012	11:13	12:49
F1	Pilot Study	Afternoon	01/08/2012	14:06	15:08

Table 3-2 Pilot Study Test Summary Table

3.5.7. Problems encountered in using infrared to measure hand skin temperature

The pilot study initial image processing used the automatic hand detection software described in MATLAB script Appendix 9.6.1 adjusted to allow for multiple images and using the new Optris camera CSV file data. Early on in the processing of this data it became apparent that the fingers of the participants were not always found using the program.

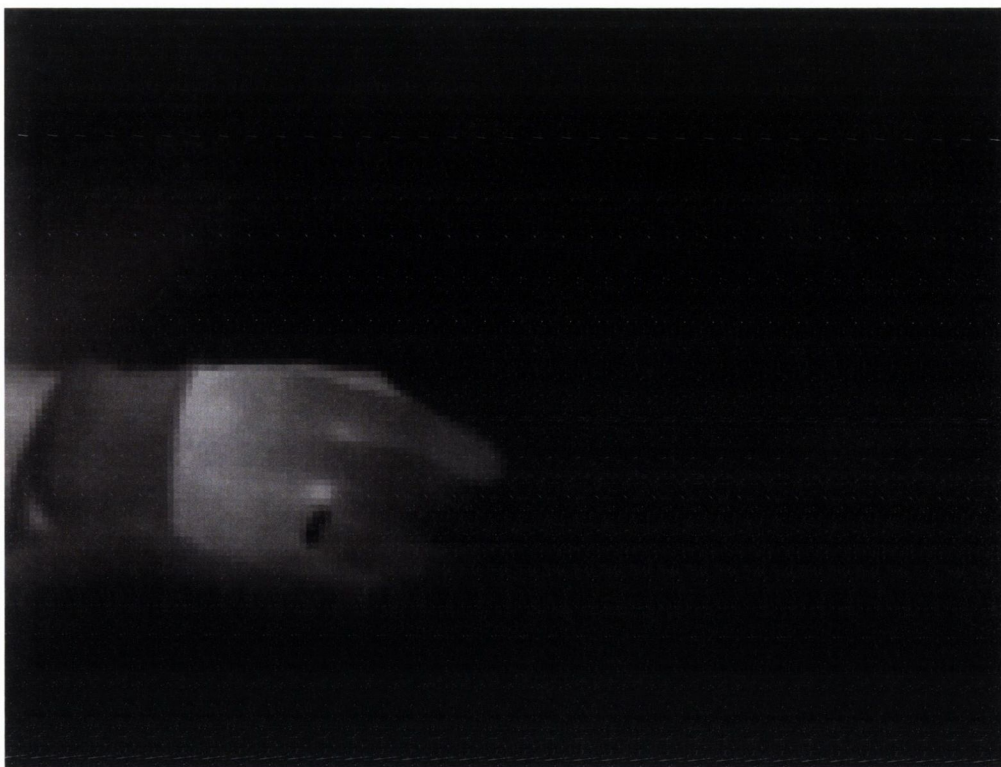


Fig. 3-29 Typical infrared image of cold hands, fingernails/fingertips not visible, skin temperature too low.



Fig. 3-30 Infrared data converted to a black and white image where brightness is turned up to show discrepancy in data for the fingers

3.5.7.1. *Automatic Hand Recognition*

The automatic hand recognition program had difficulty identifying the whole of the hand in the infrared images at times. When the background of the images, usually the desk at which the participant was working, was close or at the same temperature as portions of the skin the automatic hand recognition did not identify the entirety of the hand. Settings were adjusted to try to fix this problem but the program either identified the background being part of the hands or cut off the cold portions of the hand, usually the finger tips.

The results showed that the fingertips or fingernail of the hand showed the highest variance in temperature value allowing the accuracy of the infrared camera to be somewhat abated. However, the identification process did not identify the hand. In fact, on closer inspection of the infrared images, when the skin was found to be the same temperature as the furniture or desk area there was no data in the infrared image which could be used to identify the hand.

The MATLAB native 'edge' function and other functions used for image processing use the difference in pixel colour or brightness to find the edge. In some images the boundary between the skin or fingernail of the hand and the desk could not be identified. In these cases there is no data in the infrared image to show this boundary.

Since the data is not there and the boundary cannot be found in a number of cases, the use of an automatic program for image processing was curtailed as the temperature data for the hand and finger area especially was skewed toward the warmer parts of the fingers/opisthenar. This research was concerned with whether infrared cameras can be used for measurement of the temperature of the skin and whether skin temperature can be used to assess thermal comfort. The infrared camera was having problems in automatic identification. However, assessment of using fingernail or opisthenar temperature for thermal comfort assessment continued to be investigated.

It was decided to reassess the pilot study data using the manual technique described in Section 3.5.7. The data was considered more accurate since the operator could approximate the location of the fingernail and opisthenar more accurately than the program in conditions where the skin temperature was near that of the surroundings. Further tests were carried out as described in Section 3.6 to fully assess the use of infrared cameras in thermal comfort assessment.

3.5.7.2. *Location of Hands in the field of View*

Another problem which occurred during the testing process with infrared was determining locations of the hands. Whole tests were discarded as the participant moved hands

regularly from several locations on the desk completing work. The infrared camera was not adjusted to take into account all of these locations. In setting a system up in an office environment the location of the hands of subject would need to be clearly defined for detection. In widening the viewing angle of the camera or placing the sensor further away from the point of interest reduces the number of pixels which represent the hand in the image, which in turn reduces the number of pixels in the areas of interest. The number of pixels used to calculate T_{opis} and T_{index} is reduced and thus the accuracy of measuring the average of these values is decreased.

3.5.8. Data Processing

Following on from the initial image processing carried out on the pilot study data which showed problems in identifying the skin of the hand, the pilot study data was reassessed using a manual hand identifying technique which used an operator to point to the right areas for temperature measurement.

At the end of each session the computer data was placed in a computer folder for processing. The data consisted of CSV temperature matrix files from the infrared imager recorded every 30 seconds, a CSV file containing environmental data, downloaded from the HOBO U12 logger, and a file of the thermal sensation and thermal preference of the participant input from the paper survey filled out.

3.5.8.1. Measurement of Opisthenar Temperature

A MATLAB program was developed to combat the problems of automatic hand recognition described above. This program used a manual technique for pinpointing the skin of the hand in the images.

The program converted the temperature matrix recorded by the infrared camera (CSV file) to a black and white image using brightness to represent temperature which is presented in Appendix 9.6.6.2. These images were presented to the user. The user was asked to identify two measuring areas, index fingernail areas and the opisthenar area. The user was asked to click the centre of the opisthenar area to be measured and then the user was asked to click the centre of the index fingernail, middle fingernail and ring fingernail. The script of the MATLAB code for this is presented in Appendix 9.6.6.1.

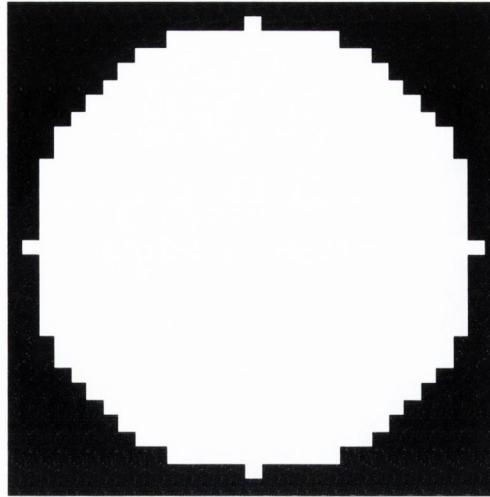


Fig. 3-31 Circle, diameter 29 pixels, to identify pixel temperatures for measuring opisthenar area

The input of the user for positions of opisthenar and fingernail areas was used to isolate an area of interest in which an average temperature of the areas was measured using a circle with centre where the user had clicked. A circle was used to allow for the different orientations of the opisthenar and fingers.

The following code presents how a circle is made in a matrix of size x by x, as shown in Fig. 3-31.

```
% Size of the opisthenar area is set by x
x = 30;

% A grid is setup rr contains column names in each row cc contains
row
% names in each row.
[rr cc] = meshgrid(1:x+1);

% A circle is set up using RR and CC defined above. The circle is a
% matrix in which the circle is represented by '1's
C = sqrt((rr-((x/2)+1)).^2+(cc-((x/2)+1)).^2)<=x/2-1;
```

MATLAB was programmed to create a circle of diameter 29 pixels, Fig. 3-31. The circle created was a logical matrix where pixels had a value of 1 or 0. Matrix locations with the value of 1, shown as white in Fig. 3-31, were the pixels in the images of interest. The matrix locations with a value of 0, shown as black in Fig. 3-31, were discarded in the image of interest in order to get the average value of the pixels within the circle. MATLAB was programmed to take the co-ordinates of the User designated position (mouse click on position of opisthenar) for the opisthenar area as the centre of a square of dimensions 31x31 pixels from the original matrix of temperatures. The square was given a new name for processing. The square was then compared to the logic circle created earlier. When the logic circle value was 0 the value of the same location on the square was set to 0. The

square now represented the area of interest with temperature values. Average temperature value was calculated by the MATLAB program for the circle of temperatures representing the opisthenar region as indicated by the user input. The temperature was calculated for all infrared images and was known as T_{opis} .

The following code is used for finding the temperature of the operator assigned opisthenar location in the image presented.

```
% The Co-ordinates need to be rounded to the nearest integer so that
% the program can find the corresponding pixel. Minimum and maximum
% values for a square surrounding the centre pixel are found and
% assigned values ymin, ymax, xmin, xmax.
ymin = round(y1-x/2) ;
ymax = round(y1+x/2) ;
xmin = round(x1-x/2) ;
xmax = round(x1+x/2) ;

% Checks to make sure that the circle is within the matrix of
% temperatures gathered by the infrared camera
if y1-x/2 < 1
    C = C(abs(ymin)+2:x+1,:) ;
    ymin = 1;
end
if y1+x/2 > high
    C = C(1:high-ymin+1,:) ;
    ymax=high;
end
if x1-x/2 < 1
    C = C(:,2+abs(xmin):x+1) ;
    xmin=1;
end
if x1+x/2 > wid
    xmax=wid;
end

CSVOpis = CSV(ymin:ymax,xmin:xmax) ;
% This line assigns a portion of the matrix surrounding the centre
% pixel given by coords. The temperature data is assigned to CSVOpis

CSVOptic = image3(ymin:ymax,xmin:xmax) ;
% as above the temperature square is found, the corresponding image
% data is also found which can be used for fault finding assigned to
% CSVOptic

CSVOptic(C==1)=0;
% All values in CSVOptic in which C equals 1 are set to zero. This
% effectively blanks a circle of the optical data rather than a
square.
% The circle has the same dimensions that C.

image3(ymin:ymax,xmin:xmax)=CSVOptic;
% image3 is assigned the value of CSVOptic. image3 now has a circle
of
% black in every point where the opisthenar temperature measurement
% average will take place.

imshow(image3)
```



```

% The operator is shown the image with the black pixels

CSVOpis(C==0)=0;
% All values in CSVOpis in which C equals zero are set to zero. All
% values outside of the 'circle' are set to zero. This effectively
% preserves all the data from the circle and can be averaged in the
% code below.

AVG(i,1) = sum(sum(CSVOpis))/sum(sum(CSVOpis~=0,1));
% Opisthenar temperature is averaged by finding the sum of all
% temperature values in the matrix CSVOpis and dividing by the number
% of nonzero values.

```

The circle for measuring average skin temperature included for 613 points which the infrared camera detected temperature. The opisthenar circle size was adjusted for each test so that only skin temperature was averaged in the calculation, the number of points of measurement would change on changing the diameter of the measurement circle. The temperature was averaged for these points. The high number of data points which were used to calculate T_{opis} ensured that any difference in the area of the opisthenar chosen by the operator of the program would be negated.

3.5.8.2. Error in measurement of Opisthenar

There was considered an error in the operator choosing the location of the centre of the opisthenar in each image. However, the error was considered negligible as the average of 613 points meant that overall change in the opisthenar temperature was the main factor influencing T_{opis} . In order to prove that the temperature measurement error was negligible, images collected by the infrared camera re-evaluated to determine the accuracy of T_{opis} and the results showed that T_{opis} was within 0.2°C in all cases. This was deemed acceptable considering the accuracy of the other variables measured and the range of values of hand temperatures recorded. Hand temperatures were found to vary by 5°C for T_{opis} and 10°C for T_{index} in the pilot study. This range was explored further in the results.

3.5.8.3. Measurement of Fingernail Temperature

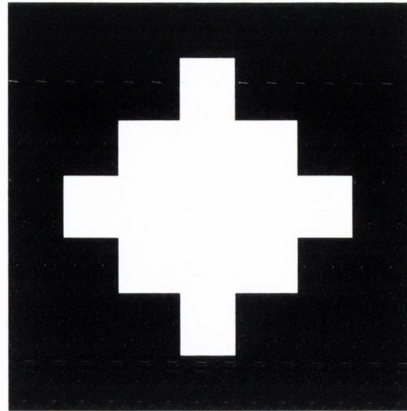


Fig. 3-32 Circle, diameter 5 pixels, to identify pixel temperatures for measuring fingernails

Similar processes were used to identify and calculate the average temperature for the fingertip regions. The fingertip in the images logged was mostly fingernail which in the literature review found that skin and nail had almost the same emissivity that it was a negligible difference [57]. It was assumed that the fingernail and skin of the finger had the same emissivity (0.98).

A circle of diameter 5 pixels was used to measure the average fingernail temperature, Fig. 3-32, from the original temperature files recorded by the infrared imager. MATLAB was programmed to ask the user to identify the index fingernail. The program then calculated the average fingernail temperatures based on the user input and the circle of diameter 5 pixels. The user was then presented with the next image in the run of images recorded to perform the same user input operations. This temperature was known as T_{index} .

Measurement of T_{index} was achieved through averaging the temperature recorded in 13 pixels of the infrared camera. The index fingernail was generally found to be a homogenous temperature, unlike the opisthenar which had temperature changes due to variations in blood flow in veins and arteries. Index fingernail does not have the same amount of blood flow therefore the temperature was found to be more homogenous. A more homogenous temperature in the skin of this area allowed a smaller area to be measured. In fact the number of pixels in which T_{index} could be calculated was found to be much lower than that of T_{opis} as the area in the image was far smaller.

The MATLAB script used for this and the opisthenar measurement including the assessment of environmental variables is presented in Appendix 9.6.6.3.

3.5.8.4. Calculation of Environmental Variables and PMV

The environmental data was imported into MATLAB in the same way as the Infrared imager data. The low cost globe thermometer readings were processed along with the air

temperature to provide mean radiant temperature using equation (2-2). The mean radiant temperature (MRT) was calculated for each line of the logged data. PMV was also calculated based on the logged parameters, the calculated MRT, assumed metabolic rate and clothing insulation rate approximated at the time of the test. The metabolic rate given sedentary sitting activity was assumed to 70 W/m^2 [1], [22]. An approximation of the clothing insulation value was made based on the tables given in ISO7730 [1], see Table 2-5 and Table 2-6. PMV was calculated for each line of environmental data recorded.

Metabolic rate and clothing insulation tables given in the ISO documents has been used in other research as well as being backed up by the research by the international standards organisation [7], [30], [40]. The clothing table is an approximation and does not account for variations in each type of clothing. In fact, clothing combinations have differing insulation values to sum of the individual garments. In order to measure the insulation of a particular set of clothing it requires lab work in a thermal chamber. This is not practical in the realms of this field type study. Clothing insulation is merely an approximation used to calculate PMV. Calculation of PMV uses clothing insulation, it is assessed by using manikins and measuring the total insulation value of the garments worn. This is laborious, so a table of clothing insulation values and ensembles were created which is used in this research to calculate PMV, Table 2-5 and Table 2-6. Metabolic rate is also used in the calculation of PMV and does not account for the variation in size, weight, height and gender of the subject. The tables provided by the ISO document are again an approximation and an error range is given, Table 2-3 and Table 2-4.

Results of infrared data, thermal sensation data and environmental data from the pilot study were presented in graphs and analysed in Chapters 4 and 5. Thermal sensation was compared to the environmental variables for correlation. Hand skin temperatures were compared to the recorded thermal sensation to investigate the relationship between hand skin temperature and thermal sensation.

3.6.Further Interpretation of the results

Further tests were carried out to investigate the results from the pilot study which are presented in Chapter 0. The tests were setup to follow the same enquiries as the pilot study but also to investigate hypotheses further to form a theory around how hand skin temperatures relate to thermal sensation and if it is a better indicator than environmental variables recorded and calculated.

The recording period and intervals from the pilot study were increased. Measurement of environmental data and infrared images was made at minute intervals, while thermal sensation and thermal preference surveys were filled in at ten minute intervals.

The MATLAB program was adjusted to take account for the amount of user input required. Processing of over 500 images proved difficult to achieve efficiently using this process but processing the available quality images as defined in the processes above and opting to take one image for each minute of the session produced less images for processing by the user. The results presented in Chapter 4 and 5 showed only minor changes in hand skin temperature at 30 second intervals. The interval of recording to 1 minute was increased to reduce the amount of data collected. The pilot study showed little variance in hand skin temperature in 30 second intervals.

Tests carried out were scheduled on relatively cool and warm days in cool and warm seasons. Each participant was tested in this way to investigate the response of hand skin temperature to different environmental stimuli. Tests were usually carried out during the entire day on a participant. Responses over the course of the day were assessed as the pilot study found that participants had varying hand skin temperatures throughout the day.

The number of participants in the study was expanded to include for more females. The pilot study had only one female participant. The results from the pilot study showed large changes in hand skin temperature and discrepancies between the Tskin of the participants when recording the same thermal sensation and thermal preference.

In the pilot study, mean hand skin temperatures (MHST) were found to be quite different between participants. The most likely reason for this was increased metabolic rate in some participants. The participants of low body mass had MHST much lower than those with higher body mass. Further interpretation of the results investigated this further.

During each phase of the study a multitude of test were carried out to investigate the differences of hand temperature during the day, after meals and between hot and cool months. Further tests were carried out much like the pilot study and retained the validity and accuracy of measurement and were designed to improve the repeatability of the research. Hand skin temperatures were compared for the same recordings of thermal sensation.

4. Pilot Study: In-depth test results

4.1.General

In July and August 2012 a pilot study was conducted with the purpose of investigating the impact and correlations of environment variables, hand skin temperatures and thermal comfort recorded by participants. The aim was to identify problems in using existing techniques for identifying the estimated thermal comfort of an environment. The use of hand skin temperature was proposed to be a more accurate measure of thermal comfort.

A test was performed on a participant sitting at a desk. The test was designed to investigate the methods for calculating thermal comfort and indoor environment quality (IEQ). The current methods for assessing thermal comfort include air temperature, mean radiant temperature, operative temperature, predicted mean vote, thermal sensation surveys and thermal preference surveys. The methods for measuring, recording and calculating these were assessed.

The participant in the test was a female, age 25 years. For the purposes of this research the participant was named F1. Participant F1 was found to weigh 60kg and height was found to be 1.68m. On interrogation, it was found that the participant varied in thermal sensation throughout the day. F1 felt cool in the environment more often than felt warm. F1 was found to have a subjective view of the thermal environment in which the participant worked and would take action easily in the case of cool or warm discomfort. The test bed for this participant was the top floor of a Georgian building which was recently refitted.

4.2.Indoor Environment Quality

4.2.1. Air Temperature

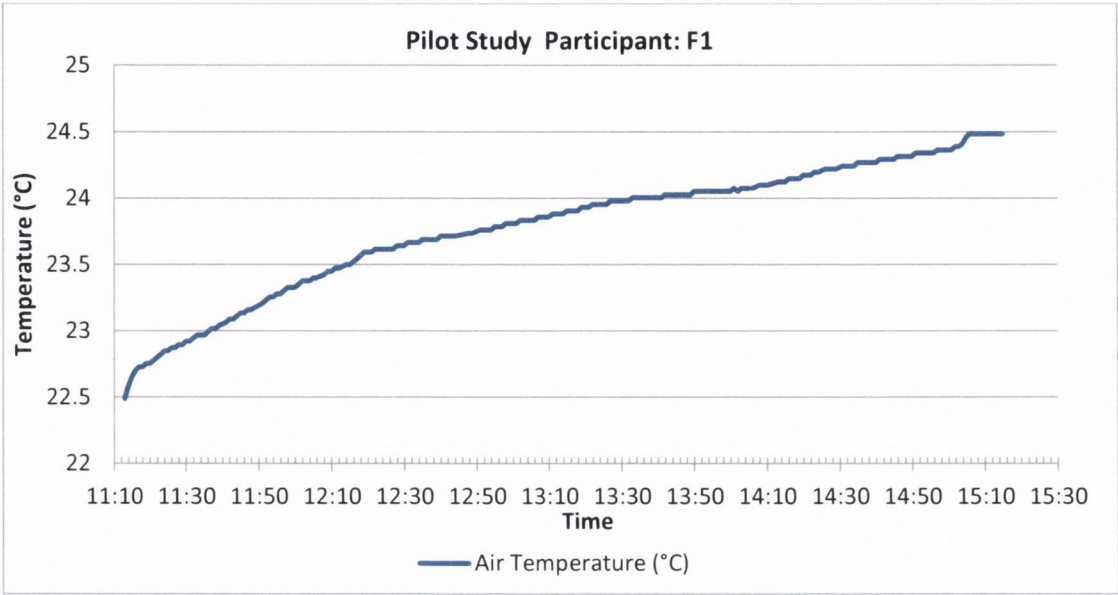


Fig. 4-1 Graph of air temperature vs. time for pilot study test on participant F1

Fig. 4-1 shows the change in air temperature over the course of the entire test on participant F1. The test begins at 11:13 and finishes at 15:15. The air temperature at the start of the test is recorded at 22.5°C. In the first 5 minutes of the test the air temperature rises quickly to 22.7°C. Over the next hour the air temperature increases at a steady rate to 23.6°C, where the rate of increasing temperature decreases slightly and over the following hour increases to 24.0°C. Between 13:50 and 15:10 the air temperature increases again with a large increase at the end of the test up to 24.5°C. Over the course of the entire test the air temperature has increased by 2°C.

The error associated with T_{air} for the HOBO U12 logger was $\pm 0.35^{\circ}\text{C}$. This error range was considered acceptable given the accuracy of other equipment, calculations and approximations, such as metabolic rate and clothing insulation would yield more error [73]. The resolution of the same was found to be 0.03°C . The precision of measurement ensures small changes in temperature were recorded however these small changes were only compared to measurements made by the same device as a comparison to the real T_{air} of the environment would be subject to $\pm 0.35^{\circ}\text{C}$.

The large increase found at the start of the test was attributed to the change in environment as the equipment was brought to the room of the participant and set up on the participant's desk. The equipment was set to log data and then brought into the room where the participant's desk was located. The participant's desk was in the same building that the equipment was set to record in, however a minor difference in air temperature

was noted when introducing the equipment to the participant room. The equipment was found to respond well to the change in environment and showed adjustment to the change within a few minutes.

The general recommendation for air temperature range in an office environment is 21°C to 23°C [74]. This recommendation is only useful when considering air temperature alone. The test began within this range, however, at 11:37 T_{air} rises above the recommended range and at the end of the test T_{air} was found to be 1.5°C above the accepted range. A rise in air temperature has been shown to lead to warm discomfort. The human body requires cooling to operate efficiently. Increased T_{air} leads to a decrease in the amount of convective heat loss from the body to the air.

It was expected that the participant felt thermally neutral in the environment at the start of the test as the air temperature was within the recommended range and felt warm discomfort by the end of the test because T_{air} rises above the recommended range. The rise in T_{air} suggested that the participant would record thermal sensation of 'slightly warm' to 'warm' on the ASHRAE scale and a preference for a cooler environment on the preference scale.

4.2.2. Globe Temperature

Globe temperature can be used to calculate the mean radiant temperature in an environment. Mean radiant temperature (MRT) is the temperature of a uniform enclosure in which the radiant heat transfer from the human body is equal to that of the actual environment. MRT is a concept of the net exchange of radiant heat.

Globe temperature is used to calculate MRT or can be used as an indicator of the radiant environment without calculation. The disparity of T_{globe} to air temperature indicates that there is a radiant energy/convective energy imbalance. The larger the difference in temperatures the larger the imbalance of the radiant environment compared with the air temperature and convective environment.

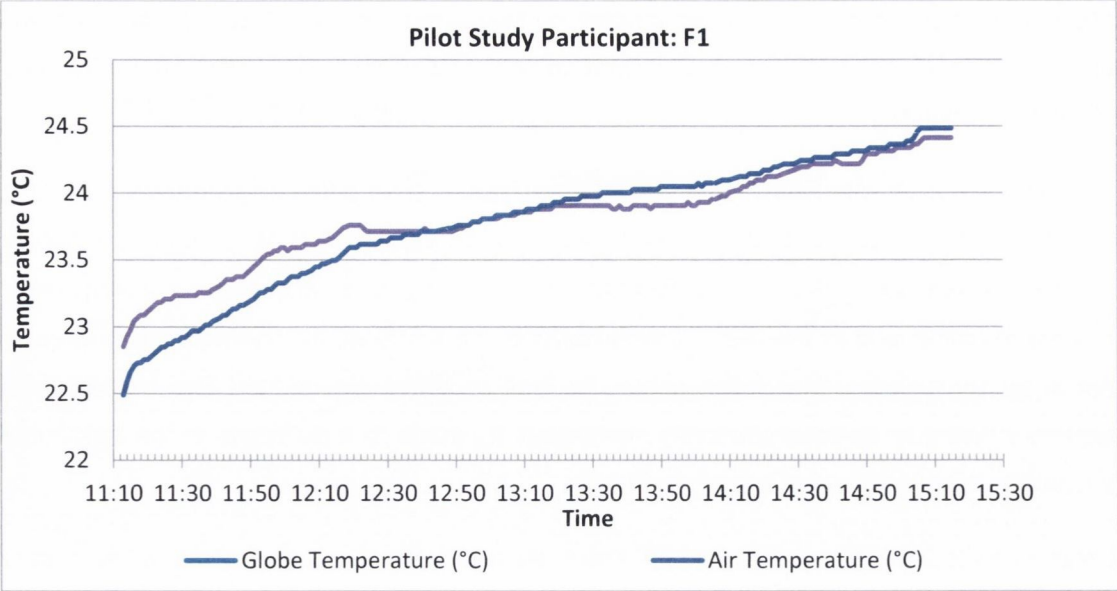


Fig. 4-2 Graph of globe temperature and air temperature vs. time for pilot study test on participant F1

Fig. 4-2 shows the graph of globe temperature and air temperature over time for the pilot study test conducted on participant F1. At the beginning of the test, 11:13, the globe temperature was found to be 22.8°C. It quickly rose to 23.2°C at 11:23. The temperature rose quickly over 10 minutes to match the environment. As previously discussed this rise was found to be due to slight differences in thermal environment between rooms in the test building and the rise was attributed to introducing the equipment to the new environment. The response of the globe thermometer was found to be slower than the air thermometer. The air thermometer responded to the change within 5 minutes while the globe thermometer responded within 10 minutes. The globe thermometer is a more complex device. A temperature probe is placed within a matt black globe. The speed of response to the environment was expected to be slower as the globe reaches equilibrium with the environment slowly due to the mass of the globe adjusting to the change in radiant environment.

After 11:23, T_{globe} was found to rise at a steady rate for the next hour up to 23.7°C. From 12:20 to 12:50 T_{globe} was found to maintain the same temperature of 23.7°C with little variation in temperatures recorded for this period. After 12:50 T_{globe} was found to increase again to 23.9 by 13:20 and then was found to plateau at 23.9°C until 14:00. After 14:00 T_{globe} increased steadily from 23.9°C to 24.4°C where the test was concluded at 15:15. Compared with the recorded T_{air} , the rate of change of T_{globe} was found to change considerably throughout the test. The occupants of the room took lunch during this test and vacated the room between 13:20 and 14:00. In a normal environment humans exchange heat with the surrounding environment. T_{globe} appeared to plateau at this time

and maintained a steady value. Humans are a large source of energy, the human body metabolises stored energy into heat. The heat produced by the body needs to be dissipated through various methods including cutaneous (skin) blood flow. The estimated metabolic rate of a human sitting in a chair doing sedentary work is 70 W/m^2 according to ISO 7730;2005. An average individual has a total body surface area of 1.6m^2 and 1.8m^2 for a woman and man, respectively [22]. For participant F1, Total heat dissipated through metabolic processes was estimated at 112 Watts (W). During the test there were 4 people in the room who all took lunch at the same time. The total heat from these 4 people was estimated at 450 W. The estimated total heat dissipated by persons in the room was the equivalent of 7x60W light bulbs. When the people in the room exited the room it reduced the total radiant energy being exchanged with the globe thermometer and found a balance, neither increasing nor decreasing, for 40 minutes.

The error associated with the measurement of T_{globe} was found to be $\pm 0.25^\circ\text{C}$ while the precision of the measurement compared to the measurements by the same device was found to be $\pm 0.03^\circ\text{C}$. The error range was found to be smaller than that of the T_{air} measurement as a more accurate PT-100 temperature sensor was used compared with the stock HOBO u12 air thermometer. The range of T_{globe} was measured over a range of 1.6°C which is over 6 times the error range.

Humphreys et al recorded globe temperatures in offices in two locations in the United Kingdom in 1996-7. The mean value of globe temperature was found to be 23.2°C with a standard deviation of 1.4°C [68]. T_{globe} measured in this test is above 23.2°C for most of the test and at the end of the test T_{globe} is close to one standard deviation above the mean recorded ($23.2^\circ\text{C} + 1.4^\circ\text{C} = 24.6^\circ\text{C}$). With T_{globe} above the mean of previous research, a thermal sensation vote indicating the participant feels warm was expected. As T_{globe} climbs throughout the test the likelihood of a thermal sensation of warm increases.

4.2.3. Relative Humidity (RH)

Relative humidity (RH) was recorded during pilot study test on participant F1. RH is the ratio of partial pressure of water vapour in a system compared to the saturated vapour pressure of water at the prescribed temperature. Changes in RH can result from changes in temperature and changes in partial pressure of water vapour in a system. The human body is sensitive to RH in that one of the cooling processes of the body is through evaporative cooling. At normal operating conditions in an office type building, the human body perceives increases in RH as increases in temperature and decreases in RH are perceived as decreases in temperature [1]. Typically the changes in RH have limited influence on the human thermal sensation. A 10% increase in RH is felt to be as warm as a 0.3°C rise in operative temperature.

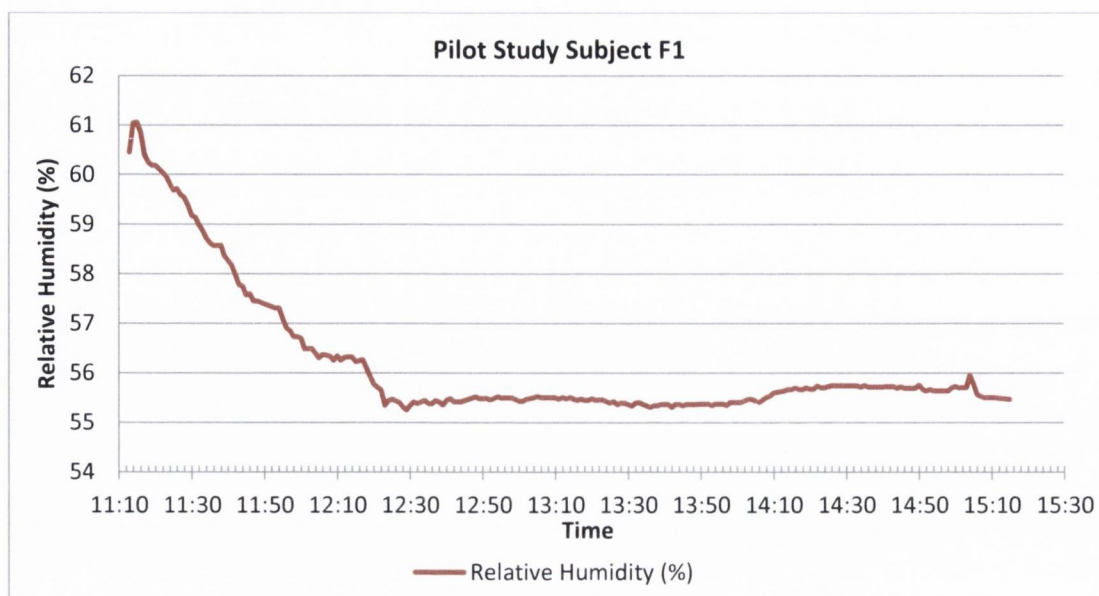


Fig. 4-3 Graph of relative humidity vs. time for pilot study test on participant F1

The relative humidity recorded over the course of the test period is shown in Fig. 4-3. Relative humidity (RH) is recorded in percentage. At the start of the test like with the other variables recorded above there was an increase in RH for the first 5 minutes as the equipment is introduced to the new environment. RH in the room was recorded at 61% at 11:15 and decreased steadily to 55.4% by 12:25. For the rest of the test RH was recorded between 55% and 56%. A decrease of 5.4% in the first hour and 10 minutes of the test was calculated to be the equivalent of a decrease in operative temperature of 0.15°C according to ISO 7730;2005 [1]. This was not considered to be a significant variable based on the variation of operative temperature.

The error associated with the RH measurement was found to be $\pm 2.5\%$. The resolution of the RH measurement was found to be 0.03%. The range of RH measurement was found to be 5.4% which is only twice the error range of the device. Over the test period, operative temperature was found to increase by 1.7°C. The error associated with operative temperature was found to be $\pm 0.5^\circ\text{C}$. The change in RH was found to be within the error range of operative temperature, therefore would have little effect on the recorded environment and excluding RH in calculations would increase error range to $\pm 0.65^\circ\text{C}$ for this test. ISO 7730;2005 [1] considers 60% RH in summer and 40% RH in winter to be the average RH expected in the built environment. The RH recorded in this test was just below the average for the summer months. This test was carried out in August, therefore was found to be in keeping with the accepted average.

4.2.4. Mean Radiant Temperature (MRT)

Mean radiant temperature (MRT) is defined as the uniform temperature of an imaginary enclosure in which the radiant heat transfer from the human body is equal to the radiant heat transfer in the actual non-uniform enclosure [21]. It is a measure of the net exchange of radiant energy between two objects. It is the most important parameter governing thermal comfort of a human in the built environment. It becomes even more important on hot sunny days as the radiant heat transfer increases significantly over the convective heat transfer [16].

MRT cannot be measured directly but only by a black globe thermometer. The black globe thermometer provides globe temperature, T_{globe} .

MRT was calculated from T_{globe} using the equation (2-2) for the entire test period. The environment was subject to natural convection as there was no source of air supply to the room. Globe thermometer used in the test had diameter 0.15m. The calculation for MRT used the variables recorded, T_{globe} and T_{air} . The calculation of MRT from these two variables gave an error of $\pm 0.5^{\circ}\text{C}$ with a resolution of $\pm 0.05^{\circ}\text{C}$.

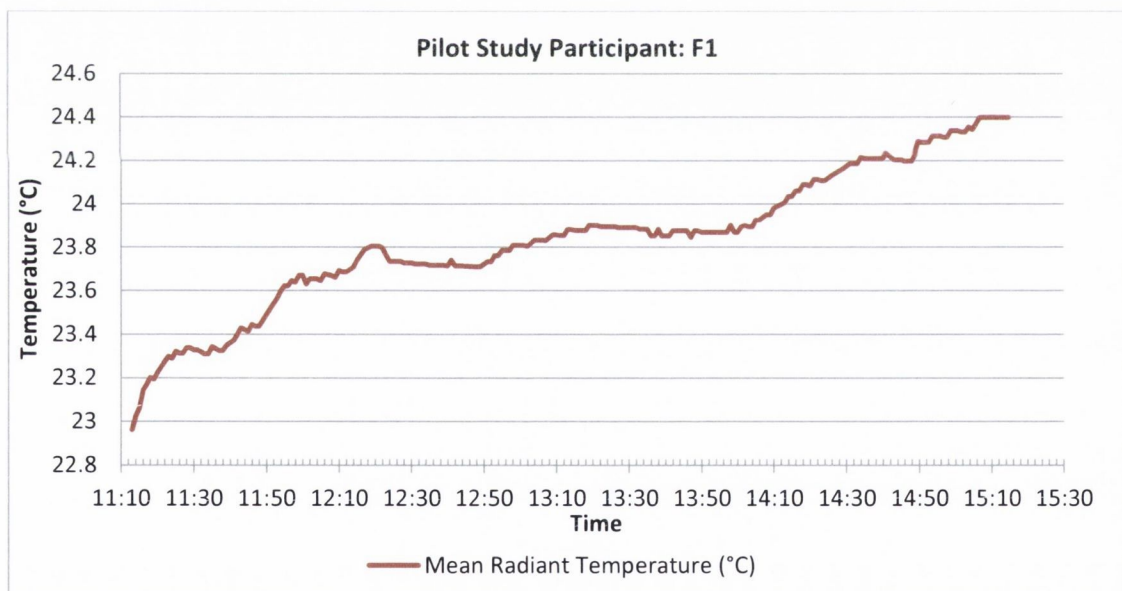


Fig. 4-4 Graph of mean radiant temperature vs. time for pilot study test on participant F1

The graph of the calculated MRT is shown in Fig. 4-4. The MRT calculated for the test period is much the same as that of the T_{globe} recorded. At the beginning of the test the MRT was found to be 23.0°C and rose steadily for the next 15 minutes to 23.3°C where there was a dip over the next five minutes of 0.1°C . After this the MRT was found to rise steadily again to become mostly coincident with T_{globe} recorded for the rest of the test. MRT was found to rise from 23.0°C to 24.4°C . In the latter half of the test recorded values of T_{air} and T_{globe} were found to be closer in value than in the first half of the test. When T_{air}

measured the same as T_{globe} , the MRT calculated was found to be the same as both measured variables. This implies that the equivalent temperature for radiant heat transfer is the same as the equivalent temperature of convective heat transfer. For applications of building management and control in offices, MRT is assumed to be the same as T_{air} for the purposes of calculating comfort [16]. Making this assumption can lead to errors. A difference between T_{globe} and T_{air} of 1°C means a 1.5°C difference between T_{air} and MRT. Therefore, assuming that MRT and T_{air} are coincident an error of 1.5°C is accepted in the case where there is 1°C difference between these measured variables. During this test the largest difference between T_{air} and MRT was found to be 0.5°C.

When sunlight plays a factor in the comfort, MRT has been shown to be more important than the T_{air} measured. In fact in warmer climates, MRT has been shown to be twice as important as air temperature and a weighting of 2:1 is applied for the equivalent measure of operative temperature [16].

4.2.5. Operative Temperature

ASHRAE standard 55 [31] describes methods for determining acceptable thermal conditions in occupied spaces. Operative temperature and predicted mean vote are two such methods. Operative temperature is a temperature measurement which places equal importance on convective heat transfer and radiant heat transfer. Operative temperature ($T_{\text{operative}}$) is used extensively in the building environment measurement industry as a measure of thermal comfort as it describes the effect of both convective and radiant heat transfer [8]. Operative temperature is the average of the mean radiant and ambient air temperature weighted by respective heat transfer coefficients, radiant and convective, as given in the equation below.

$$T_{\text{operative}} = \frac{h_c \cdot T_{\text{air}} + h_r \cdot \text{MRT}}{h_r + h_c}$$

When the subject has a metabolic rate between 1.0 MET (Metabolic Equivalent of Task) and 1.3 MET, there is little air movement, less than 0.20m/s and the subject is not in direct sunlight, $T_{\text{operative}}$ can be expressed as the arithmetic mean of mean radiant temperature (MRT) and T_{air} .

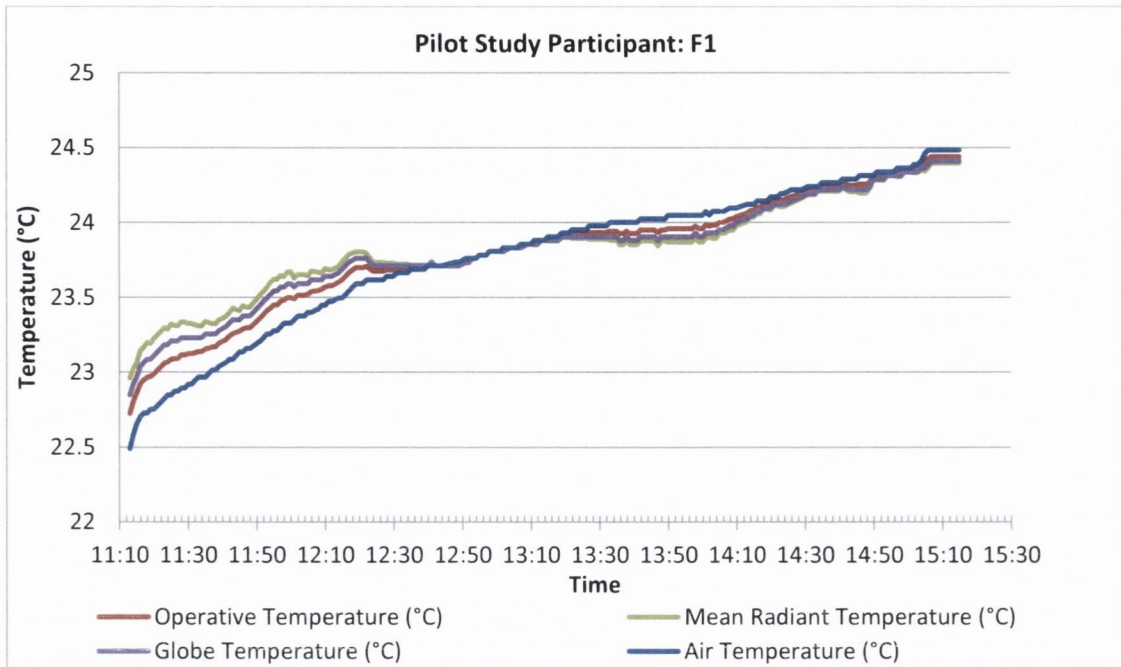


Fig. 4-5 Graph of operative temperature, mean radiant temperature, globe temperature and air temperature vs. time for pilot study test on participant F1

In this test the participant was working at a computer or writing on paper while seated at a desk. The metabolic rate of such a person is approximated in ISO 7730 as 1.2 met or 70 W/m² [1]. The participant was not in direct sunlight and the air velocity was estimated to be less than 0.20m/s. All constraints for using the arithmetic mean of MRT and T_{air} were met. Fig. 4-5 shows the plot of operative temperature calculated from the two temperatures recorded. The plot also shows globe mean radiant and air temperatures to show the coincidence of each variable. There are times when air and mean radiant temperatures are different by up to 0.5°C. Operative temperature is used to average the impact of each temperature.

Operative temperature ($T_{operative}$) according to ASHRAE standard 55 recommends between 19°C and 24°C for clothing insulation value 1.0 clo with 0.5 PMV limits, for the thermal environment given in this test [31]. For a value of 0.5 clo, the recommendation is between 23.5°C and 26°C. These ranges are those recommended to ensure 80% occupant acceptance of the environment. 10% of the occupants in the environment would feel general discomfort and 10% would express dissatisfaction due to local thermal discomfort. During the test the participant was found to change clothing from 0.5 clo to 0.8 clo. At the beginning of the test the participant has 0.5clo clothing insulation and the $T_{operative}$ starts at 22.7°C and ends at 23.2°C. The recommendation for this level of clothing was found to be 23.5°C minimum which the measured $T_{operative}$ does not satisfy. A level of thermal discomfort would be expected based on these findings. When the participant increases the clothing insulation the closest recommendation found in ASHRAE standard

55 was found to be that of 1.0clo. The $T_{\text{operative}}$ was found to rise from 23.2°C to 24.4°C over time. The rise in temperature was likely due to the heat sources in the room, such as computers and humans, and solar heating through the walls and roof. Given the recommended range for 80% occupant acceptance the participant would be expected to be thermally comfortable in the environment leading to warm discomfort by the end of the period as the $T_{\text{operative}}$ measured increased beyond the recommended range. Compared to the ASHRAE scale votes recorded the recommended range compares well in the afternoon part of the test where some warm discomfort is recorded. However, in the morning part of the test, there was significant cool discomfort

4.3. Thermal Comfort of Occupants

A number of measures of thermal comfort were explored in the experiment predicted mean vote is a calculated measure of comfort which uses environmental variables. ASHRAE and thermal preference scales are direct measures of comfort through interrogation of the subject.

4.3.1. Predicted Mean Vote calculation

Predicted mean vote (PMV) is an industry standard for predicting the thermal comfort of a large group in an environment [1]–[3], [31]. It was developed using the principles of heat balance and experimental data collected in controlled climate chambers. Thermal comfort is affected by heat conduction, convection, radiation and evaporative heat loss. The human body maintains heat by metabolic processes which are dissipated by these heat transfers.

Predicted mean vote attempts to find the conditions in which most of the subjects express satisfaction with the environment. There are large variations from person to person in metabolic rate, clothing and activity so finding a balance in which all subjects are happy is difficult.

The factors affecting thermal comfort for the purposes of calculating PMV can be split into environment variables and personal variables. The environment variables include air temperature, mean radiant temperature, relative humidity and relative air velocity. The personal factors affecting thermal comfort are clothing insulation values, metabolic rate and clothing surface temperature. The work done on calculating PMV was carried out in a controlled environment. As such the application of the equation only works in a steady state environment where there is little change in the variables monitored [31].

For the purposes of this research the inputs for the calculation are air temperature, mean radiant temperature, metabolic rate, air speed, relative humidity and clothing insulation value.

4.3.1.1. Clothing Insulation Assessment

Clothing insulation has a large impact on thermal comfort. When a human puts on extra clothing there is an expectation of warmer thermal sensation, when removing clothing there is an expectation of cooler thermal sensation. Humans use clothing to become accustomed to the environment. Typically in cooler seasons humans wear clothing with a higher insulation value and in warmer seasons the clothing amount and insulation value decreases. The noted change of clothing is voluntary response of adaptation to the thermal environment.

Clothing insulation is measured in clothing unit, clo. An average business suit worn with shirt, underwear, shoes and socks has an insulation value of 1.0 clo. An ensemble of underwear, shorts, t-shirt, socks and sandals has a value of 0.3 clo. A lower clo value implies there is lower clothing insulation due to the garments on the human. The tables given are most accurate for light sedentary work where the human has a metabolic rate of 1.2 met (70 W/m^2) [1]. In this test and subsequent test the participant is involved in light sedentary work where the metabolic rate was assumed to be within the limits of clothing insulation value estimation. Where the human is sitting on a chair, the chair has an associated clothing insulation. Insulation values range from 0.00 clo to 0.15 clo. For this test and for subsequent tests in the pilot study, the participant was found to sit on a standard office chair where the chair has a clothing insulation value of 0.10 clo.

At the beginning of the test the participant was assessed for the clothing choice during the test. Clothing insulation was estimated according to the tables for clothing insulation Table 2-5 and Table 2-6 from ISO standard 7730,2003 [1]. The participant was asked to record any change in clothing made during the test. The participant in this test was found to be wearing an ensemble that gave a clothing insulation value of 0.5 clo. This value included the insulation of the standard office chair on which the participant was sitting, which was estimated to have a value of 0.10 clo. Later in the test the participant put on a jumper and the clothing insulation value was found to increase to 0.8 clo for the rest of the test.

4.3.1.2. Metabolic Rate Assessment

Metabolic rate is the conversion of chemical energy into mechanical and thermal energy by the human body for the purposes of movement and supporting life functions. Metabolic rate is an important determinant of comfort. The higher the metabolic rate the more heat the body has to dissipate. With a higher metabolic rate there is more conversion of stored chemical energy into mechanical and thermal energy. The body cannot solely rely on

natural dissipation of heat to the environment but has processes such as sweating which greatly increase heat loss by the body through evaporative heat loss. For this research, it is assumed that there is little to no evaporative heat loss through sweating and any sweating is quickly evaporated. For a human working at a desk in an office the mechanical work is almost nil and assumed to be nil. Total energy consumption by the participant is equal to the heat production. ISO 8996;2004 assumes that metabolic rate is equal to the energy consumption [22].

ISO 8996;2004 reported on accepted methods for determining metabolic rates. These methods were classified into 4 levels of accuracy, from screening based on occupancy up to expert methods such as direct calorimetry study at level 4. Level 2 observation provided methods such as group assessment tables and tables for specific activities. These tables detailed the estimated metabolic rate for certain activities. The accuracy associated with this method was $\pm 20\%$. For level 2 observation method the following observations were made:

1. The body segment involved in work was monitored. In this test and further tests in the pilot study the hands were the body segment which was involved in work. The movement of the hands was monitored by the infrared camera and workload was judged to be light for this test and further tests in the pilot study.
2. The body posture was observed during the course of the test and was generally found to be sitting.
3. The work speed of the participant was monitored.

The participant was observed to be using both hands while in the seated position. Work was observed to be of light intensity. The tables (Table 2-3, Table 2-4) for these activities, given in ISO 8996;2004, were cross referenced with the observed conditions. The mean of metabolic rate was found to be 70 W/m^2 , while the range of metabolic rates for these activities was found to be less than 75 W/m^2 .

During this test due to observations on the participant, the participant was found to have a metabolic rate of 70 W/m^2 , according to Table 2-3. While the supplement of metabolic rate for body posture was found to be 0 W/m^2 , as per Table 2-4. The metabolic rate found using these tables was an approximation to the type of work the participant was doing and did not take into account factors such as weight, age, gender and height of the participant. These physiological variables have been shown to make an impact on the basal metabolic rate for differing individuals, however, for the calculation of PMV these variables are not taken into account and the metabolic rate is estimated from the tables or based on occupation alone.

4.3.1.3. *Relative air velocity*

Relative Air velocity is an important characteristic of thermal comfort. When there is a cool breeze there is increased convective heat transfer. When the air is static there is less convective heat transfer. Air speed in a free running office is slight. A free running building has no ventilation component for maintaining control on the indoor environment. In an office where there is climate control, the relative air velocity is a factor that needs to be measured, as the ventilation systems increase the amount of air flow. The building in which the pilot study was carried out was found to be a free-running building, which had a ventilation supply that wasn't in operation. The walls of the building on each floor housed single air conditioning units for increased heating and cooling. These units supplied cool or warm air depending on participant choice through a fan.

The test was carried out using an assumption of slight relative air velocity. This assumption would not be valid when the air conditioning unit was turned on or the ventilation handling unit was turned on. During the pilot study test on participant F1 and subsequent pilot study tests, neither ventilation unit was found to be operating during the test period.

The building in which all the tests were conducted is a naturally ventilated building. For the purposes of this research the air speed was assumed to be 0.1 m/s as other research on similar buildings has measured [6]. This velocity is slight and unnoticed. The human body can only perceive relative air velocities above 0.5 m/s [16]. The recommendation for office workers is air velocities below 0.20 m/s [31]. In a free running building, relative air velocity has been measured as 0.1 m/s [6]. For this research a value of 0.1 m/s will be assumed. The building in which the pilot study was conducted was of Georgian/Victorian build. While there was no ventilation, the gaps and cracks created as part of the construction process would allow a certain amount of air velocity in the building. Where a window is opened the air velocity would be assumed to rise to 0.2 m/s unless it was a very windy day in which the wind would create a greater relative air velocity inside the building.

For the purposes of calculating PMV, relative air velocity is used to calculate the convective heat transfer coefficient (h_{cl}). h_{cl} is used to calculate clothing surface area temperature. Using the equations given in (2-6), the calculation for h_{cl} uses the square root of relative air velocity. At the levels of air velocity assumed for this research and those measured in previous research the change in air velocity has a large effect on the PMV calculated. If an air velocity of 0.1 m/s was assumed in an ideal environment where a subject has sufficient clothing the PMV was found to be 0.00, which are ideal conditions according to the PMV scale where most people will be satisfied with the environment. When less air velocity was assumed, 0.05 m/s, the PMV calculated was found to be 0.31 and when an assumption of air velocity of 0.2 m/s was made the PMV was found to be -

0.19. The difference in air velocities assumed was 0.05 m/s lower and 0.1 m/s higher than the original assumption of 0.1 m/s but gave a PMV of 0.31 higher and 0.19 lower PMV scale units, respectively. The imbalance in the change is a symptom of the square root calculation of relative air velocity in the PMV equation. The error associated with the assumption of an air velocity figure of 0.1 m/s was approximated to +0.1 m/s and -0.05 m/s. At the lower end of the error scale the assumption is much less as an environment where the air velocity approaches zero m/s would be stuffy and hard to work in. This is not true of the building in which the pilot study was carried out.

4.3.1.4. Air temperature, globe temperature and relative humidity

Measurements of air temperature, globe temperature and relative humidity were needed to calculate the PMV in the environment where the tests in the pilot study were carried out. These variables, discussed above, were used in the equations (2-4), (2-5) and (2-6) to calculate PMV.

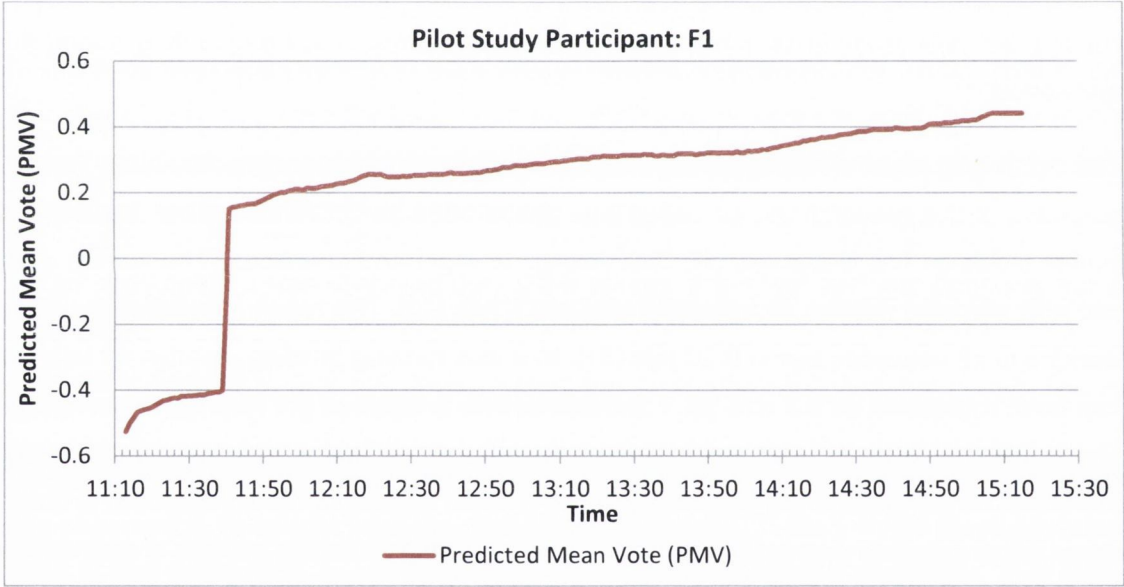


Fig. 4-6 Graph of predicted mean vote vs. time for pilot study test on participant F1

Fig. 4-6 shows the graph of calculated predicted mean vote (PMV) over the course of the test carried out on participant F1. The graph shows the initial PMV calculated from variable measured to be -0.5. This indicates the environment was more likely to have subjects which reported feeling between cool and neutral. The PMV quickly rises to -0.4 and then jumps to 0.15. It is at this point that the participant was noted to have put on a thick jumper, the clothing insulation value of which was calculated from tables to be 0.3 clo which had an effect on the calculation of PMV. This jump in PMV brings the thermal sensation approximation to 0.15 units which indicated that the thermal sensation expected would be neutral. Over the rest of the test The PMV calculated rises gradually to a maximum value of 0.44 units. The rise in PMV over the course of the test was expected

as variables such as air temperature and MRT were found to rise steadily over the period. The ASHRAE scale thermal sensation experienced by the participant was expected to be slightly cool at the beginning of the test period, rising to neutral and possibly slightly warm.

The error associated with the calculation of PMV is significant. The metabolic rate taken from a table based on the activity being carried out was found to be subject to $\pm 20\%$. The clothing insulation ensemble was estimated to have an error of $\pm 20\%$ as the calculated figures were based on tables also. The relative air velocity was assumed to have an error of $+0.1\text{m/s}$ and -0.05 m/s . The error associated with the variables involved in calculating PMV is shown in Table 4-1. When the variables assumed were used to calculate the error in PMV, the error in PMV was found to be $+0.8$ and -1.3 . When the environmental variables were used the error was calculated to be more than this range.

	Assumed Value	Error
Air Temperature	Measured	$\pm 0.35^{\circ}\text{C}$
Mean Radiant Temperature	Measured	$\pm 0.5^{\circ}\text{C}$
Relative Humidity	Measured	$\pm 2.5\%$
Metabolic Rate	70 W/m^2	$\pm 20\%$
Clothing Insulation	0.5 clo, 0.8 clo later in test	$\pm 20\%$
Relative Air Velocity	0.1 m/s	$+0.1\text{m/s } -0.05\text{m/s}$

Table 4-1 Table of error ranges for PMV calculation

The error involved in calculating PMV even when using highly accurate equipment for environmental variables was found to be large. In order to increase the accuracy of the PMV calculation, more accurate measurements of clothing insulation and metabolic rate would need to be made. To increase the accuracy of metabolic rate assessment according to ISO 8996;2004 [22], the participant would need intrusive equipment such as heart rate monitors and oxygen monitoring chambers. This is not a practical solution for the everyday measurement of thermal comfort. In order to increase the accuracy of clothing insulation, tests would need to be carried out on the participant's clothing. Particular ensembles would need measurement of clothing insulation values as the combined effect of a clothing ensemble is not equal to the sum of the garment insulation values [75]. For each day a participant wore a new ensemble of clothing a new set of tests would be required to work out the clothing insulation. This again is not practical to do. Measurement of relative air velocity would increase the accuracy of the PMV calculation, however with already large errors in metabolic rate and clothing insulation the increase in accuracy of air velocity would not make a large impact on overall error associated with PMV calculation.

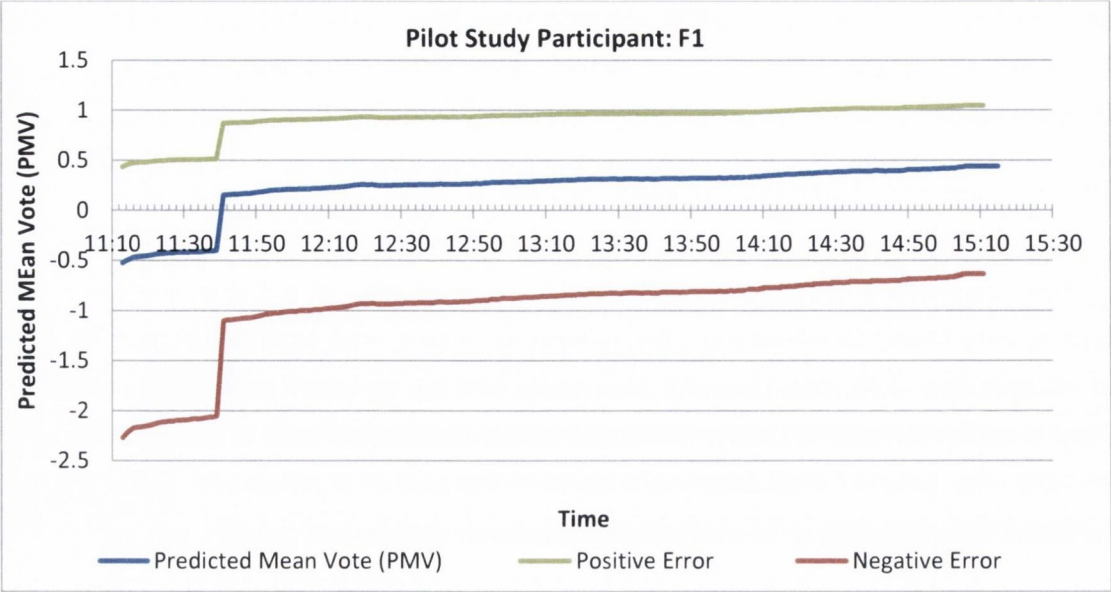


Fig. 4-7 Graph of predicted mean vote vs. time for pilot study test on participant F1 showing positive and negative calculated error for assumed variables

The graph shown in Fig. 4-7 shows the same calculated values of PMV as that in Fig. 4-6, but details the positive and negative error calculated from the assumed variables. At the start of the pilot study test on participant F1 the PMV calculated was found to be -0.5, however the positive error was found to be 0.5 and negative error was found to be -2.2. The range of the error is large. PMV ranges from -3 to +3. The error range was found to be 2.7 units, which is almost half the scale of PMV. That means that at the start of the test the participant could be feeling 'cold', 'slightly warm' or in between these sensations which spans 4 of the 7 thermal sensation scale units. Over the period of the test the error calculated for the assumed variables involved in calculating PMV was found to decrease. At the end of the test when the PMV calculated was found to be 0.4 the error range was found to be +0.6 and -1.0. The error range of PMV was reduced from 2.7 to 1.6 units. The reduction in the range of error was found to be due to the increase in the calculated PMV. At lower values of PMV the error in calculation increases.

4.3.2. ASHRAE scale

ASHRAE scale is a thermal sensation scale, as given in Table 2-1. It is a measure of the thermal feeling of a person. In this research the seven point scale developed by ASHRAE as used in previous research [68]. ASHRAE scale is a direct enquiry to the thermal sensation felt. The participant was asked to circle a number on the scale given in Table 2-1 based on the question 'How do you feel at this time?'. Participants were asked to fill in this question every 5 minutes during the course of the test.

ASHRAE Scale	
1	Cold
2	Cool
3	Slightly cool
4	Neutral
5	Slightly warm
6	Warm
7	Hot

Table 4-2 ASHRAE scale

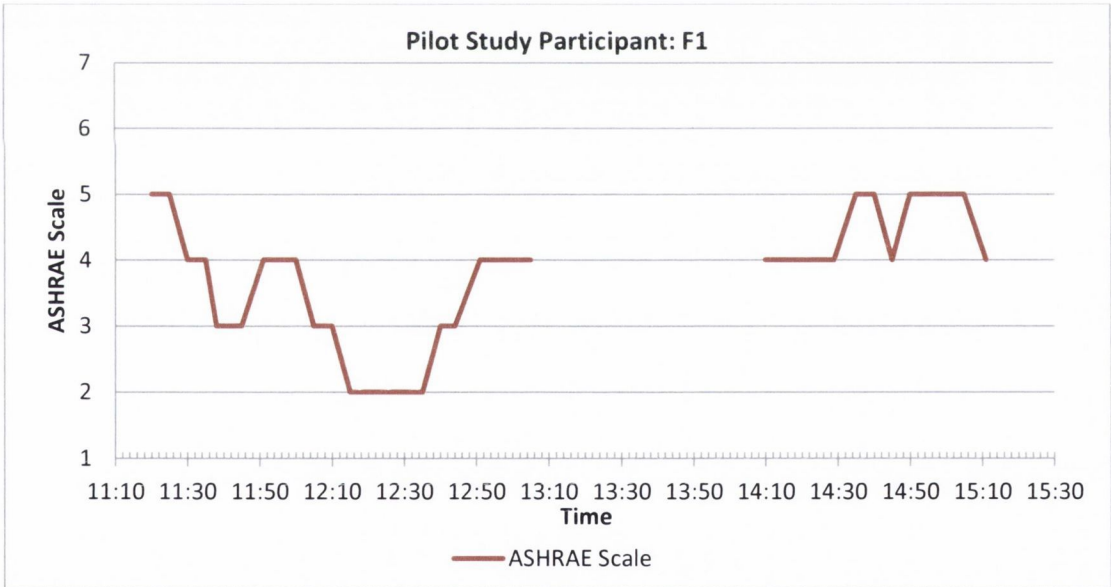


Fig. 4-8 Graph of ASHRAE scale vs. time for pilot study test on participant F1

Fig. 4-8 shows the plot of the ASHRAE scale vote recorded by the participant at the given time over the course of the test period. The participant recorded a vote while seated in the test room at the test desk. There is a gap in the recordings between 13:05 and 14:10 while the participant took lunch in a different room. The recorded ASHRAE scale vote at the beginning of the test was found to be 5. 5 on the scale indicates the participant was feeling 'slightly warm'. The participant recorded two votes of 5 and subsequently recorded two votes of 4. 4 on the scale indicates the participant felt 'neutral'. The next two

recordings were 3. A 3 on the ASHRAE scale indicates a feeling of 'slightly cool'. Over the previous 30 minutes the trend for this participant was found to be a recorded ASHRAE scale vote indicating cooler and cooler sensations. The reduction was found to be from 5 to 3 ASHRAE scale votes. For the next 10 minutes from 11:50 to 12:00, the participant recorded a return of ASHRAE scale to 4, 'neutral'. This was observed to be the time which the participant put on a thick jumper. The participant was allowed to improve the perceived thermal sensation by normal methods such as opening or closing windows and putting on or taking off clothing. The thick jumper which the participant was found to put on to improve cool discomfort was estimated to have a 0.3 clo insulation value. When the participant put on the jumper the calculated PMV rose by 0.6. The effect it had on the participant comfort was a rise of 1 ASHRAE scale unit. The resolution of the ASHRAE scale recorded in this test was 1 scale unit. The increase in thermal sensation of 1 unit would be expected based on the increase in PMV. After 12:00 the participant recorded a drop in thermal sensation again to 3, 'slightly cool' which reduces to an ASHRAE scale of 2, 'cool'. The thermal sensation of 2, 'cool' was recorded from 12:15 to 12:35. At this point the PMV calculated was found to be 0.2 and the negative error was found to give a value of -1.0. The PMV calculated at this point indicates that in the recorded environment the mean vote of thermal comfort would be just above neutral. Taking into consideration the error associated with the assumed variables at the lower end of the error the mean vote of the environment was found to be -1.0 meaning 'slightly cool'. The vote of participant F1 was recorded to be 2, which is equivalent to -2.0 on the PMV scale, 'cool'. The PMV calculated during this phase of the test shows the mean vote increasing over the course of the test with a jump in value when the participant puts on clothing. The trend of the ASHRAE scale recorded was expected to follow the trend of PMV with some possible offset associated with personal preferences. The trend of ASHRAE was at times found to be the opposite of the PMV trend indicating there is more happening to affect the thermal comfort of the participant than the recorded environmental variables.

When the participant returned after lunch the ASHRAE scale recorded was 4, 'neutral' and rose to 5, 'slightly warm' and swapped between the two values of 'neutral' and 'slightly warm' for the rest of the test period. For the test period after the participant took lunch the PMV calculated was found to rise from 0.3 to 0.4 units. A PMV of 0.0 indicates a mean thermal sensation of 'neutral' and a PMV of 1.0 indicates a mean thermal sensation of 'slightly warm'. The ASHRAE scale votes recorded were found to be between these two sensations. As PMV increases after the lunch period the frequency of the participant recording an ASHRAE scale of 5, 'slightly warm' also increased. ASHRAE scale recorded and PMV calculated correlated well during this part of the test as opposed to the first part of the test, where the scales did not correlate well at all.

There is little error in ASHRAE scale recorded. The participant subjectively analyses thermal sensation and comes to a conclusion. Errors could occur in notation of the thermal sensation. The major error in recorded ASHRAE scale is the resolution of the scale. Participants were asked to circle the number which best describes how they are feeling. In most cases the participant circled a number leading to a resolution of 1 unit. However, on occasion the participant circled between the numbers to indicate a 0.5 unit resolution. The calculation of PMV has a high resolution and low accuracy, the ASHRAE scale has low resolution and high accuracy.

In order to compare ASHRAE scale to Thermal Sensation Scale, ASHRAE scale was converted to thermal sensation scale. Table 4-3 shows the conversion for each value of ASHRAE scale.

ASHRAE Scale		Thermal Sensation Scale
1	Cold	-3
2	Cool	-2
3	Slightly cool	-1
4	Neutral	0
5	Slightly warm	1
6	Warm	2
7	Hot	3

Table 4-3 Conversion of ASHRAE scale to Thermal Sensation Scale

4.3.3. Thermal preference scale

Thermal preference scale is much like the ASHRAE scale, in that it asks for the subjective view of the participant. It differs in asking what preference the participant has for change in the thermal environment. It may be thought that a subject in an environment would want to feel 'neutral', however, Humphreys et al [10], showed that thermal preference did not always reflect thermal sensation. Humphreys found that when a participant preferred 'no change' in the environment, many had a thermal sensation other than 'neutral'. Indoor and outdoor temperatures were found to have an effect on the thermal preference recorded.

Preference Scale	
5	Prefer much cooler
4	Prefer a bit cooler
3	Prefer no change
2	Prefer a bit warmer
1	Prefer much warmer

Table 4-4 Preference scale

In this pilot study the participant was given a survey to fill in every 5 minutes in which the participant was asked to record answers to two questions. The thermal preference scale question was phrased 'How would you like to feel?' to which the participant was given five choices corresponding to five numbers, as shown in Table 4-4. The participant was asked to circle the number which best described the thermal preference felt.

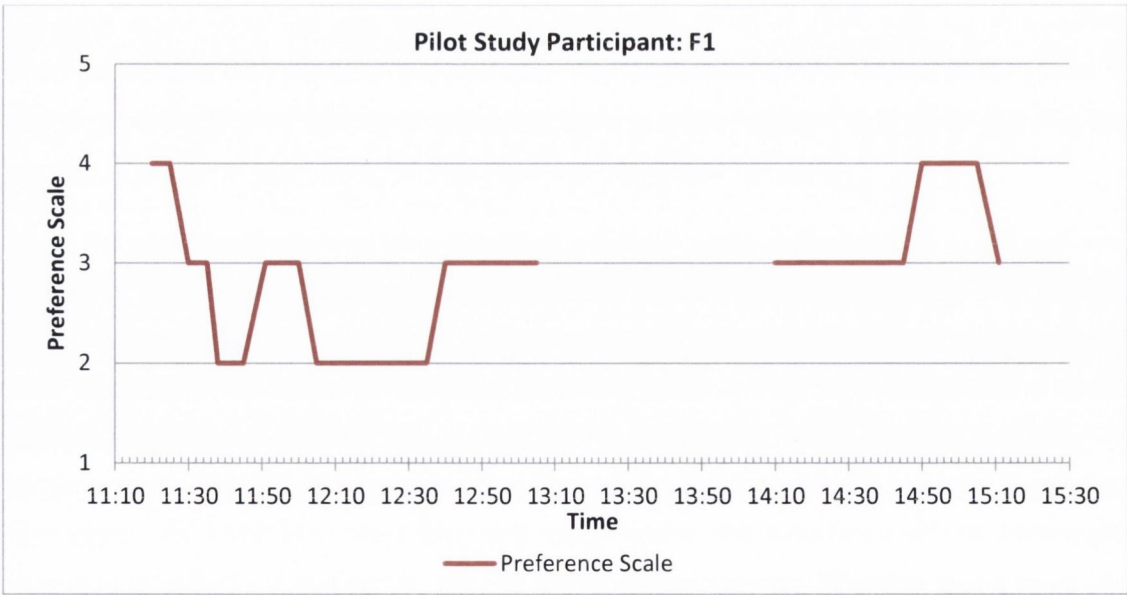


Fig. 4-9 Graph of Preference scale vs. time for pilot study test on participant F1

Fig. 4-9 shows the graphs of Preference scale recorded over the time period of the test on participant F1. There is a gap between 13:05 and 14:09 as previously noted when the participant took lunch. At the beginning of the test the participant was found to note a preference of 4, 'prefer a bit cooler'. This matches with the thermal sensation data which recorded the participant felt 'slightly warm'. The participant was found to change preference along with sensation to feeling 'neutral' and 3, 'preferring no change' down to feeling 'slightly cool' and 2, 'preferring a bit warmer'. This trend of sensation and preference scale coinciding followed until 12:15 when the sensation of the participant was found to drop to 'cool', however the preference scale did not change from 2 'prefer a bit warmer' to 1 'prefer much warmer' as was expected. When the participant recorded a sensation of 'slightly cool' at 12:40, the preference scale recorded changed to a value of 3, 'prefer no change'. At this point the participant wants no change in the environment however feels 'slightly cool'. The participant noted feeling 'cool' in the previous 20 minutes. There is evidence for thermal adaptation in short term and long term application in a field environment [76]. The participant felt warmer than the immediate previous conditions and may have adapted to the lower thermal sensations with a preference for 'no change' once the participant felt warmer than previous conditions. The participant recorded two points where sensation and preference data was not found to match. In the afternoon session the participant recorded preference for 'no change' rising to 'a bit cooler' at 14:50 which dipped back to 'no change' by the end of the test.

Overall thermal preference follows the thermal sensation felt. There are times when preference is different to the expected thermal sensation, which is backed up by previous research centred on field studies [10]. The variations to those expected were found to be a preference for less change in the environment which shows an adaptation to the environment, which has also been shown by previous research [76].

4.4. Infrared Measurements

4.4.1. Average Opisthenar Temperature

While logging of the environmental variables was carried out in the pilot test on participant F1, ASHRAE scale and preference scale recording was taking place and imagery from an infrared camera was being recorded. The infrared camera was trained on the area where one hand of the participant was probably located as the participant carried out work at a desk. Infrared images of the participant's hand were recorded at 30 second intervals. The 'image' recorded by the infrared camera was a temperature profile of the entire viewing area of the camera.



Fig. 4-10 Typical infrared temperature profile converted to black and white image based on temperature

At the end of the test the infrared images were analysed. The temperature profile recorded was a file with a matrix of temperature values. In order to view the image recorded each temperature was converted into a pixel brightness based on the temperature of the 'pixel'. The image could then be recognised by the human eye to identify features of the image. Fig. 4-10 shows the typical image created from this process. It is clear from the image that there is a right hand in the image. The hand image shown is a very warm hand compared with the surroundings, the test was conducted in a warm room in summer. A brighter pixel indicated an area of higher temperature and a darker pixel indicated an area of lower temperature. The keyboard was difficult to see but present in the right side of the image. A ring was noticed on the right hand ring finger of the participant. The ring was found to be made of silver. Silver has a low emissivity and high reflectivity compared to that of the skin. The ring appears to be a much lower temperature than the rest of the hand. In reality the ring was the same temperature as the hand. The metal of the ring has an estimated emissivity of 0.03, which means the reflectivity of the material is very high. As such the metal only emits infrared light 0.03% of the amount a black body should but reflects a large proportion. The reflected infrared light is the main component in the infrared light which the camera recorded and converted to temperature. Therefore the metal of the ring would reflect the infrared light from the environment. In this pilot study test on participant F1, the environment was found to be between 20°C and 25°C which was found to be the same temperature as that recorded for the ring of the participant. A reflection of the hand can be seen directly below the hand and arm on the desk. This is infrared light reflecting from the hand off the desk and into the lens of the camera.

The temperature of the hand of the participant appears to be uniform. There was found to be a small variance in temperature between the back of the hand (opisthenar) and the fingers. The forearm appears to have a duller pixel intensity, which suggested that it was at a lower temperature.

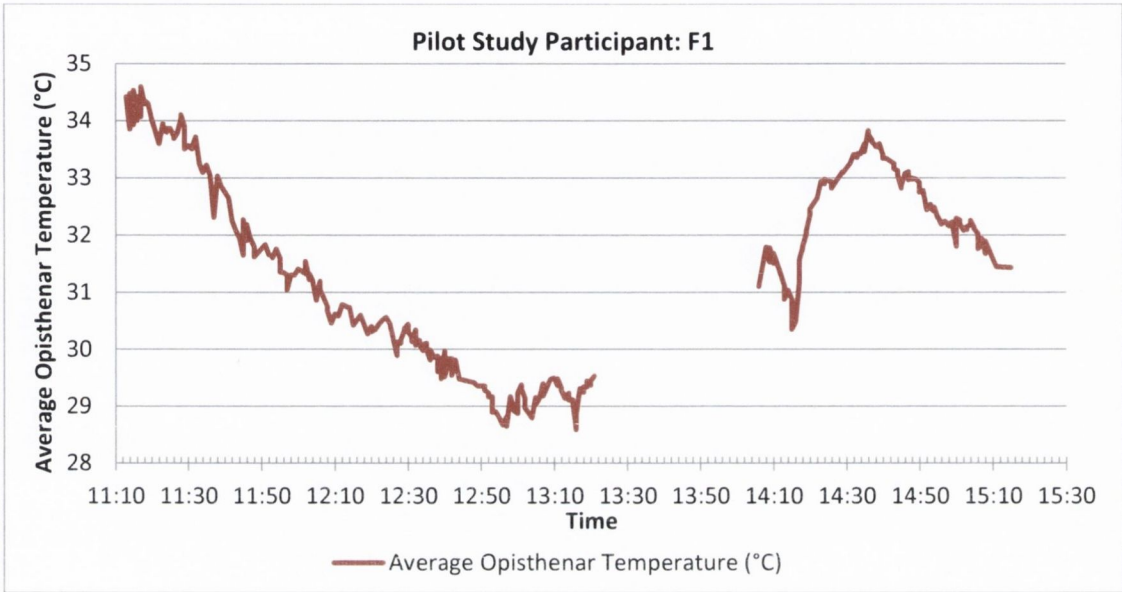


Fig. 4-11 Graph of mean opisthenar temperature vs. time for pilot study test on participant F1

For the pilot study test results all infrared imagery captured was converted to a black and white image like that in Fig. 4-10 for processing by the operator. This was done through the software program MATLAB. The operator was asked to pick the centre of the opisthenar area. The program then processed an area, circular in shape around the operator indicated centre of the opisthenar. The arithmetic mean temperature of the opisthenar area was then calculated. This process was carried out for all recorded infrared images. A database of each calculated mean opisthenar temperature (T_{opis}) was built for each time. The graph shown in Fig. 4-11 shows the plot of T_{opis} recorded and calculated by this process over time. T_{opis} ranges in temperature from below 29°C to almost 35°C. During the first part of the test, before lunch, the initial recordings of T_{opis} are above 34°C. The recorded T_{opis} dropped steadily down to the 29°C before rallying somewhat to 29.5°C. When the participant put on more clothing, at 11:39, the T_{opis} raised significantly from 32.3°C to 33.0°C before declining again. The rate of decline of T_{opis} waned as T_{opis} dropped and recovered in value to more than 29.5°C by the lunch period. After the lunch period, T_{opis} was recorded at 32.8°C before declining quickly to 30.4°C, T_{opis} then rose suddenly to 33°C and continued to rise up to a maximum value of 33.9°C before declining to 31.4°C. Over the course of 6 hours the T_{opis} was found to change dramatically at some stages. The T_{opis} recorded showed small variances in temperature between successive

recordings of T_{opis} . On the graph this showed as noise or variation in the plot of the values calculated. An explanation for this was that in the measurement of T_{opis} the operator was asked to select the centre of the opisthenar. This was not always done accurately. Therefore the opisthenar area being used to calculate the T_{opis} was different in successive recordings creating a variance or noise in the plot. The overall trend of T_{opis} was found to be clearly displayed despite the noise in the signal, as the noise was found to only account for differences of 0.5°C in measurement.

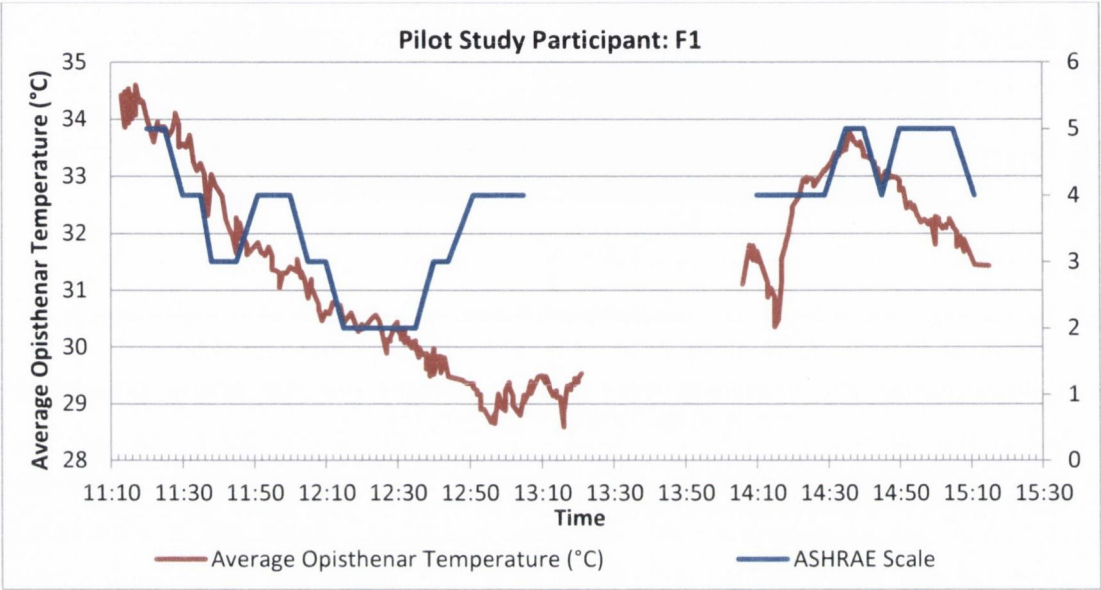


Fig. 4-12 Graph of mean opisthenar temperature and ASHRAE scale vs. time for pilot study test on participant F1

On comparing the T_{opis} recorded to the ASHRAE scale noted by the participant there appear to be similarities. The graph in Fig. 4-12 shows the T_{opis} and ASHRAE scale in the same graph. The ASHRAE scale votes are plotted on the secondary Y-axis to the right of the graph. The T_{opis} values are plotted as normal with the Y-axis on the left of the graph. Before the lunch period the participant recorded cooler and cooler thermal sensations. During this period the T_{opis} recorded was found to decline by over 5°C . From the lowest value of T_{opis} recorded, 28.6°C , T_{opis} temperatures recover slightly as the test nears the lunch period. The ASHRAE scale noted at this point recovers from 'cold' to 'neutral'. When the participant put on extra clothing at 11:39, T_{opis} is seen to rise by 0.8°C , however the ASHRAE scale recorded was found to drop to 'slightly cool' from 'neutral' after the clothing was put on and for the next 10 minutes of recording the ASHRAE scale was found to be 'slightly cool' which recovered to 'neutral' after this. This indicates the thermal sensation does not change immediately once a subject has made changes to the thermal comfort. It was shown to be a gradual change in thermal sensation. Previous research has shown gradual changes in thermal sensation over the course of a test and even adaptation to the

thermal environment [8], [30]. T_{opis} was found to rally by 0.8°C almost immediately after the participant put on the extra clothing, however, the values of T_{opis} were found to decline after this quickly to below the value of T_{opis} when the clothing was put on. After this stage, the rate of decline of T_{opis} was found to slow. During this period ASHRAE scale votes recorded were found to move from 'neutral' to 'slightly cool' to 'cold'. There was found to be 20 minutes of recorded 'cold' sensation by the participant. During this time the recorded T_{opis} levelled off, indicating the skin temperature of the opisthenar reached equilibrium at between 30°C and 31°C . The ASHRAE scale from 12:40 to 13:05 recovered from 'cold' to 'slightly cool' to 'neutral'. During this time T_{opis} measured dropped off considerably. This was unexpected as T_{opis} had followed the cooling trend of the ASHRAE scale votes, it was also expected to follow the warming trend of the vote. When the image data from the infrared camera was examined during this period, it was found that the participant had pulled the sleeve of the jumper over most of the opisthenar. This would give erroneous values of T_{opis} , as most of the opisthenar covered by clothing would have a much lower temperature than that of T_{opis} .

After the lunch period the participant was found to have a T_{opis} much higher than that which was recorded before lunch. The participant noted an ASHRAE scale of 'neutral' while the T_{opis} recorded oscillates between 30°C and 32°C . The T_{opis} was then recorded to rise quickly to 33°C at 14:29 while the participant recorded 'neutral'. T_{opis} was found to rise to 33.8°C by 14:36 when two ASHRAE scale votes of 'slightly warm' were recorded. As the test reached a conclusion the ASHRAE scale votes were found to swap between 'neutral' and 'slightly warm', T_{opis} was found to decline at the same rate of decline as that found at the beginning of the test to 31.4°C . It was expected that as T_{opis} declined, the ASHRAE scale votes would change from 'neutral' to cooler sensations.

Overall compared with the predictions of PMV to ASHRAE scale votes, T_{opis} compares well to ASHRAE scale votes recorded. PMV was calculated to be increasing over the entire course of the test, however ASHRAE scale votes show a large variance in thermal sensation experienced by the participant from 'cool' to 'slightly warm'. T_{opis} recorded temperatures were found to vary between 28.6°C and 34.6°C , when T_{opis} recorded was at the lower end of the scale, generally the ASHRAE scale recorded was cool discomfort, 'slightly cool' and cooler.

Correlation is a statistical measure of the dependence of two variables on each other. Correlation compares two data sets of variables through a statistical equation which results in a correlation factor of value between -1 and 1. A value of 1 means the two data sets are highly dependent on each other, a value of -1 means the data sets are highly inversely dependent while a value of 0 shows no correlation whatsoever. Correlation is a measure of dependence which can compare variables which don't have the same units.

Correlation factors can be compared between variables correlating a common dependence to find which variable best fits the relevant data.

The correlation of ASHRAE scale to T_{opis} was found to be 0.57 whereas the correlation of ASHRAE to calculated PMV was found to be -0.01. The correlation of operative temperature to ASHRAE scale was found to be 0.32. T_{opis} showed very good correlation to ASHRAE scale votes recorded. PMV had very poor correlation while operative temperature was found to have good correlation. Humphreys et al [68] in 1999 found a correlation of 0.37 between finger temperature and ASHRAE scale votes for the entire study. Humphreys found that finger temperature showed the best correlation to ASHRAE scale of the measured variables.

4.4.2. Index Fingernail Temperature

Images were recorded at 30 second intervals from the infrared camera used in this test. When the mean opisthenar temperature was calculated using MATLAB, the index fingernail temperature was also calculated. The operator of the program was presented with the black and white image where the centre of the opisthenar was selected. The operator was asked to choose the index fingernail in the image. On choosing the index fingernail the temperature at this chosen point the program calculated the temperature from surrounding 'pixels'. The index fingernail temperatures (T_{index}) was calculated for all infrared images and graphed over time in Fig. 4-13.

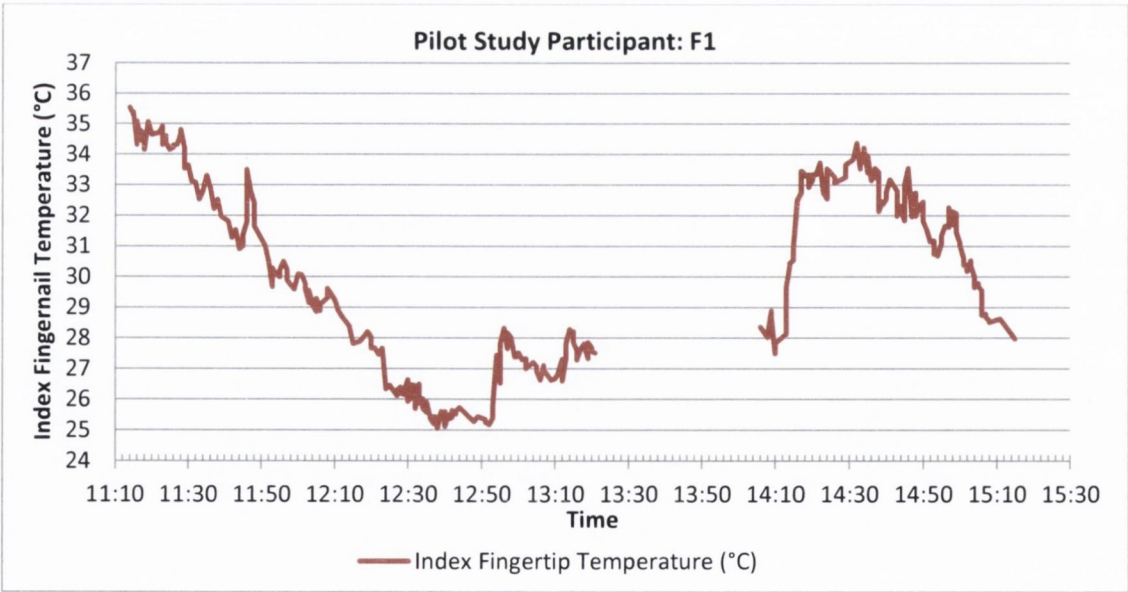


Fig. 4-13 Graph of index fingernail temperature vs. time for pilot study test on participant F1

At the beginning of the test the index finger temperature recorded (T_{index}) was found to be 35.5°C. T_{opis} at this time was a little lower at 34.4°C. AS with T_{opis} , T_{index} was found to

decline in value at a steady rate until 12:40. There was one jump in T_{index} at 11:46, 7 minutes after the participant put on extra clothing. At this time the value of T_{index} was found to rise from 31.7°C to 33.5°C before declining rapidly to a value of 29.7°C at 11:53. T_{index} continued to steadily decrease in value up until 12:25 when T_{index} appeared to cease declining. For the next 30 minutes T_{index} ranged from 25.0°C to 26.4°C. After 12:55 the values of T_{index} rose suddenly to 28.2°C before declining to 26.6°C at 13:12. After lunch the T_{index} recorded was found to be 28.4°C at 14:06 and oscillated around this value until T_{index} was found to rise rapidly from 14:13 to 14:23 to a T_{index} value of 32.7°C. This rapid rise in T_{index} recorded was considered to be due to the change in environment. As the participant entered the room at 14:06, T_{index} was found to be low compared to the ASHRAE scale vote recorded. The participant could have been in a cooler environment that the one in which the test was carried out before entering the room again. The participant on entering the room was subject to different conditions causing the heat loss through convective and radiant energy transfer to also change. When the subject entered the room the skin temperature was found to rise rapidly after just 6 minutes. It was considered that the rapid rise of T_{index} was due to the increased blood flow to the skin. Cutaneous (skin) blood flow occurs when the body is trying to increase convective and radiant heat transfer. When the participant entered the warmer environment of the test room, there was reduced heat transfer from the skin to the environment. The body then increased cutaneous blood flow to increase skin temperature and increase convective and radiant heat transfer. T_{index} was found to increase up to a maximum value of 34.2°C at 14:34 and then decrease to 28.0°C by the end of the test at 15:15. During this time the T_{index} was found to rally on three occasions at 14:38, 14:45 and 14:53. At the end of the test T_{index} was found to be in the same region as when the participant entered the room after lunch.

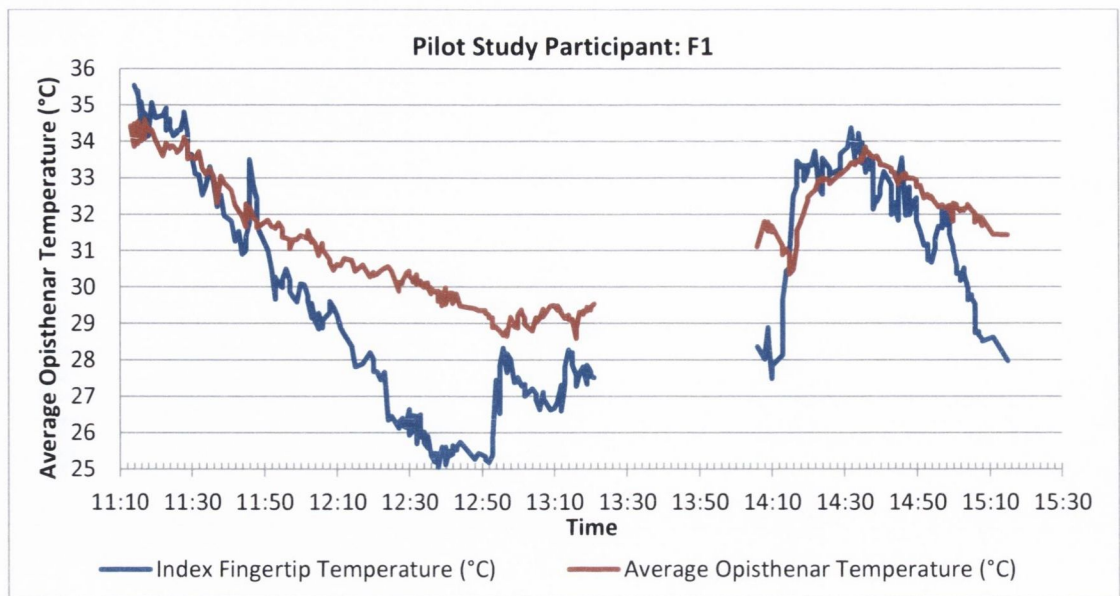


Fig. 4-14 Graph of index fingernail and mean opisthenar temperature vs. time for pilot study test on participant F1

Fig. 4-14 shows the graph of T_{index} and T_{opis} over time for the pilot study test on participant F1. T_{index} was found to vary much more than T_{opis} in this test. T_{opis} varied between 28.6°C and 34.6°C. T_{index} was found to vary between 25.0°C and 35.5°C. T_{opis} was found to have a range of 6°C for this test whereas T_{index} was found to have a range of 10.5°C, almost twice the range of T_{opis} . At the beginning of the test period T_{opis} and T_{index} were almost coincident. As the temperatures of both dropped T_{index} declined at a higher rate than T_{opis} . By 12:40, there was a 5°C difference between the two values calculated. When the temperatures rallied at 12:55, T_{index} was found to increase much more than T_{opis} and the difference between the two values was closed to between 0.5°C and 3°C. When the test was resumed at 14:06 there was a large discrepancy between T_{index} and T_{opis} which quickly narrowed as both skin temperatures rose and became almost coincident again before dropping down at approximately 14:55 to have a difference of 3.5°C by the end of the test.

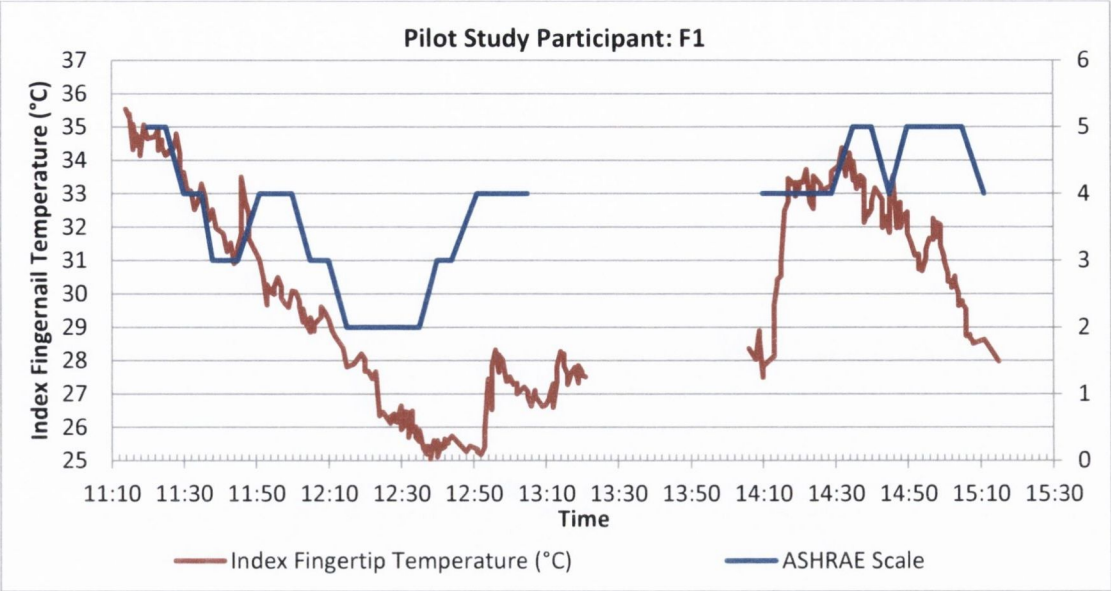


Fig. 4-15 Graph of index fingernail temperature and ASHRAE scale vs. time for pilot study test on participant F1

The correlation factor of ASHRAE scale and T_{index} was found to be 0.64. This factor was the highest correlation found to any measured variable. Fig. 4-15 shows the plot of both variables measured and recorded. The correlation of ASHRAE scale and T_{index} is more pronounced than that of T_{opis} and ASHRAE scale, which is represented in the higher correlation factor calculated. The T_{index} responds better to the change in ASHRAE scale vote at 12:35, in which T_{index} was found to rise in temperature to 28.2°C at 12:55. When T_{index} was at the lowest value for the test the thermal sensation recorded changed from 'cool' to 'slightly cool'. As the T_{index} recovered to 28.2°C at 12:55 the sensation changed again from 'slightly cool' to 'neutral'. While the ASHRAE scale vote recorded was 4, 'neutral', values of T_{index} were found to be between 26.5°C and 33.6°C, a large range of skin temperatures based on the same thermal sensation recorded. For ASHRAE scale votes of 3, 'slightly cool', T_{index} was found to range between 25.6°C and 32.5°C. This range is slightly lower than that of 'neutral' but has a large crossover in the ranges. The same trend was noted of T_{opis} where 'neutral' votes were found to have a large range of values. This implies that there is a large range of hand skin temperatures in which the participant felt comfortable in the environment. The cutaneous blood flow attempts to change the feelings of comfort rather than directly measuring comfort. At 12:55 in the test when T_{index} and T_{opis} were found to rise in temperature the ASHRAE scale shows the participant recorded 4, 'neutral'. The values of T_{opis} and T_{index} are far below the expected value for a feeling of 'neutral' however for the previous 25 minutes the values of T_{opis} and T_{index} were lower than at 12:55. It appears that the comfort of the participant is based on the previous state.

4.5.Discussion

In the pilot study test carried out on participant F1, the comparison of ASHRAE scale to other variables was shown to be more favourably linked to hand skin temperature than operative temperatures and PMV calculated. PMV was found to have a large amount of error in its calculation due to the number of assumptions it encompasses. Air temperature, globe temperature and mean radiant temperature were found to be largely the same with some variation in values. Operative temperature was proposed to be the singular measure of the thermal environment for the next set of tests as it uses both MRT and T_{air} in its calculation. The error in operative temperature was found to be 0.5°C.

In further tests, predicted mean vote was proposed to be used as it is a largely accepted measure of the mean thermal acceptance of an environment [1]–[3], [31], [77]. PMV compared to the ASHRAE scale gives a direct comparison of thermal sensation felt by one participant versus that calculated for a large group of people. In the comparison of PMV to ASHRAE scale, participant F1 was found to have large variances in ASHRAE scale vote while the PMV calculated was found to increase slowly. A comparison of these large variances shown by participant F1 should be compared to other participants in the study.

Mean opisthenar temperature and index fingernail temperature were shown to have the highest correlation to the ASHRAE scale recorded of any other variables measured. Both measurements were found to correlate better than previous research by Humphreys et al [68]. However, Humphreys et al conducted tests over the course of a year and included 200 participants. This test over the course of a day included just one participant. Tests on more participants should be carried out in order to confirm the link of hand skin temperature to thermal sensation.

Infrared imaging of hand skin temperature was found to be successful in this study. When the camera is set up using a wide view of the participant's desk the hand of the participant is usually in frame. Using infrared in practice was found to be much easier in set up and for participant comfort than thermocouple type temperature measurements. The infrared camera has a large amount of error in calculation of the temperature which a thermocouple does not have. A thermocouple offers an instant measurement while the infrared measurement needs some kind of processing in order to calculate temperature. Measurement of the temperature of any part of the skin could be made and averages of certain areas of the skin were easily made. Thermocouples placed on the skin measure on point of temperature and need to be fixed to the skin. In fixing the thermocouple to the skin insulation of the heat loss may occur and the measured temperature could be

different to that present before the thermocouple was placed on the hand. In infrared there is no direct contact with the hand. The infrared camera produced temperatures which were only accurate to 2°C. However, the precision of the imager was 0.1°C. Since the precision of the imager is high but the accuracy is low measurements made by this imager are directly comparable. However, when comparing between infrared imagers and to other measurement devices the low accuracy must be taken into account. Calibration of the imager in the factory counteracts the lower accuracy of the imager. In this study and in future studies the same infrared imager is used therefore infrared measurements can be cross correlated with high precision.

One of the research aims of this thesis is to attempt to assess thermal comfort of occupant of an office. In order to utilise infrared imagery in the office environment several infrared imagers would be required to determine the thermal comfort of all occupants in the space. Since the accuracy of infrared imagers is large, at $\pm 2^{\circ}\text{C}$, there would be problems in cross correlating the skin temperature between imagers. This is one of the most important factors in considering using infrared cameras for measurement of skin temperature.

5. Pilot study: Other participant results

5.1.General

Following the test conducted on participant F1 the pilot study was widened to include more participants in the same and different rooms of the test building. Participants were chosen to give a broad range of thermal preferences, basal metabolic rates, clothing insulation values and weights. Table 5-1 shows the participant information and estimated values of basal metabolic rate and clothing insulation. The participant was given a survey to record how they feel and how they would prefer to be. Preferences were marked down on the sheet throughout the test at 5 minute intervals. The participant was allowed to leave the desk for any reason and was allowed to proceed with their day as normal. While at their desk they would record thermal sensation preferences but not while away from desk.

Participant	Gender	Age	Weight (kg)	Height (cm)	Basal Metabolic Rate (estimated) (kcal/day)	Estimated Clothing Insulation (clo)	General Thermal Feeling
M1	Male	29	99	1.84	1259	0.3	Generally warm in environment
M2	Male	25	92	1.8	1188	0.5	Generally warm in environment
M3	Male	31	58	1.78	698	0.5	Fluctuates throughout the day
F1	Female	25	60	1.68	899	0.5 and 0.8	Fluctuates throughout the day

Table 5-1 Participant information for pilot study

Table 5-1 shows the physiological information of each participant in the pilot study. Participant F1 was assessed during the initial test results in Chapter 4. The participants in the pilot study ranged in age from 25 to 31 years, in weight from 58kg to 99kg and estimated clothing during the pilot study showed values of insulation from 0.3 clo to 0.8 clo. Participants were additionally asked how they feel generally in the environment compared to other people which is represented in the column 'general thermal feeling'. Estimated basal metabolic rate was calculated, using the modified Harris-Benedict equations (2-9) and (2-10), for each participant as an indicator of the metabolic rate of the participant during the test.

5.2. Participant M2

Participant M2 was male, 25 years old, 95kg in weight and wore clothing which was calculated to give an insulation value of 0.5 clo. This value represents a summer clothing ensemble where the participant was wearing a light t-shirt, underwear and jeans. The estimation of clothing insulation is highly inaccurate and has a large impact on calculated PMV, as was shown in Chapter 5. The participant reported feeling 'generally warm in environments', meaning the participant felt warm compared to others and would be the first to try to cool down by opening a window but wouldn't be the first to put heating on in a cool environment. Participants M2 and F1 shared the same room on the top floor of the test building. The options for cooling down the room included opening windows to the atrium area or the street area. Options for heating the room included turning on the radiators however it was found that the hot water supply to the radiators was turned off for the summer season. There were be wall mounted air conditioners on two walls in the room, each of which could be turned on by one of two panels to select heating or cooling the room.

5.2.1. Indoor Environment Quality

A pilot study test was performed on participant M2. The participant sat in the same room as participant F1. A comparison of the thermal sensation and hand skin temperature data could be made considering the participants occupied the same environment. Operative temperature was found to be a good indicator of the thermal environment in the detailed results section of Chapter 4. Operative temperature was calculated as the mean of air and mean radiant temperatures.

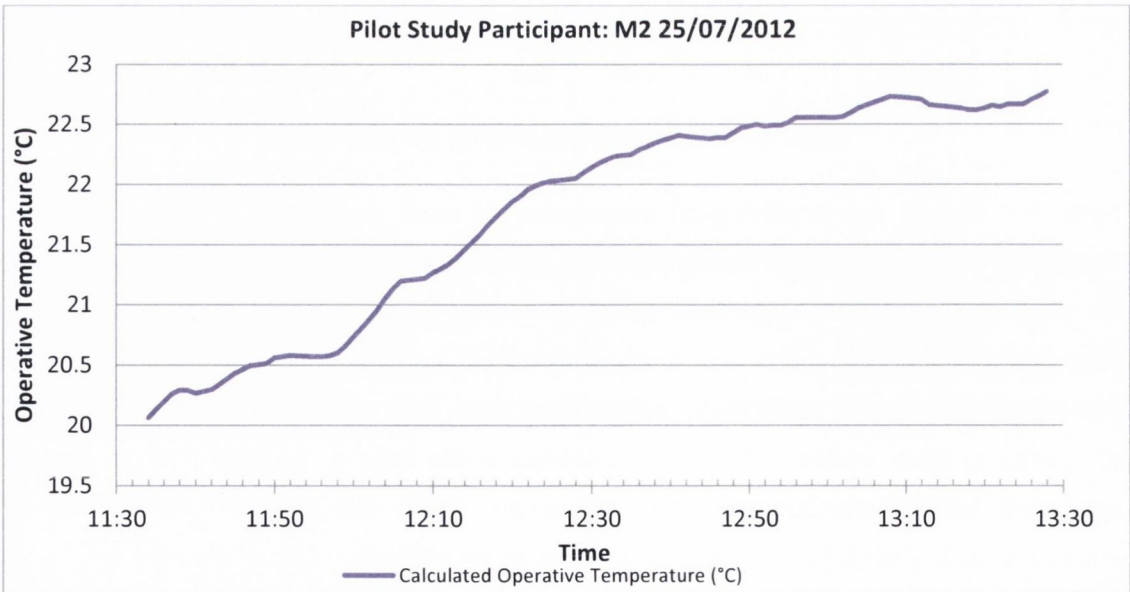


Fig. 5-1 Graph of operative temperature over time for Morning test on participant M2

The graph in Fig. 5-1 shows the change in $T_{operative}$ over the course of a test carried out on participant M2 during the pilot study. Operative temperature was found to be coincident with air temperature and mean radiant temperature in the in depth results section. $T_{operative}$ at the beginning of the test was found to be 20.1°C. By the end of the 2 hour test $T_{operative}$ was found to be 22.8°C which was also the highest recording of $T_{operative}$ from the test. The range of $T_{operative}$ was calculated to be 2.7°C. The mean of values recorded was found to be 21.8°C and the standard deviation of the values was found to be 0.88°C. $T_{operative}$ was found to increase over most of the test. The rate of increase was not constant. The rate of increase reduced near the end of the test. Between 12:00 and 12:20 the largest increase in $T_{operative}$ was noticed from 20.7°C to 21.9°C, an increase of 1.2°C over a 20 minute period.

The recommendations for 80% occupant comfort for 0.5 clo insulation value were found to be between 23.5°C and 26°C according to ASHRAE standard 55;2003 [31]. The participant was estimated to be wearing clothing which provided a clothing insulation of 0.5 clo, which is the same as the values on which the recommendation was based in ASHRAE standard 55. During the test $T_{operative}$ was found to be below the recommended value in which 80% of occupants in an office environment would feel thermally comfortable. At the maximum temperature recorded, $T_{operative}$ was found to be 0.7°C below the lower end of the recommended temperature. The participant should experience cool discomfort. The sense of cool discomfort was also predicted by PMV, as shown in Fig. 5-2.

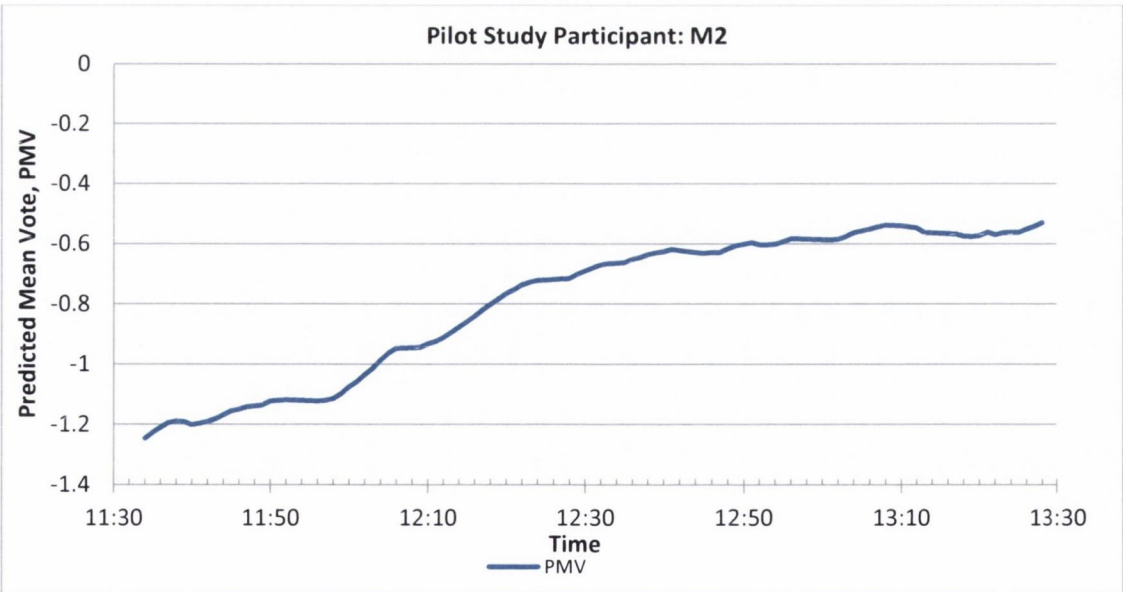


Fig. 5-2 Graph of predicted mean vote over time for Morning test on participant M2

Fig. 5-2 shows the graph of calculated predicted mean vote (PMV) against time for the period of the pilot test on participant M2. At the start of the test the PMV was found to be -

1.25 rising to -0.53 by the end of the test. These values of PMV suggest that for an average occupant, a feeling of slightly cool was expected at the beginning of the test while nearing the end of the test the probability of cool discomfort decreases and the occupant was expected to feel between neutral and slightly cool. The PMV was found to act much like the $T_{operative}$ shown in Fig. 5-1. PMV was found to rise quickly between 12:00 and 12:20 and decreases and increases were found to match those from the recorded $T_{operative}$. $T_{operative}$ and PMV use mean radiant temperature and air temperature for calculation, PMV uses more variables which were assumed to be constant during the course of the test carried out. While $T_{operative}$ and PMV were found to follow the same trend, they are both useful measurements. $T_{operative}$ can be compared from environment to environment and gives a real estimate of the temperature of the environment for convective and radiant heat transfer. It is a simple variable to calculate. PMV is more difficult to calculate but offers a comparison to thermal sensation data gathered from participants. PMV gives a direct calculation of thermal sensation expected based on the environment which uses the same units as thermal sensation.

5.2.2. Thermal sensation

ASHRAE scale and preference scale data was recorded by the participant at 5 minute intervals by the participant. ASHRAE scale was converted to thermal sensation scale as per Table 4-3. Preference scale was converted to be centred on zero like thermal sensation. A value of zero indicated a preference for 'no change'. The scale was adjusted to range from -2 to +2 instead of 1 to 5 in order to easily compare thermal preference with thermal sensation which came from the ASHRAE scale and adjusted to compare to PMV. Thermal sensation, preference and PMV all are centred on zero and negative numbers indicate the cool side and positive numbers indicate the warm side.

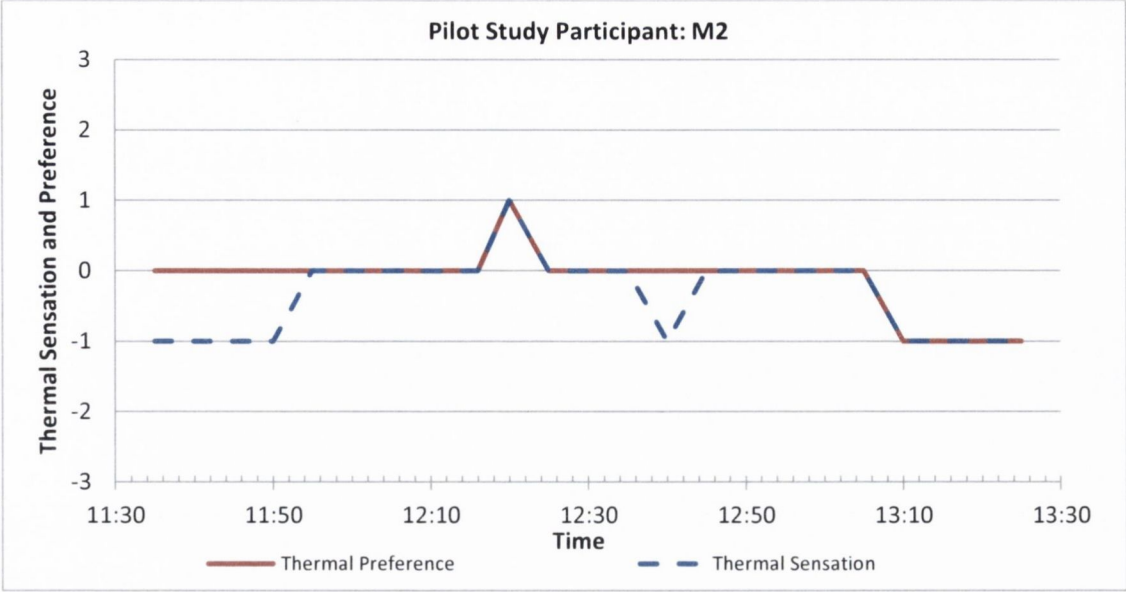


Fig. 5-3 Thermal sensation and preference vs. time for pilot study test on participant M2

Fig. 5-3 shows the thermal sensation and preference data over time recorded during the test. At the beginning of the test the thermal sensation was found to be recorded at -1 meaning the participant felt 'slightly cool' at the same time the participant recorded a thermal preference of 0, preferring 'no change' in the environment. The participant recorded the same values until 11:55 when the thermal sensation recorded changed to 0, indicating a feeling of 'neutral'. At this point the thermal preference remained the same at 'no change'. PMV was calculated to be -1.12 at 11:55. At the beginning of the test PMV was recorded between -1.25 and -1.12 and correlated well with the thermal sensation of -1. At 11:55, the thermal sensation diverges considerably from the PMV correlation of the previous recording of the test. At the end of the large increase in $T_{operative}$ of 1.2°C from 12:00 to 12:20 the participant recorded a thermal sensation of 1, 'slightly warm'. The rise in operative temperature over the previous twenty minutes showed a change in thermal sensation. However the participant recorded a return to feeling 'neutral' 5 minutes later. The thermal preference changed from preferring 'no change' to preferring 'a bit cooler' at 12:20. At 12:20 the PMV was calculated to be -0.77, which represented the largest gap between thermal sensation and PMV during this test. The environment was shown to be changing rapidly with a 1.2°C increase in $T_{operative}$ over a 20 minute period. PMV was constructed on the premise that the environment is changing slowly [77]. It is at this point that PMV shows a large discrepancy in value which could be due to the rapid change in environment. At 12:25, the participant recorded a thermal sensation of 0, feeling 'neutral', the $T_{operative}$ was found to be increasing at this point but at a slower rate compared with the previous 20 minute section. The environment was not found to have changed however the participant shows an adaptation to the increased $T_{operative}$ by feeling neutral again.

Previous research has shown that in a warm season, in which this test was carried out, occupants have been found to prefer thermal sensations of 'slightly cool' [76]. At the beginning of the test the participant feels 'slightly cool' but prefers 'no change' in the environment. The pilot study was carried out in July and August when mean outdoor temperatures are highest. The preference for 'no change' indicates the participant is satisfied with feeling 'slightly cool'. This trend would not be expected in a winter season test.

Between 12:25 and 13:05 the environment was found to be more stable with a slow increase in $T_{\text{operative}}$ from 22.0°C to 22.7°C. During this time PMV was calculated between -0.72 and -0.55. Thermal sensation and thermal preference were recorded at 'neutral' and 'no change' for this period, excluding a feeling of 'slightly cool' at 12:40 while the thermal preference remained the same. During this period the correlation of PMV to thermal sensation increased, after 13:05 and for the rest of the test the participant recorded feeling 'slightly cool' and preferring 'a bit warmer'. At this time PMV was found to be -0.5 and $T_{\text{operative}}$ was recorded at the highest value of the test, however there was found to be a drop in $T_{\text{operative}}$ recorded over the period 13:10 to 13:30. The most votes of 'slightly cool' come from the time when $T_{\text{operative}}$ and PMV are at the warmest recorded during the entire test. The values of PMV and thermal sensation compare well at this point with PMV recorded at -0.5 and thermal sensation was found to be -1. However looking at the whole of the test the maximum values of PMV and $T_{\text{operative}}$ were found at this period and if there was correlation to the PMV and $T_{\text{operative}}$, the participant was expected to record values of 'neutral' or 'slightly warm' given the rise in both recorded variables.

On looking at the conditions experienced by participant F1 in the pilot study the $T_{\text{operative}}$ and PMV are much warmer than those measured in this test. However, F1 showed a larger range of cool discomfort with several recordings of thermal sensation 'cool' and a preference for a 'much warmer' environment. The two participants were located in the same room, tests were carried out on different days. It was expected given the reduction in $T_{\text{operative}}$ for the test on M2 that a feeling of cool discomfort would be more prevalent considering the prevalence of cool discomfort during the test on F1 in a warmer environment. Participant M2 was found to be a male with a much larger body than that of F1. The metabolic rate assumed for all participants carrying out similar work would not be accurate given the difference in size of the participants. Previous research has shown that estimated basal metabolic rates of individuals is different based on factors such as height, weight, age and sex [78]. Actual metabolic rates of individuals doing sedentary work was shown to vary by as much as 20% using the method of measurement in this research [22]. Considering participant has a basal metabolic rate higher than F1 based on the estimation using the Harris-Benedict equations, M2 would be expected to have a metabolic rate

higher than F1 doing the same activity as the main component of metabolic rate in light sedentary work is the basal metabolic rate, that is, the minimum rate in which bodily functions are able to operate.

M2 recorded long periods of the same thermal sensation whereas F1 recorded changes in thermal sensation with no one thermal sensation recorded for longer than 20 minutes. This suggests F1 is more sensitive to the thermal environment.

5.2.3. Hand skin temperature

Measurements of hand skin temperature were made using the same techniques as those used in the pilot study test on participant F1. Index fingernail temperature and mean opisthenar temperature were calculated from the infrared images gathered at 30 second intervals during the test. In the pilot study test on participant F1, hand skin temperature was shown to correlate well to the thermal sensation and preference data collected as explored in Chapter 5. In this test a different participant is compared to the thermal sensation data in an attempt to correlate data gathered between participants of different height, weight and gender.

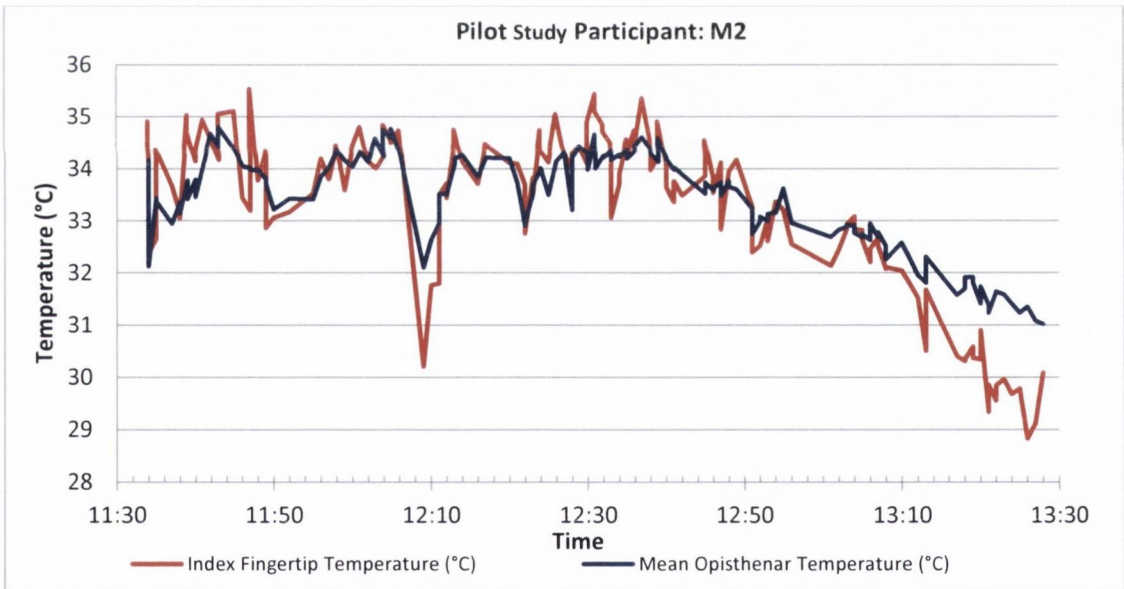


Fig. 5-4 Index fingernail and mean opisthenar temperature vs. time for pilot study test on participant M2

Fig. 5-4 shows the hand skin temperatures recorded over the course of the test on participant M2. Index fingernail temperature (T_{index}) was found to range from 28.8°C to 35.5°C. The arithmetic mean of values of T_{index} was found to be 33.2°C. The standard deviation of the values was found to be 1.6°C. The range of T_{index} was large at 6.7°C. The range of T_{index} recorded on the pilot study test on participant F1 was found to be 10.5°C, which was 3.8°C higher than the range found for M2. F1 recorded a much greater range

of thermal sensation which correlates with the much greater range of T_{index} . M2 recorded a mean value of T_{index} much higher than F1, 30.0°C. The mean of T_{index} was found to be 3.2°C higher for M2 than that recorded for F1.

From the start of the test, at 11:34 until 12:50, T_{index} rarely dips below 33.0°C. At the beginning of the test T_{index} was found to quickly rise above 33.0°C. It is at this time that the participant recorded a thermal sensation of 'slightly cool'. T_{index} was found to vary significantly up to 12:50. At one point at 12:09 the T_{index} is recorded at 30.2°C. Interrogation of the participant showed that the participant had washed the hands just before this recording. It was found that T_{index} recovered quickly from this low value back to values previously recorded for the same thermal sensation. After 12:50 the T_{index} was found to be in slow decline to the lowest recorded value of T_{index} of 28.8°C. As T_{index} was found to drop below 33.0°C the thermal sensation recorded was found to change from 'neutral' to 'slightly cool'. When participant F1 recorded a feeling of 'slightly cool' T_{index} was recorded below 32.0°C and more commonly below 30.0°C. Participant M2 was found to have much higher T_{index} than F1 in all aspects of the test. When thermal sensations of 'neutral' were recorded, the T_{index} of M2 was over 3.0°C higher than that of F1. This suggests that M2 has more cutaneous blood flow in a case where M2 feels neutral. The cooler environment in this test compared to that of F1 shows a greater temperature difference indicating that M2 requires more heat transfer due to the metabolic rate. A larger temperature difference means the heat transfer will be higher in both convective and radiant transfers.

Mean opisthenar temperature (T_{opis}) was found to range from 31.0°C to 34.8°C. The mean T_{opis} was found to be 33.4°C. The mean of T_{opis} and T_{index} was found to be within 0.2°C of each other. The standard deviation of T_{opis} was smaller at 1.0°C indicating the range of values recorded was smaller than that of T_{index} . T_{index} and T_{opis} recorded similar values over the course of the test. T_{opis} was found to oscillate much less than recorded values of T_{index} . At 13:05 when the participant recorded a thermal sensation of 'slightly cool', T_{index} and T_{opis} start to diverge in values. Previous to this point the values were found to be almost coincident. At 13:05 and later, T_{opis} was found to decline at a slower rate than T_{index} .

At the start of the test the participant recorded a thermal sensation of 'slightly cool' rising to 'neutral' after 20 minutes. During this time the values of T_{opis} and T_{index} vary dramatically, rising to 35.0°C before declining to 33.0°C before rising again to just below 35.0°C again. This trend was not seen previously in tests on participant F1. The rise and fall of temperatures over the course of 40 minutes represented the increases and decrease in blood flow to the skin. The body regulates temperature of core by increasing blood flow to extremities and skin. The increased blood flow increases the skin temperature by heat transfer processes. When there is no external heat acting on the hand of the participant in

an environment which isn't rapidly changing, the only source for the increase in temperature is increased skin blood flow. External heat sources in an office environment include cups of hot liquid, sunlight and handling warm electronics.

Overall the hand skin temperature of participant M2 was found to be much higher than that of F1. In an environment with low operative temperature, the expectation was cool discomfort, which was only found to be evident at the end of the test. Hand skin temperature was shown to oscillate much more in M2 than in F1 however this could be due to the thermal sensation state in which the participant was found to be. F1 felt cool discomfort for most of the test therefore lower hand skin temperatures would be expected since the body would try to reduce heat loss by curtailing cutaneous blood flow.

5.3. Participant M1

Participant M1 was found to be the heaviest of the participants but also the tallest. The estimated basal metabolic rate of M1 was also found to be the highest. Participant M1 was found to sit at a desk on the ground floor in the same building as F1 and M2. The room in which M1 was seated was found to have much higher ceilings than the top floor room. The room was found to have the same methods of heating and cooling as those described in the top floor room, however windows to the street were sealed and only windows to the atrium space were found to open. There were two wall mounted air con units and radiators on the walls below each of the four windows, much like the top floor room. Both areas were found to be the same size. During the test neither air con units were on nor were the windows opened, therefore air flow was at a minimum.

5.3.1. Indoor Environment Quality

Two tests were performed on participant M1 in the morning and in the afternoon. The tests were performed on consecutive days during the month of July.

5.3.1.1. Morning Test

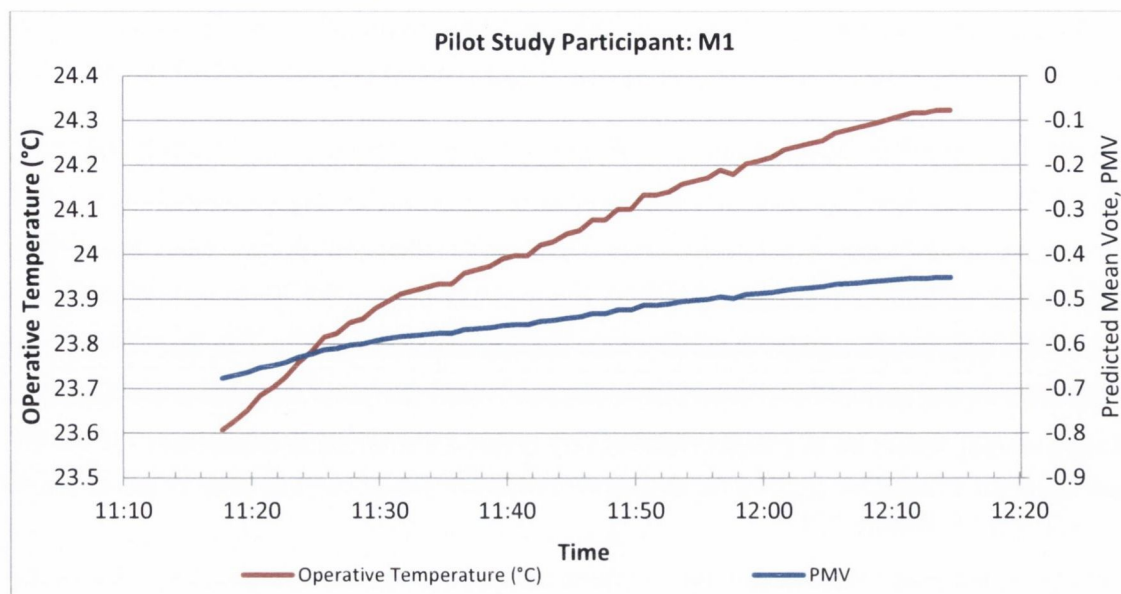


Fig. 5-5 Graph of operative temperature and PMV vs. time in pilot study for participant M1 (Morning test)

A test was carried out on participant M1 in the morning when the participant first arrived at the desk in the test building. Fig. 5-5 shows the operative temperature ($T_{\text{operative}}$) and predicted mean vote (PMV) over time. PMV and $T_{\text{operative}}$ are represented on the same graph. PMV is graphed on the secondary Y-axis as $T_{\text{operative}}$ and PMV have different units.

$T_{\text{operative}}$ ranges from 23.6°C to 24.3°C with an arithmetic mean of 24.0°C. During the course of the test on M1 $T_{\text{operative}}$ was found to rise steadily over the test period. The room in which this test was conducted was in the same building as those pilot study tests performed on M2 and F1 but in a different room on a different floor. The test was performed in a ground floor room where temperatures were found to be lower compared with those on the top floor of the building in which the test on M2 and F1 were performed. $T_{\text{operative}}$ in this test shows a steady rise of only 0.7°C. In tests on M2 and F1, rises in $T_{\text{operative}}$ were found to be more than three times that of tests on M1. $T_{\text{operative}}$ measured in the test on M1 is similar to that measured in the test on F1. Tests on F1 produced lower and higher $T_{\text{operative}}$ than that measured in this test.

The PMV calculated from the measured variables was found to range from -0.68 to -0.45. The mean value of PMV was found to be -0.54. The PMV calculated in this test differed significantly to that recorded in the test on F1 as the clothing insulation was found to be different. M1 was found to be wearing a short sleeved shirt and shorts which was estimated to have a clothing insulation value, including the insulation of the chair, of 0.3 clo. F1 was estimated to be wearing 0.5 clo rising to 0.8 clo when extra garments were put on. This was the reason for the lower PMV value calculated. Clothing is used by humans

to alter the thermal state and in this example M1 may feel generally warm at this time of year so has chosen a clothing ensemble with a low insulation value.

5.3.1.2. Afternoon Test

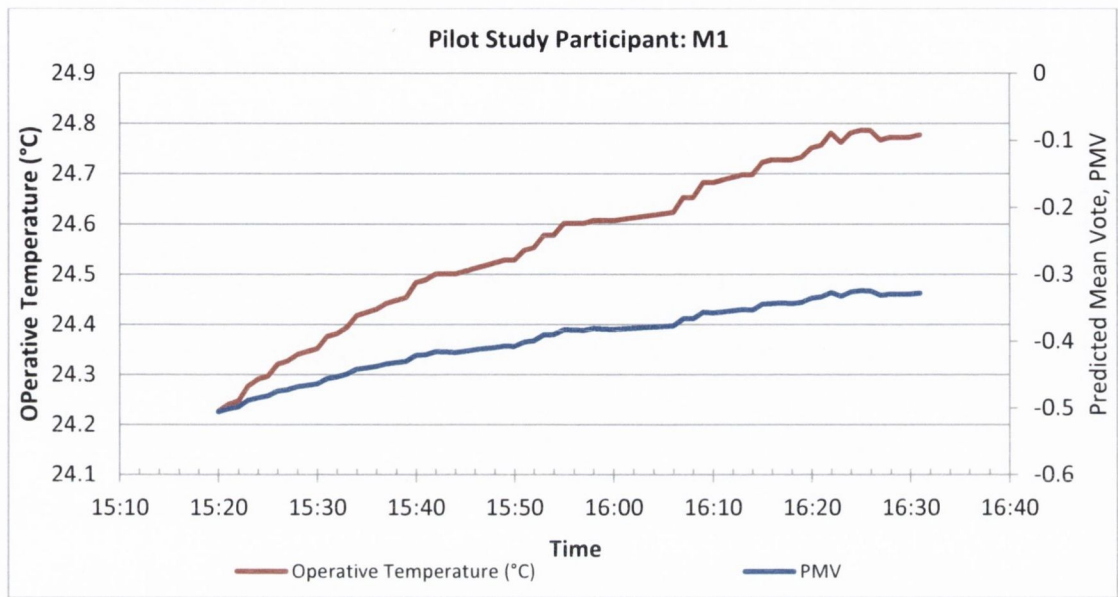


Fig. 5-6 Graph of operative temperature and PMV vs. time in pilot study for participant M1 (Afternoon test)

Fig. 5-6 shows the graph of $T_{operative}$ and PMV over time for the afternoon test on participant M1. $T_{operative}$ was found to range between 24.2°C and 24.8°C during the test. The arithmetic mean of $T_{operative}$ was found to be 24.6°C which was found to be 0.6°C higher than that of the morning test. Like in the morning test $T_{operative}$ was found to increase over the course of the test up to a final value of 24.8°C. The $T_{operative}$ in the pilot test on participant F1 was found to be similar to $T_{operative}$ found in this test. Like in the morning test, M1 was found to be wearing lighter clothing meaning a lower insulation value. PMV for the test ranged from -0.51 to -0.31 meaning the environment was approaching a PMV value in which most occupants would feel comfortable, that is 0.

5.3.2. Thermal sensation

5.3.2.1. Morning Test

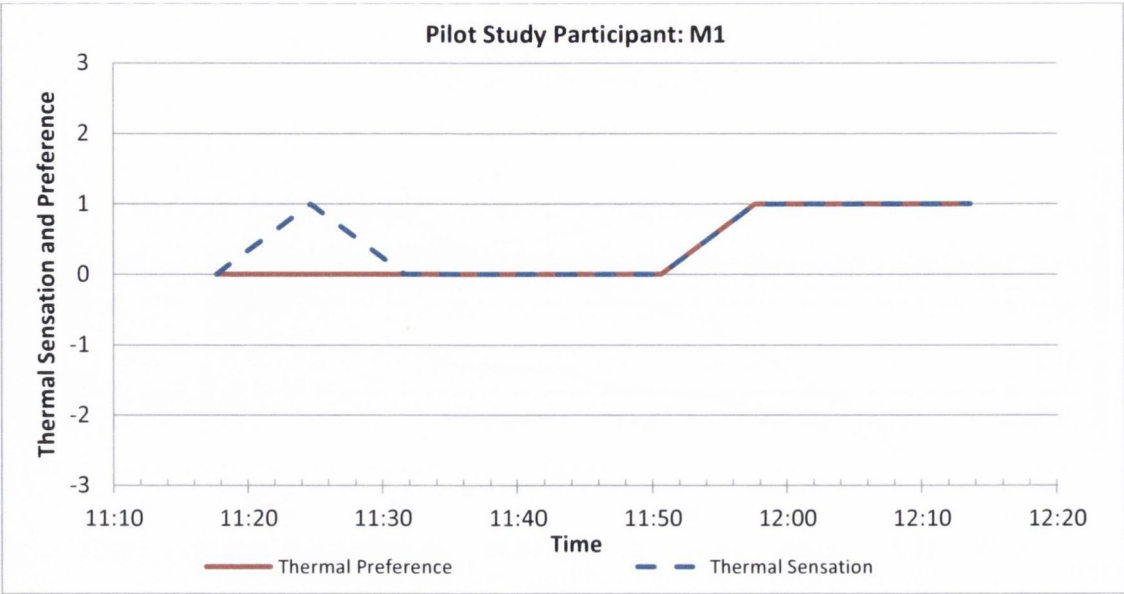


Fig. 5-7 Graph of thermal sensation and preference vs. time in pilot study for participant M1 (morning test)

Fig. 5-7 graphs the thermal sensation and thermal preference participant M1 recorded during the morning test. It is clear from the graph that thermal sensation followed thermal preference except on one occasion. During the test the participant recorded thermal sensations of 'neutral' and 'slightly warm'. At the start of the test, the participant recorded feeling 'neutral' rising to 'slightly warm' at 11:25 then was found to return to 'neutral' until 11:58. The PMV predicted cool discomfort, which the participant did not display. The participant recorded feeling 'slightly warm' from 11:58 onwards. PMV calculated was found to rise over the course of the test. The rise in PMV and $T_{operative}$ would be expected to cause a rise in thermal sensation to warmer sensations which was found to occur in the latter part of the test. Thermal preference correlates well with thermal sensation indicating the participant prefers to feel 'neutral' compared to feeling 'slightly warm'.

5.3.2.2. Afternoon Test

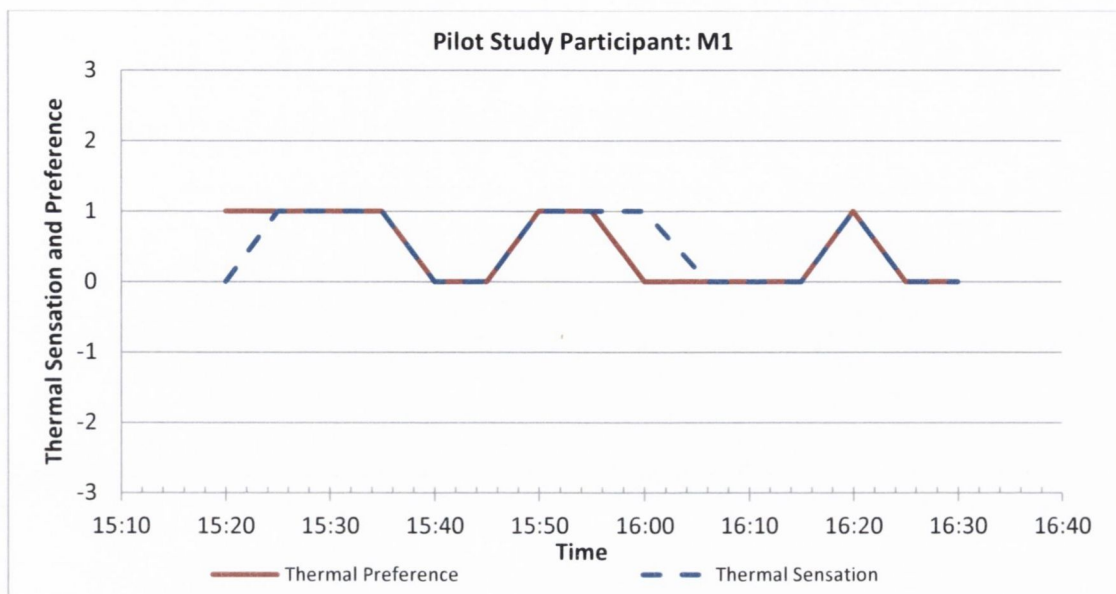


Fig. 5-8 Graph of thermal sensation and preference vs. time in pilot study for participant M1 (afternoon test)

Fig. 5-8 shows thermal sensation and preference data collected during the afternoon test. PMV and $T_{\text{operative}}$ were found to be higher in this test than the morning test and the data in Fig. 5-8 reflects these increases. Thermal sensation was found to change over much of the test between 'neutral' and 'slightly warm'. 6 instances of 'slightly warm' were recorded and 8 instances of 'neutral' were recorded. Thermal preference follows thermal sensation for much of the test and in one case the participant note preferring 'a bit cooler' while the sensation was found to be 'neutral', the participant was found to prefer a cooler environment even though sensation was neutral. This indicates a preference of participant M1 for a cool environment.

The environment in both morning and afternoon tests was found to compare well to that of the pilot study test on participant F1. M1 recorded thermal sensation and thermal preference at a more constant value than that recorded by F1. Thermal sensation recorded by F1 was found to be of cool discomfort for much of the test, whereas Thermal sensation for M1 was 'neutral' and 'slightly warm'. PMV was found to be much different to that calculated for F1 which was due to the change in clothing insulation. Participant M1 was found to have warm discomfort in much of the pilot study test in which the participant chose to wear less clothing to increase heat loss from the body. F1 chose to wear more clothing in a similar environment in order to decrease heat loss from the body.

5.3.3. Hand skin temperature

5.3.3.1. Morning Test

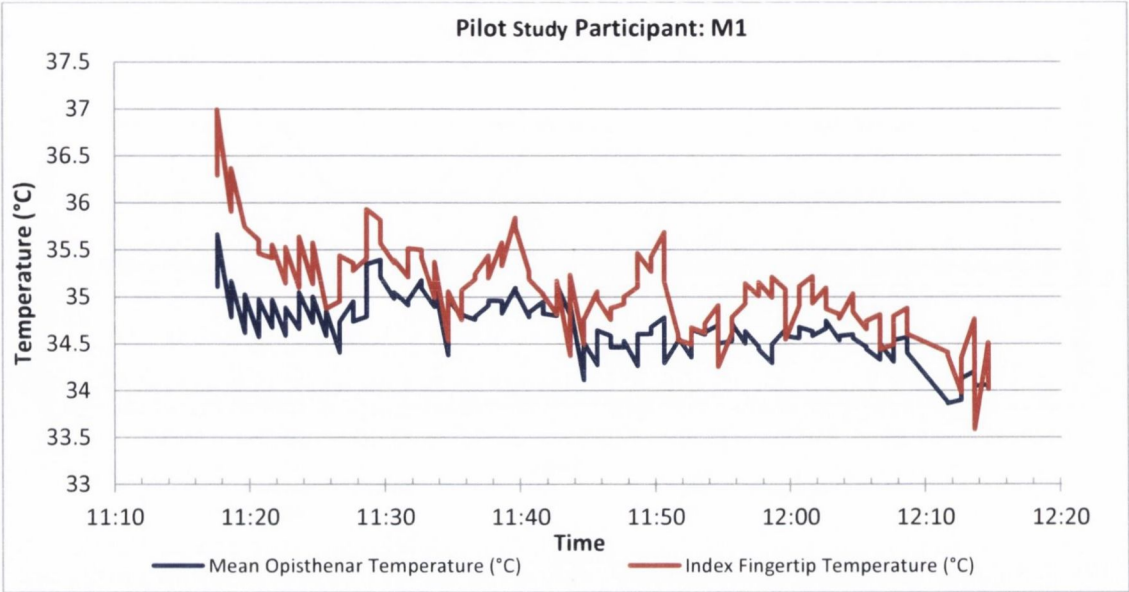


Fig. 5-9 T_{index} and T_{opis} vs. time for pilot study test on participant M1 (morning test)

T_{opis} and T_{index} were calculated from the infrared images. The result of the calculations made is presented in Fig. 5-9 for the morning test on participant M1. At the beginning of the test both hand skin temperatures measured were found to be raised. T_{opis} was found to have a maximum of 35.7°C while T_{index} was found have a maximum of 37.0°C. T_{index} recorded at this time was found to be the same as the assumed core temperature of 37.0°C. When skin temperature of the finger approaches core temperature the cutaneous blood flow is large and the body is trying to increase heat transfer to the environment. This indicates that metabolic rate is raised. Interrogation of the participant found that the participant had just finished a 10 minute intense bicycle ride. Metabolic rate and body heat transfer would reduce slowly after this exercise. The hand skin temperature was found to decrease over the course of the test, initially quickly in the first 5 minutes. The reduction in metabolic rate expected was found to be replicated in the reduction of hand skin temperature. For most of the test period T_{index} was found to be higher than T_{opis} . Compared to hand skin temperatures of M2 and F1, M1 was found to have much higher temperatures. The mean of T_{opis} was found to be 34.7°C while the mean of T_{index} was found to be 35.1°C. However, it is difficult to compare the hand skin temperature calculated here to other participants as M1 was found to have completed exercise immediately before the test was started. As a result, M1 was not in the same condition of metabolic rate as the other participants and this was represented by the increased hand skin temperature. It is interesting to note that the recordings of thermal sensation show the participant was comfortable in the environment with an increased hand skin temperature.

The participant was found to have exercised outdoors, entering the new environment of the test room may have had an effect on the thermal sensation.

5.3.3.2. Afternoon Test

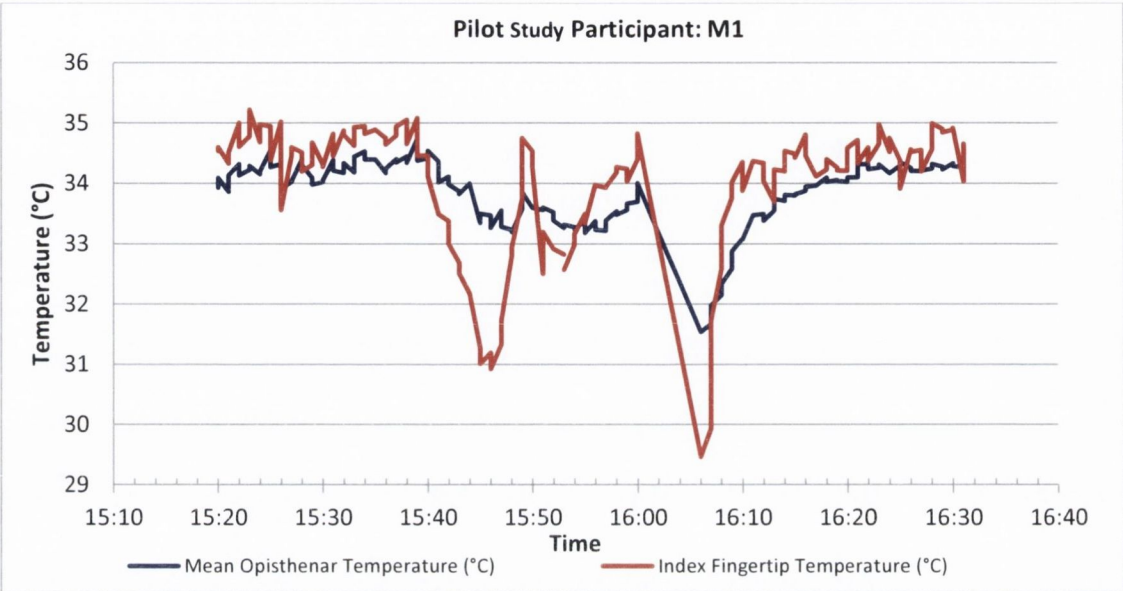


Fig. 5-10 Index fingernail and mean opisthenar temperature vs. time for pilot study test on participant M2 (afternoon test)

The hand skin temperature in the afternoon test on participant M1 is shown in Fig. 5-10. T_{index} was found to range from 29.5°C to 35.2°C, while T_{opis} was found to range from 31.5°C to 34.7°C. At 16:06 the hand skin temperature was noted to drop considerably from the last skin temperature recorded. At this time the participant was found to have washed the hands. The washing of hands in cold water was found to reduce hand skin temperature. T_{index} quickly recovered the temperature back from a low of 29.5°C while T_{opis} took longer to recover from a higher low of 31.5°C. T_{opis} recovered back to the same temperature recorded before hand washing, of 34.0°C, within 10 minutes. T_{index} was found to recover to a similar temperature within 3 minutes. T_{opis} was expected to be slower in recovering temperature as the opisthenar has a larger volume compared to the index fingernail. In this reheating of the hand skin the index fingernail was found to be the first area to reach the recovered temperature. The intermediate phalange skin was found to be the next area to recover the temperature before hand washing and the proximal phalange skin of the index finger was found to be the final area of the finger to recover temperature. The volume and surface area of each phalange of the index finger are approximately equal. Increased blood flow to the index finger was found to warm from the fingernail back. The expected mode of reheating was from the source of the blood, the heart, arm and hand, to the fingernail.

Fig. 5-11 shows the reheating of the hand skin in this part of the test. Each image shown in the figure represents the infrared imagery collected which has been converted to a black and white image where brighter pixels represent higher temperatures. The min and max temperatures of blackest and whitest pixels was chosen at 28°C and 34°C to use a close range to show the development of skin temperature in the images presented.

In the first line of images the hand is cold represented by a darker colour. In the last image of the first line the index fingernail, and other fingernails, is shown to be at a higher temperature to the rest of the hand. As the hand reheats through cutaneous blood flow the index finger was found to increase in temperature from the fingernail toward the opisthenar. In the final set of three images the arteries and veins in the opisthenar is clearly visible.

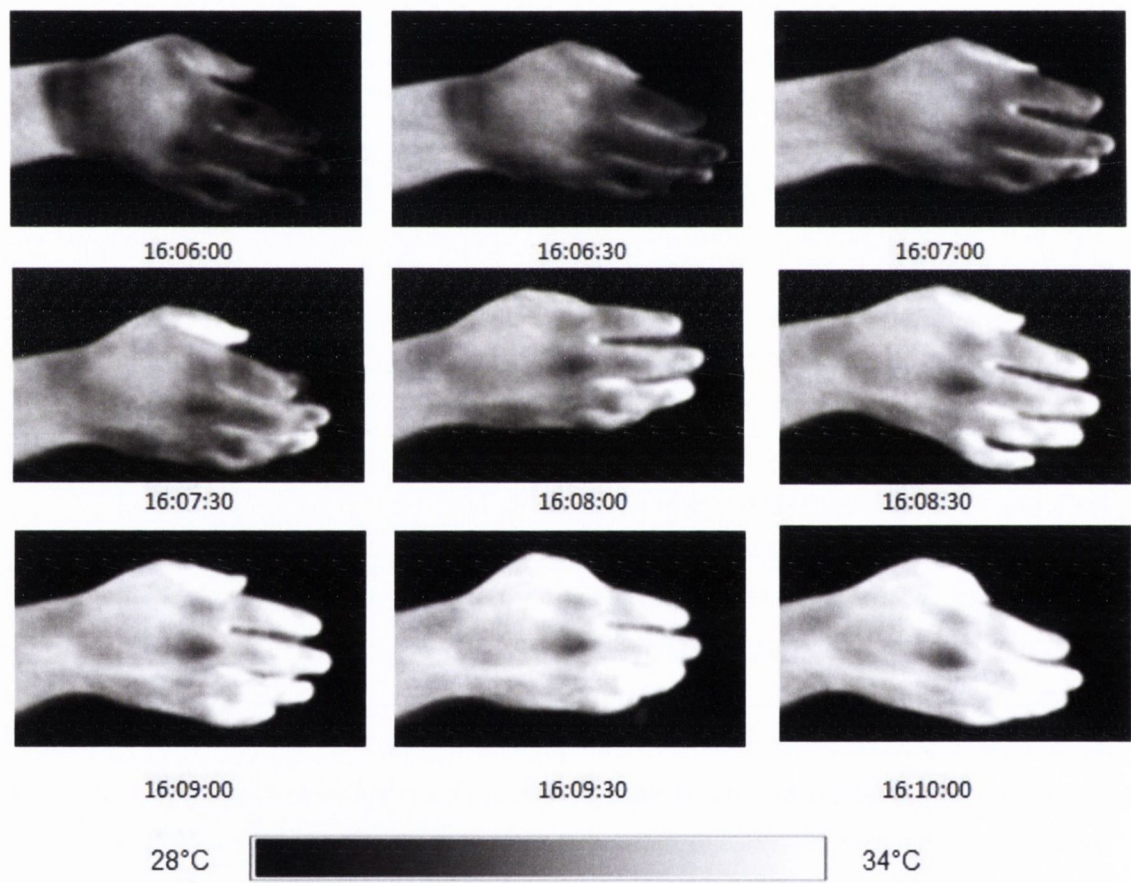


Fig. 5-11 Pilot study afternoon test participant M1 hand reheating at time marks shown,
 $T_{\text{image, min}}=28^{\circ}\text{C}$, $T_{\text{image, max}}=34^{\circ}\text{C}$

At the beginning of the afternoon test on participant M1 the hand skin temperature was found to be between 34.0°C and 35.0°C for most of the time until 15:40 when T_{index} reduces quickly to a low of 31.0°C by 15:45. The thermal sensation at this time was found to reduce from 'slightly warm' to 'neutral' at 15:40 and remain at 'neutral' at 15:45. T_{index}

returned to above 34.0°C when the next recording of thermal sensation was made in which M1 recorded feeling 'slightly warm'. T_{opis} declined below 34.0°C at 15:42 and did not decline as much as T_{index} . Some reheating of T_{opis} was found at 15:50 when 'slightly warm' was recorded as the thermal sensation.

After the hand washing at 16:06 hand skin temperature was found to reach 34.0°C again while 'slightly warm' thermal sensation was recorded. The hand skin temperatures were found to remain between 34.0°C and 35.0°C while the thermal sensation was found to drop to 'neutral' at the end of the test. The reduction of thermal sensation to neutral while the hand skin temperature remained the same could be explained by the body having reached equilibrium. The convective and radiant heat transfer from the body could have reached an optimum level based on the skin temperature levels recorded reducing the need for increased heat transfer and the body was found to be comfortable in the environment.

5.4. Participant M3

Participant M3 was seated in the same building as the other participants. M1 and M3 shared the same room on the ground floor of the test building. M3 was found to be the lightest male participant by some way and had an estimated basal metabolic rate similar to that of F1. M3 was found to feel ranges of hot and cold throughout the day much like F1. M3 was found to have the lowest estimated basal metabolic rate of the participants. The test on participant M3 was carried out over the course of one day in July.

5.4.1. Indoor Environment Quality

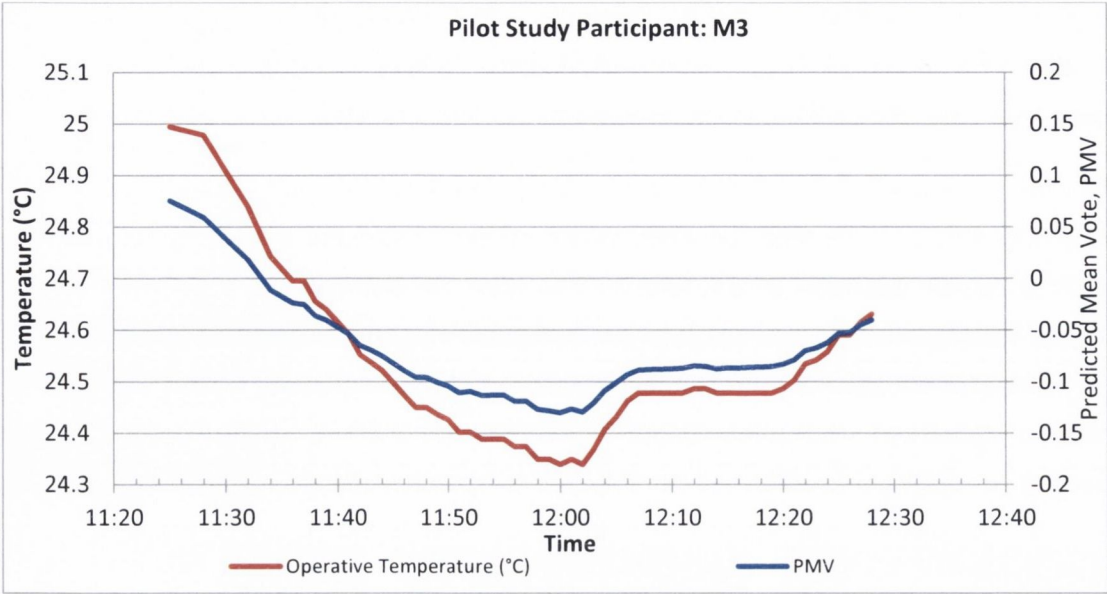


Fig. 5-12 Graph of operative temperature and PMV vs. time in pilot study for participant M3 (morning test)

Fig. 5-12 shows $T_{\text{operative}}$ and PMV over the course of the morning part of the pilot study test on participant M3. $T_{\text{operative}}$ was found to decrease during the test period, notably the first time $T_{\text{operative}}$ has decreased in a test. $T_{\text{operative}}$ was found to range between 25.0°C and 24.3°C. At the start of the test $T_{\text{operative}}$ was found to be 25.0°C and at the end, 24.6°C. The mean of $T_{\text{operative}}$ was found to be 24.5°C. The environment was found to be similar to that found in the pilot study test on participant F1. $T_{\text{operative}}$ is within the recommended range of 23.5°C to 26.0°C given by ASHRAE standard 55 [31]. The PMV calculated from the test variables recorded was found to be within 0.2 of 0.0 for most of the test indicating the environment was optimum for most occupant comfort. PMV was found to follow $T_{\text{operative}}$ as the same variables recorded are used to calculate both. The clothing insulation of M3 was estimated to be 0.5 clo which was the same as that of participant F1 in the early stages of the pilot test before placing an extra garment on. The expected response of the participant in this test was of neutral thermal sensation.

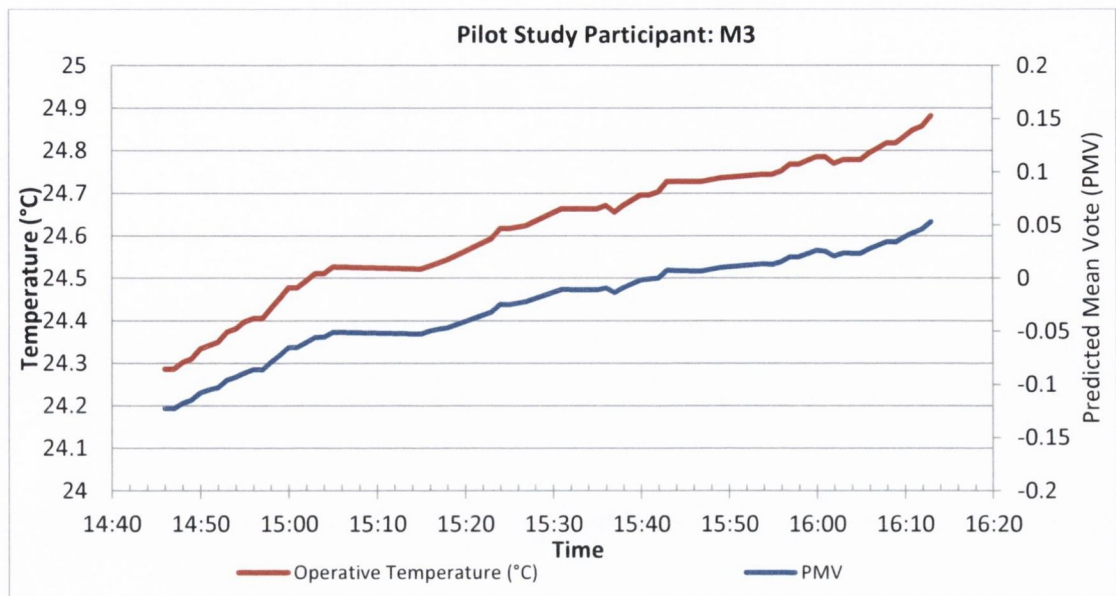


Fig. 5-13 Graph of operative temperature and PMV vs. time in pilot study for participant M3 (afternoon test)

In the afternoon part of the pilot study test on M3, $T_{\text{operative}}$ was found to increase at a steady rate from 24.3°C to 24.9°C, as shown in Fig. 5-13. PMV was found to be within 0.2 of 0.0, like in the morning test, which was found to be the perfect conditions according to PMV for maximum comfort of occupants in this environment with the same clothing insulation level and activity level. $T_{\text{operative}}$ was within the recommended guidelines of ASHRAE standard 55 like the morning test and increased in value like most other tests reviewed so far in the pilot study.

5.4.2. Thermal sensation

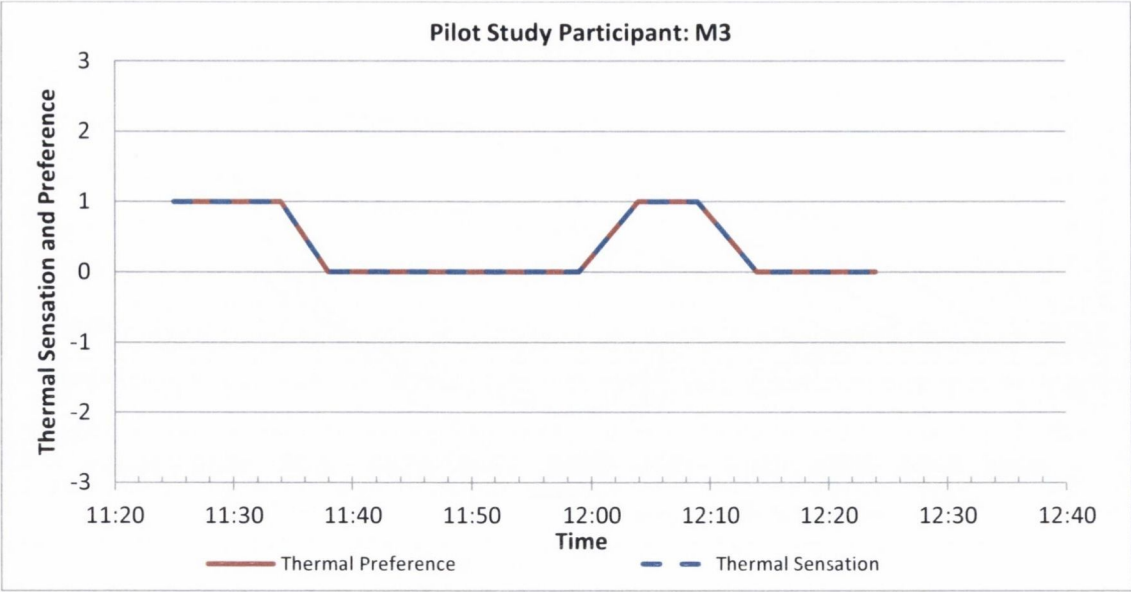


Fig. 5-14 Thermal sensation and preference vs. time for pilot study test on participant M3 (morning test)

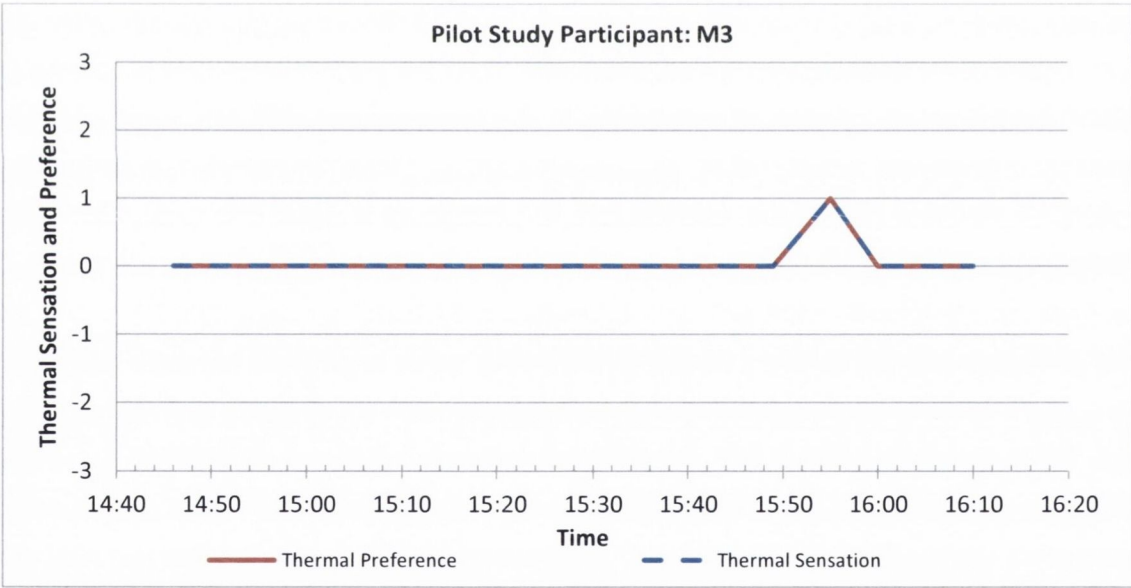


Fig. 5-15 Thermal sensation and preference vs. time for pilot study test on participant M3 (afternoon test)

In both morning and afternoon tests on participant M3 the thermal sensation recorded was found to be either 'neutral' or 'slightly warm'. Thermal preference was found to be either preferring 'no change' or 'a bit cooler' as shown by graphs of thermal sensation and preference in Fig. 5-14 and Fig. 5-15.

During the morning test the initial thermal sensation was recorded as 1, 'slightly warm', which dropped to 0, 'neutral' at 11:38. It was at the start of the test that the highest $T_{\text{operative}}$

was recorded. PMV predicts 'neutral' feeling for most occupants. At 12:04 and 12:09 a thermal sensation of 'slightly warm' was recorded

5.4.3. Hand skin temperature

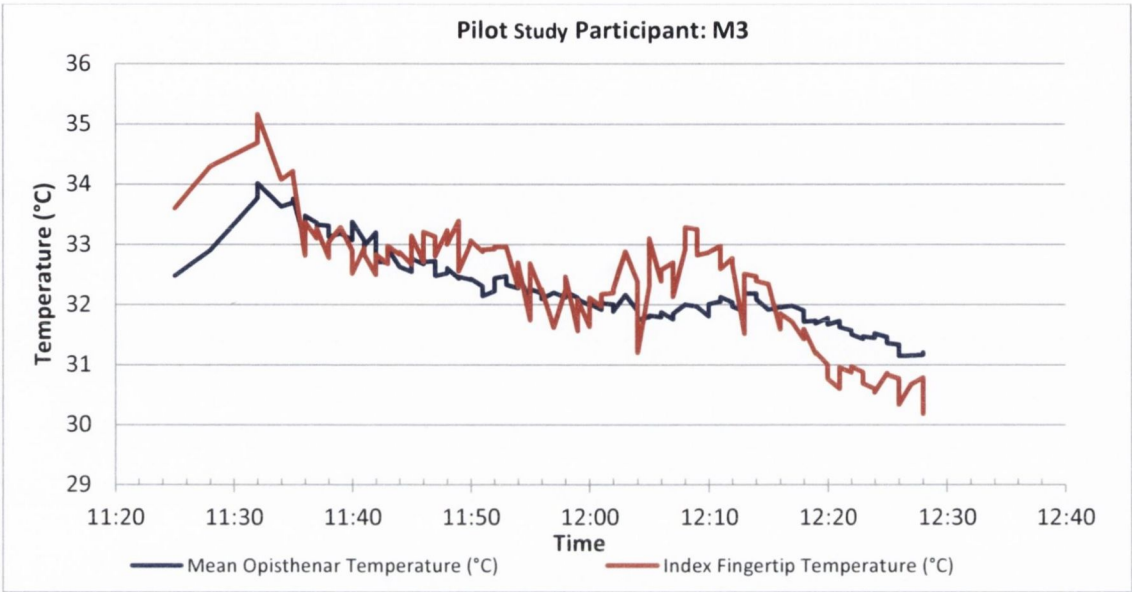


Fig. 5-16 Index fingernail and mean opisthenar temperature vs. time for pilot study test on participant M3 (morning test)

Over the course of the morning test on participant M3 hand skin temperatures were found to drop overall, Fig. 5-16. Index fingernail temperature (T_{index}) was found to increase at various times whereas T_{opis} was found to decrease for most of the test. T_{opis} was found to have a maximum of 34.0°C and minimum of 31.1°C. The mean of T_{opis} was found to be 32.3°C. T_{index} was found to have a larger range with maximum and minimum, 35.2°C and 30.2°C, respectively. The mean of T_{index} was found to be 32.4°C. Both hand skin temperatures were found to have an arithmetic mean close together. T_{index} was found to range above and below T_{opis} at various times. At the end of the test T_{index} was found to be much lower than T_{opis} , however throughout the test T_{index} was found to oscillate between slightly lower than T_{opis} and slightly higher. At 12:05 T_{index} was found to increase dramatically above T_{opis} until 12:10. At this time T_{opis} was found to increase very slightly. The corresponding thermal sensation was 'slightly warm' which reduced to 'neutral' by 12:15. T_{index} raised above T_{opis} by up to 1.0°C in this period. At the start of the test the hand skin temperature was found to be higher than in the rest of the test period. At this time the participant recorded feeling 'slightly warm'. Later in the test when the participant was found to record 'slightly warm' again, T_{opis} was found to increase only slightly from that recorded at 12:05 and was found to be much lower (32.0°C) than those values recorded at the beginning of the test (34.0°C). T_{index} was found to increase more than T_{opis} to 33.0°C while the participant recorded 'slightly warm'. The overall decrease in hand skin

temperature was found in other tests in the morning on all other participants. The decrease of hand skin temperature was not as clear in the afternoon tests on participants.

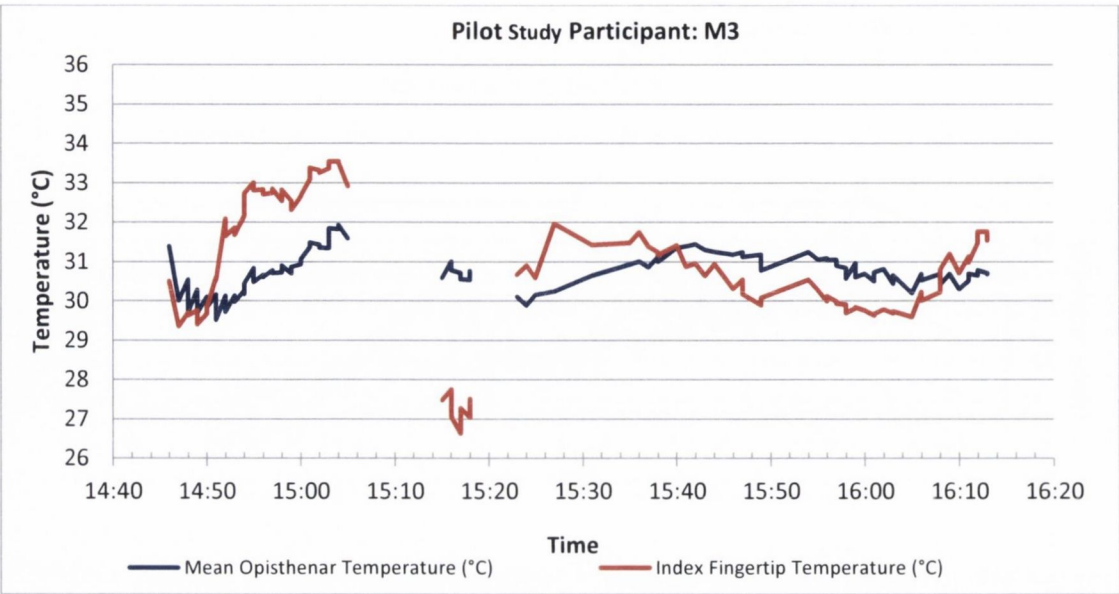


Fig. 5-17 Index fingernail and mean opisthenar temperature vs. time for pilot study test on participant M3 (afternoon test)

Fig. 5-17 shows the hand skin temperature recorded for the afternoon test on participant M3. There are large gaps in the data recorded at 15:10 and 15:20 when the participant was absent from the desk where the test was carried out. Participants in these tests were allowed to leave and return to ensure a normal working environment. When the participant returns at 15:15, hand skin temperature was found to be much lower than when the participant left the desk. T_{opis} was found to have a mean of 30.7°C while the T_{index} was found to have a mean of 27.2°C during this time. T_{index} recorded was found to be 3.5°C lower than the T_{opis} recorded and values for T_{index} were the lowest recorded at this time for this participant in the pilot study test. For most of the test the participant was found to record a thermal sensation of 'neutral'. 15:55 was the single time when the participant was found to record a different thermal sensation, 'slightly warm'. For the period from 15:25 to the end of the afternoon test the hand skin temperature of the participant was found to range between 30.0°C and 32.0°C. T_{index} and T_{opis} were not found to be coincident for much of the time but the means of recorded skin temperature were found to be within 0.3°C for this period. At the beginning of the test, T_{index} was found to be coincident with values recorded for T_{opis} until 14:50 before increasing significantly above T_{opis} by 2.0°C. T_{opis} and T_{index} were found to increase more at this point up to a maximum of 31.9°C and 33.5°C, respectively. The mean values of T_{opis} and T_{index} recorded over the entire test were found to be 30.7°C and 30.9°C, respectively. The morning test showed a close proximity in mean values of hand skin temperature. The afternoon test showed T_{opis} and T_{index} mean

values within 0.2°C. Overall hand skin temperatures were higher in the morning test than in the afternoon test.

During the afternoon test on participant M3 the hand skin temperature ranged from 26.6°C to 33.5°C while the participant recorded a thermal sensation of 'neutral'. This large range of temperature variance while a single thermal sensation is recorded is unexpected. It is interesting to note the much lower hand skin temperatures in the afternoon test compared with the morning test. Hand skin temperature dropped steadily during the morning test. In the afternoon test hand skin temperatures were stable but lower in value for this participant. Further tests should identify this trend.

5.5.Statistical overview

Table 5-2 show the summary statistics for the entire pilot study. It includes the data from all participants and collates the values recorded and calculated. The summary statistics are used to compare to other research carried out.

A total of 110 ASHRAE scale and preference scale measurements, 860 infrared imaging temperature measurements and 515 measurements of the thermal environment were made in the pilot study. ASHRAE and preference scale was recorded at 5 minutes intervals or while the participant was at the test desk. Environment was recorded at 1 minute intervals while infrared imagery was recorded at 30 second intervals. The infrared data did not always contain useable information and was dropped from the study. Ineffective infrared images included hands not within camera frame, fingers obscured by hand position and fingers obscured by placement on the computer mouse. Adjustments were made in subsequent tests to ensure infrared data gathered was usable. Participant M2 in particular showed a large degree hand movement throughout the tests. In one such test the infrared data was unusable as the hands were out of shot of the camera for most of the test. The field of view of the camera was widened to take into account the various usual positions of the hands. These positions were estimated from the initial test in which data was found to be unusable.

	N	Min	Max	Mean	Standard Deviation
ASHRAE Scale	110	2.0	5.0	4.0	0.8
Preference Scale	110	2.0	4.0	3.1	0.6
Average Opisthenar Temperature (°C)	860	28.6	35.7	32.6	1.7
Index Fingernail Temperature (°C)	860	25.1	37.0	32.2	2.7
Operative Temperature (°C)	515	20.1	25.0	23.7	1.1

Table 5-2 Summary statistics from pilot study

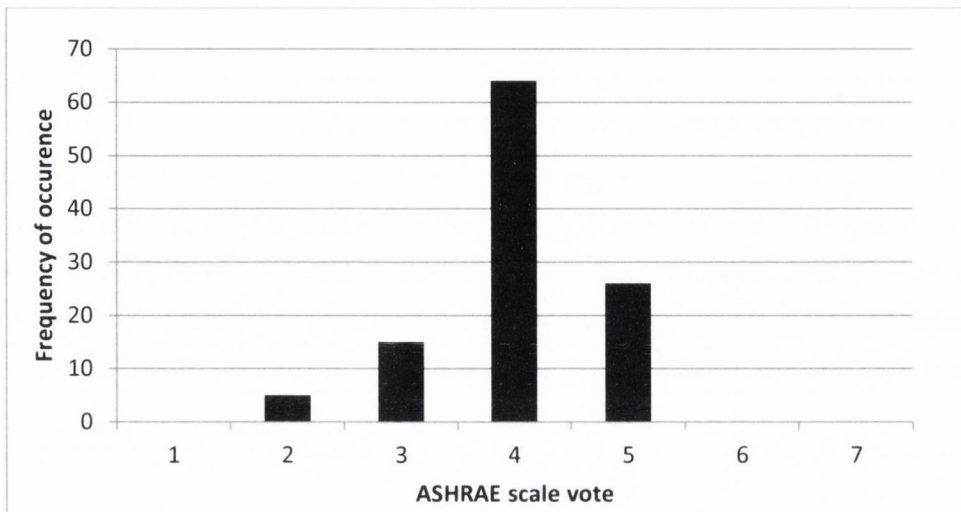


Fig. 5-18 Distribution of ASHRAE scale votes for pilot study

The full scale of ASHRAE is 1 to 7 scale units however the pilot study only had responses of 2 to 5 scale units, that is 'cool' to 'slightly warm'. The pilot study was carried out during the summer months in Ireland and mean operative temperatures were found to be 23.7°C. It was expected that the ASHRAE scale data would show neutral to warm discomfort as $T_{operative}$ was high and outside temperatures were found to be high. This proved not to be the case and there were many time when 'cool' to 'slightly cool' was recorded. The warmest recording was found to be 'slightly warm' during the pilot study. The most common recording was found to be 'neutral' followed by 'slightly warm'. The ASHRAE scale recorded was not found to be a normal type distribution. The limit of warm discomfort in the pilot study was found to be 'slightly warm'. If the distribution was to be normal ASHRAE scale votes of 'warm' that matched those of 'cool' would be expected. Fig. 5-18 shows the distribution of ASHRAE scale votes recorded. The distribution was found to give a mean of 4.0 units. The rationale for no ASHRAE scale votes of 'warm' or warmer is not clear. The human body has many processes for temperature regulation, such as sweating and shivering. The human body has also shown adaptation to the thermal environment. The pilot study showed slow increases in operative temperature yield no change in thermal sensation recorded.

Preference scale was found to range between 2 and 4 scale units, preferring 'a bit warmer' and 'a bit cooler'. Preference scale was not found to range as much as ASHRAE scale. This could be due to the smaller scale it operates in, 5 units versus 7 units. It was expected that when a participant felt 'cold' the participant would prefer an environment which was 'much warmer', however no preferences for 'much warmer' were recorded during the pilot study test. The mean of preference scale was found to be 3.1 or 0.1 above

preferring 'no change'. More preference for a cooler environment was recorded than preference for a warmer environment. It was interesting to note that preference scale did not always follow the ASHRAE scale recorded. Times when participant felt 'slightly cool' were not matched with preferring 'a bit warmer' but with preferring 'no change'. Other research has shown that the optimum point for thermal comfort is not always the neutral point and when outdoor temperatures are high the preferred sensation is for slightly cooler than 'neutral' [10].

The maximum T_{opis} was found to be 35.7°C compared with maximum of 37.0°C for index fingernail temperature, T_{index} . Body core temperature is about 37°C, this is the maximum value that skin temperature can have without any external heating. Having a skin temperature close to core temperature values suggests the cutaneous blood flow is large and the body is trying to dissipate as much heat as possible. The maximum temperatures of hand skin temperature came from test period where the participant had finished some exercise and had returned to the test desk to start the test. Some sweating of the participant was observed as the body cooled and metabolic rate decreased due to the cessation of activity. Mean T_{opis} and T_{index} temperatures were found to be 32.6°C and 32.2°C, respectively. The range above the mean of T_{opis} was found to be 3.1°C and for T_{index} was found to be 4.8°C. The range below the mean values was found to be far higher for both T_{opis} and T_{index} . The upper limit of hand skin temperature is the core temperature. While there is no lower limit due to heat loss to environment, a reasonable lower limit would be operative temperature in a normal office environment in which there is little change. Minimum temperature shows a much lower minimum of T_{index} to T_{opis} . T_{opis} and T_{index} minimum temperatures were found to be 28.6°C and 25.1°C, respectively. The range of hand skin temperatures shows a distribution which is impacted by an upper limit which does not have a corresponding lower limit. The data is skewed toward the upper end of the scale.

	ASHRAE Scale	Preference Scale	Average Opisthenar Temperature (°C)	Index Fingernail Temperature (°C)	Operative Temperature (°C)
ASHRAE Scale	1	0.863	0.397	0.502	0.362
Preference Scale	0.863	1	0.385	0.446	0.249
Average Opisthenar Temperature (°C)	0.397	0.385	1	0.900	-0.187
Index Fingernail Temperature (°C)	0.502	0.446	0.900	1	-0.109
Operative Temperature (°C)	0.362	0.249	-0.187	-0.109	1

Table 5-3 Correlation Matrix for Pilot Study

The correlation matrix of values for the pilot study are presented in Table 5-3. Correlation of operative temperature to ASHRAE scale and preference scale shows values of 0.362 and 0.249 respectively. T_{opis} has higher correlation factors of 0.397 and 0.385 for ASHRAE scale and preference scale, respectively. T_{index} shows an even better correlation to ASHRAE and preference scales with 0.502 and 0.446, respectively. A higher correlation means the change associated with ASHRAE and preference scale is more likely to be replicated in the hand skin temperature rather than the operative temperature. More data is needed to show true correlation of thermal sensation to hand skin temperature. T_{opis} and T_{index} have a correlation factor of 0.900. The high correlation is backed up by the experimental data which shows mean hand skin temperatures to be almost the same while T_{index} and T_{opis} are closely linked in value. T_{index} was found to be fluctuate more than T_{opis} which was found to have a steady temperature. It is interesting to note from the pilot study data that T_{index} correlates better to ASHRAE and preference scale than T_{opis} does. The fluctuation of T_{index} compared to T_{opis} appears to be more sensitive to changes in thermal sensation, that is, cutaneous blood flow to the fingernails is a better measure of thermal sensation than blood flow to the Opisthenar. Fingernails have less mass than the opisthenar area and are more susceptible to changes in blood flow. These are also the end of an extremity meaning there is a large surface area on which external heat transfer can act.

There is a negative correlation of T_{index} and T_{opis} to operative temperature meaning there is little to suggest that $T_{\text{operative}}$ had any effect on the hand skin temperature recorded in the pilot study. A negative value of correlation factor means there is an inverse relationship between variables, however the factors are so low in this case that it was regarded that $T_{\text{operative}}$ had no effect. It was expected that $T_{\text{operative}}$ would have some correlation to hand skin temperature. Radiant and convective heat transfers from the human body depend on the environmental temperature and skin temperature. In order to maintain the same level of heat transfer from the body, skin temperature would need to increase, when environmental temperatures are high. However no trend of skin temperature to $T_{\text{operative}}$ was found in the pilot study. In Humphreys et al research, 1999, finger temperature was found to correlate with a factor of 0.250 to globe temperature [68].

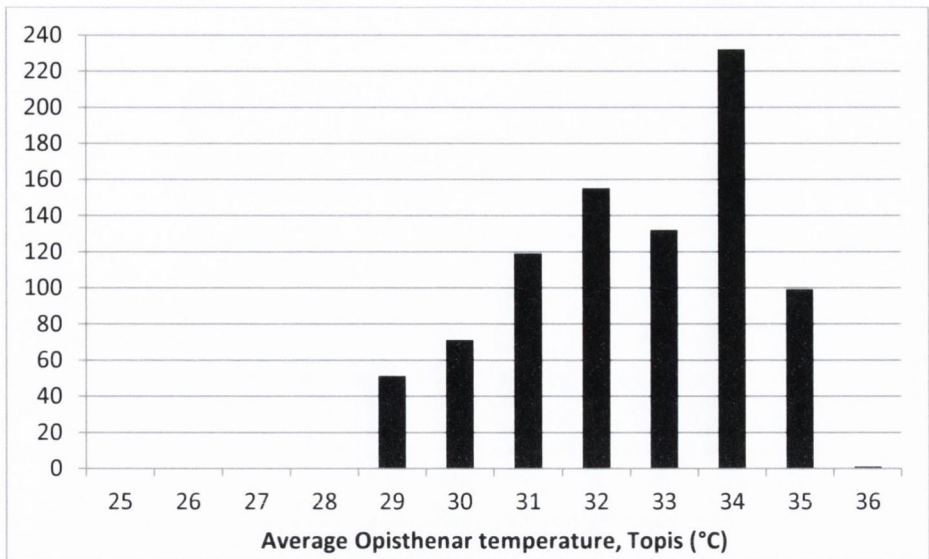


Fig. 5-19 Histogram of average opisthenar temperature, T_{opis} for pilot study

Fig. 5-19 shows the histogram of values of average opisthenar temperature. The histogram represents the frequency at which a value of a given temperature was recorded. For values of T_{opis} between 28.5°C and 29.5°C there were 51 occurrences of T_{opis} in that range. This is represented on the graph on the T_{opis} scale at 29.0°C. A histogram gives important information on the distribution of values which is not obvious from mean and standard deviation data, as can be seen in Fig. 5-19. Peaks of occurrence of T_{opis} were found at 34°C and a lesser peak at 32°C. From 29°C to 32°C occurrence of T_{opis} increased steadily to the secondary peak before dropping at 33°C and then increasing to the maximum occurrence of values at 34°C in which there were 232 values recorded. At 35°C the number of values recorded drops to below the amount recorded for 31°C to 35°C. At 36°C there was found to be one value in the range captured by 36°C. The distribution of T_{opis} was found to be unlike a normal distribution. It is heavily skewed to the upper end of the range.

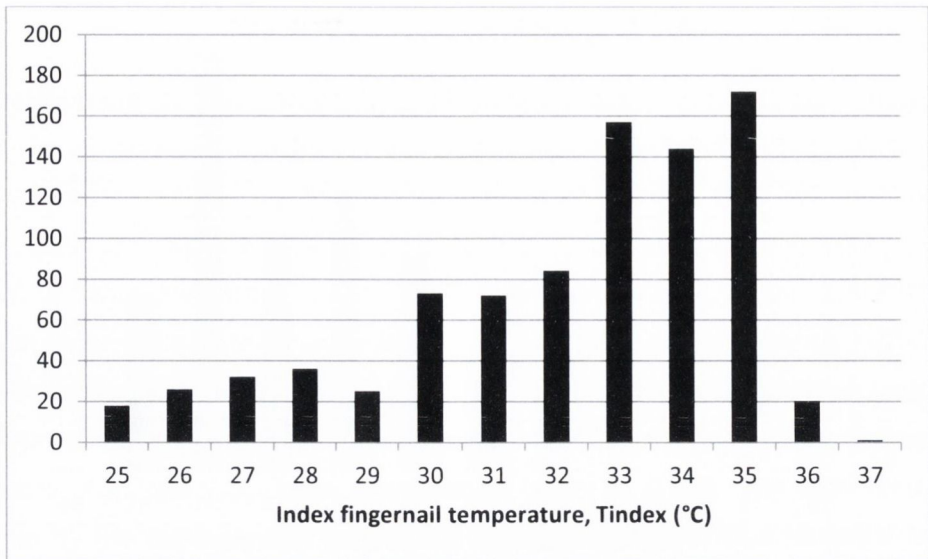


Fig. 5-20 Histogram of index fingernail temperature, T_{index} for pilot study

The histogram, Fig. 5-20, shows the distribution of values of index fingernail temperature, T_{index} . The distribution is not a normal distribution but skewed toward the upper end of the range as discussed above. There is a peak at 33°C and 35°C in values and a secondary peak at 28°C. Mean temperature for T_{index} was found to be 32.2°C. T_{index} was recorded 84 times between 31.5°C and 32.5°C. Peak values of T_{index} were found to be above the mean calculated. This again suggests a skew in data which is shown by the increasing frequency of occurrence of T_{index} with increasing temperature peaking at a value of 35°C. T_{index} was recorded 20 times above a value of 35.5°C. T_{opis} was recorded once above this temperature.

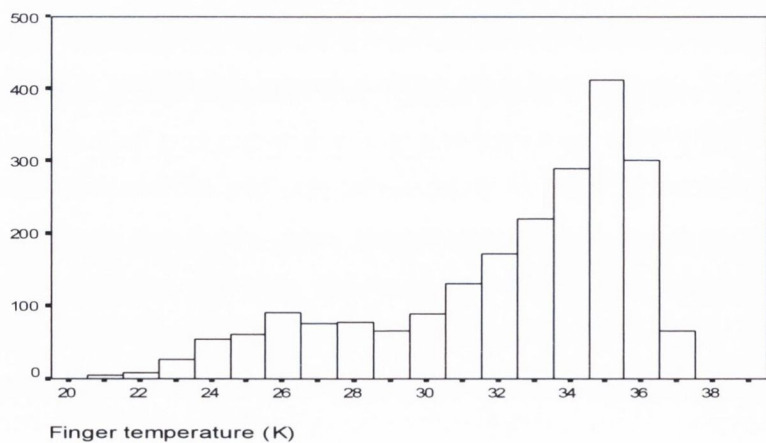


Fig. 5-21 Distribution of finger temperature recorded in study on 200 office workers in Oxfordshire, UK. Humphreys et al 1999 [68]

Humphreys et al found that finger temperature had a bimodal response in test carried out on 200 office workers in Oxfordshire, UK [68]. Humphreys research noted a strong peak in

finger temperature at 35°C and a secondary peak at 26°C. The pilot study shows a number of peaks in data at 28°C, 30°C, 33°C and 35°C. The distribution noted by Humphreys is similar in that it is skewed toward the upper end of recorded values. There was found to be low occurrences of values below 30°C and increasingly higher occurrences as temperature increased from 30°C to 35°C. The data in this pilot study matches the data recorded by Humphreys in the trend however extra peaks in the pilot study data could be from the small sample set.

5.6. Notable events during pilot study

5.6.1. Hand Reheating

During the pilot study instances where large increases and decreases in hand skin temperature were noted on a number of participants. During some tests the hand skin temperature was found to fluctuate considerably with index fingernail temperatures, T_{index} , often decreasing below recorded values of T_{opis} and subsequently rising above T_{opis} again. It is interesting to note the fluctuation in hand skin temperature which corresponds to the changing cutaneous blood flow. Over the course of a short period cutaneous blood flow was found to increase dramatically which in turn warmed the skin around the veins and arteries near the skin surface initially and then the entire skin surface area.

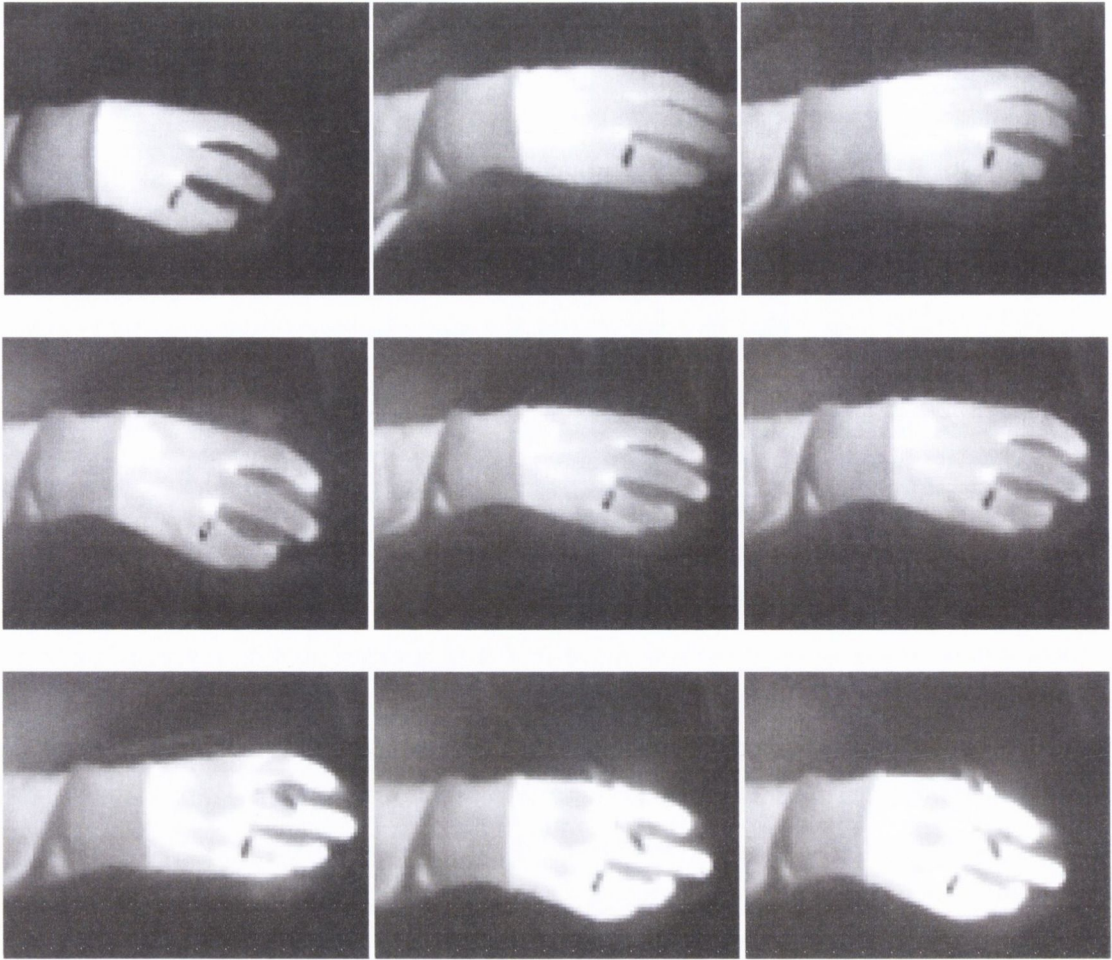


Fig. 5-22 Infrared Images Participant F1 Test no.8 14:06 - 14:20

Fig. 5-22 shows the infrared imagery captured during the pilot study test on participant F1 between 14:06 and 14:20. In the images brighter pixels represent higher temperatures while darker pixels represent lower temperatures. The 9 images are presented in chronological order from top left to bottom right. In the first set of images representing 14:06 to 14:10, on the top line of Fig. 5-22, images show little change in temperature represented by pixel brightness. The second set of three images on the middle line of the figure show the fingernails increasing in temperature. The veins are visible at this time showing the cold blood they are drawing away and being replaced by increased blood flow. In the third set of three images the fingers are fully heated and the opisthenar is beginning to be heated. The skin of the knuckles on the opisthenar is the final area that is left to have increased temperature.

During this period of hand reheating the participant notes a thermal sensation of 'neutral' and preferring 'no change' in the environment, yet hand skin temperature is changing rapidly over time. If thermal comfort were to be approximated by skin temperature large changes in temperature would be detrimental. This research and other research [30], [68],

would expect that increasing skin temperature would lead to increases on the thermal sensation scale. For this participant in this test it does not follow.

5.6.2. Mean hand skin temperature difference of participants

The pilot study was conducted on 4 participants each of which had different physical and physiological attributes as well as occupying different spaces within the test environment. Some participants in the study were found to be heavysset individuals who participated in sport while others were found to engage in light activities. All participants showed some level of activity above sedentary activity more than 2-3 times a week.

Participant	Number of Measurements, N	Mean Opisthenar Temperature (°C)	Mean Index Fingernail Temperature (°C)
M1	242	34.2	34.5
M2	140	33.4	33.2
M3	203	31.5	31.7
F1	275	31.5	30.0

Table 5-4 Average hand skin temperatures per participant in pilot study

Table 5-4 shows the number of measurements made, the mean opisthenar temperature and mean index fingernail temperature recorded by participant over the course of the pilot study test. Participant M1 was found to have a mean T_{opis} of 34.2°C and mean T_{index} of 34.5°C. The entire data for the pilot study showed that T_{index} and T_{opis} averages were close and with participant M1 this trend is repeated. The participant M1 shows higher mean skin temperatures compared with the mean values for the all participants of 32.6°C and 32.2°C for T_{opis} and T_{index} , respectively. M1 mean T_{opis} was found to be 1.6°C over the average of all participants. The same is true for participant M2 who was found to record mean T_{opis} 0.8°C over the average and for T_{index} 1.0°C over the average.

On looking at the data from participants F1 and M3 it was found that the recorded mean T_{opis} was below the average value of all participants. Participant M3 was found to record a T_{index} and T_{opis} similar in value however F1 recorded a T_{index} 1.5°C lower than the mean T_{opis} recorded. Comparing F1 and M1, the difference in mean T_{opis} and T_{index} was found to be 2.7°C and 4.5°C, respectively. The environment in which tests were performed on M1 and F1 were not found to be dissimilar. Further tests should be carried out to investigate the difference in skin temperatures shown. The difference in skin temperatures could have an effect on the prediction of thermal comfort based solely on hand skin temperature as a person with cool hands who is feeling neutral could be thought to feel cool. M3 and F1 both show cooler hands compared to M1 and M2. On looking at the difference between participants in Table 5-1 it was found that M3 and F1 have much lower body mass than

M1 and M2, coupled to that the basal metabolic rate was found to be different between the two groups. Basal metabolic rate (BMR) is used to indicate the amount of energy used by a human in a day. The higher the number the more the human needs to use for vital services. More energy use means higher heat dissipation required which in turn means greater use of the skin to cool the body. With higher cutaneous blood flow temperatures of the skin are raised [51].

From the estimated basal metabolic rates in Table 5-1 it is clear that two participants (M1 and M2) have a much higher BMR than the other two participants. The histogram of the distribution of values for fingernail and opisthenar temperatures, Fig. 5-19 and Fig. 5-20, gives a bimodal distribution but this may be due to participants with highly different BMR. Graphing the distribution of temperatures for each individual participant may show a different result. More data would be needed on each participant to graph a distribution accurately. Humphreys does not mention the BMR of any participants and produced a bimodal distribution of finger temperatures. Wang did not mention BMR either.

The difference in responses by participants with highly different BMR is subject to an increased surface area of skin in high BMR participants as the estimated BMR is based solely on age, height and weight. Estimated BMR is shown to break down when a subject of large fat mass is calculated as the fat mass does not actually increase metabolic rate, but in the estimation formula it does.

In this pilot study there is only one female participant. It is generally thought that there is little difference between males and females in thermal comfort [7], however the differences lie in clothing choices, reduced size of females compared to males and more critical assessment of the environment by females [79]. For future studies the number of female participants should be increased to investigate the impact of gender difference. The pilot study was carried out over the summer in Dublin, a number of tests should be carried out in future studies over the course of a year and on a range of maximum daily outdoor air temperatures.

Fingernails were found to be the point at which most participants reheating cycle starts. The reheating of the hand starts at the fingernail and moves slowly backwards toward the opisthenar. Opisthenar is heated slowly, firstly around the arteries and veins carrying the warm blood to the skin. Humphreys et al and Wang et al both use a thermistor on the fingernail to find finger temperature. In this research the finger temperature is found using the infrared imaging analysis on the posterior side, back of the finger, as opposed to the anterior side. The finger is assessed using a number of pixels from the area of the fingernail to find the average temperature of the fingernail. Previous research has used thermistors placed between the thumb and forefinger which takes the temperature from a

single point on the finger and thumb area [68]. The area is subject to insulation and temperatures of the finger/thumb area could increase because of this insulation. Strapping of the thermistor to the finger causes insulation which could also increase temperatures recorded [30]. The infrared camera used in this research has been factory calibrated. Calibration files are used to start the imager, however the imager is still subject to an accuracy of $\pm 2^{\circ}\text{C}$. Precision is increased due to the number of pixel measurements made.

6. Further interpretation of the results

6.1.Introduction

Further tests were set up to take recommendations from the pilot study and investigate hypotheses formed during analysis of the results from the pilot study. These hypotheses were that hand skin temperature correlates to thermal comfort, skin temperature is different for the same conditions of thermal sensation depending on season, infrared can be used to measure thermal comfort through hand skin temperature image processing and hand skin temperature differences can be accounted for by differences in basal metabolic rates.

Tests were conducted using the same method of the pilot study but the tests were lengthened and recording interval was extended in order to cover a larger range of thermal sensation responses. The length of tests was extended to include full days or series of measurements over a week to increase the breadth of the values being recorded. The frequency for recording thermal sensation and thermal preference data was lengthened to every 10 minutes as the pilot study showed slow change in participant's thermal sensation. The frequency of infrared imager recording was lengthened to one image every minute as there was little significant change in images every 30 seconds. Tests were set up in the same way as in the pilot study and included noting the positioning of hands.

The pilot study noted that differing mean hand skin temperatures (T_{skin}) were found for the different participants. However, environmental differences were noted between tests so further tests were set up to investigate thermal sensations when environmental variables were coincident. Tests were designed to investigate the difference in mean T_{skin} further and was used to propose a hypothesis for the difference in T_{skin} recorded. The pilot study was carried out during the summer months and previous research noted thermal adaptability based on outdoor conditions [76]. Thermal adaptation has been shown in preferred indoor temperatures based on outdoor temperatures, however the response of hand skin temperature to the change in outdoor temperatures has not been investigated. In further tests, experiments were carried out on participants during cool and warm seasons to investigate the differences in mean T_{skin} recorded. The pilot study noted that T_{skin} recorded had good correlation to the thermal sensation recorded during the test. Previous research [30], [68] found that thermal sensation is correlates well to T_{skin} in a controlled chamber and in single measurements in a field study. Further tests were designed to investigate the relationship of T_{skin} to thermal sensation with multiple

measurements of T_{skin} in a field study environment to further assess the links of thermal sensation and T_{skin} .

6.2.Participant Information

Participant	Age	Weight (kg)	Height (cm)	Est. Basal Metabolic Rate (kcal/day)	Est. Clothing Insulation (clo)
M1	29	99	1.84	1259	0.3
M2	25	92	1.8	1188	0.5
M3	31	64	1.78	778	0.5
F1	25	56	1.65	862	0.5 and 0.8
F2	31	56	1.68	836	0.5 and 0.8

Table 6-1 Participant information for further tests

The table of participant information, Table 6-1, shows the details of participant height, weight, age and gender. Each participant is named by gender and then by number, M being male and F being female. Estimated basal metabolic rate was calculated using the data recorded for participant height, weight, age and gender using the Harris-Benedict revised equations [45]. At the beginning of every test an approximate value of clothing insulation was made based on the clothing the participant was wearing using the tables of clothing insulation in ISO 7730 [1].

It was noted that those with higher estimated BMR were those with greater mass and height than the others. Participants with lower estimated BMR had estimated BMR within 100kcal/day of maximum and minimum values. Those with higher estimated BMR were found to be within 80kcal/day of each other and were found to be 326kcal/day greater than the maximum value of the lower estimated BMR group.

6.3.Differences between participants for recorded hand skin temperatures

Tests were performed on participant M1 over the course of a year in various seasons of the year. Tests were performed in Ireland. Given the climate of Ireland which has cool and warm seasons the data was split up into the two types of seasons. Seasons were split up based on the mean monthly air temperatures ($T_{mean,monthly}$) recorded by the Irish Meteorological Service, Met Éireann. Months with monthly mean air temperatures above 10°C were assumed to be a warm month and those below 10°C were assumed to be a cool month. The data collected split by $T_{mean,monthly}$ showed that there was a large difference between variables measured in tests carried out for cool and warm months in 2013 and 2012. May, June, July and August were found to be months in which monthly

mean air temperatures were above 10.0°C and the other months were found to be lower than this figure. Once the months of the year were split into cool and warm seasons the data was analysed in order to investigate the difference in hand skin temperature, thermal sensation and the indoor environment quality.

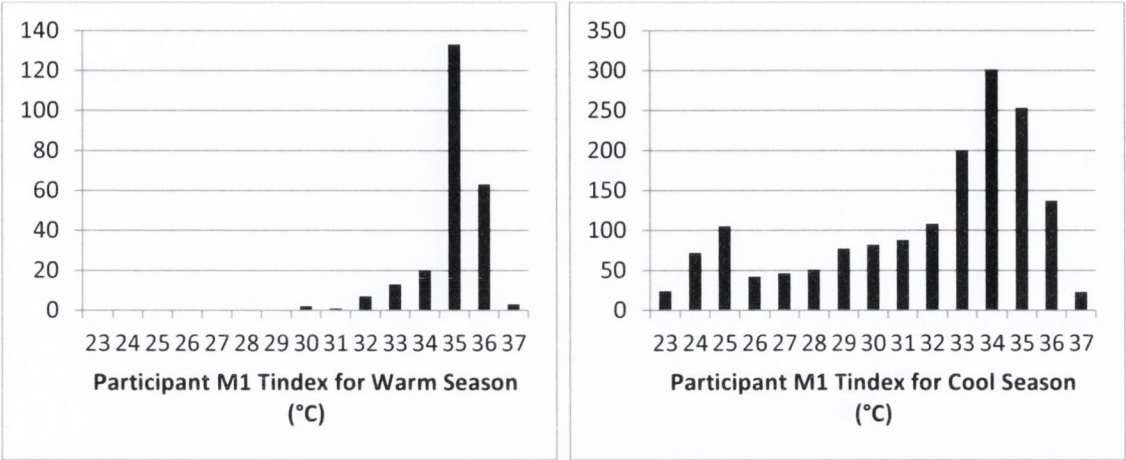


Fig. 6-1 Histogram of Index Fingernail Temperature, T_{index} , of participant M1 for Cool and Warm seasons

Fig. 6-1 shows the histogram of T_{index} for both cool and warm seasons as split according to monthly mean air temperatures. It is clear from the histograms that in the warm season, T_{index} remains above 30°C and was mostly found to be between 34°C and 37°C. In the cool season the range of T_{index} was found to be much broader, between 23°C and 37°C. The same trend is reflected in the mean of T_{index} which was found to be 34.5°C in the warm season and 31.2°C in the cool season for participant M1. The difference in mean T_{index} is large at 3.3°C and may indicate the change in hand skin temperature based on the change of outdoor mean air temperatures.

Average opisthenar temperature, T_{opis} , was found to have the same trend of T_{index} . In the warm season, T_{opis} was found to range between 31.5°C and 35.7°C with a mean value of 34.2°C. In the cool season, T_{opis} was found to range between 26.0°C and 35.7°C with a mean of 31.5°C, which is a significant difference of 2.7°C in opisthenar temperature recorded. T_{opis} was found to follow the trend found in T_{index} in that hand skin temperature was cooler in cooler seasons.

In order to confirm the change in hand skin temperature due to the change of seasons the thermal sensation votes were analysed. When participant M1 recorded a thermal sensation of 'neutral' in the warm season the mean of T_{index} was found to be 34.1°C. In the cool season the value of T_{index} for 'neutral' thermal sensation was found to be 33.2°C. The difference between these figures was found to be 0.9°C which is not insignificant. Mean T_{opis} for 'neutral' votes was found to be 34.0°C and 32.5°C between warm and cool

seasons, respectively. In this case the difference was found to be 1.5°C. The mean of 'neutral' votes during the cool season for hand skin temperatures was found to be much higher than the overall mean for all values of T_{opis} and T_{index} recorded and the differences were also reduced. This suggests that in the cool seasons there is more likely to be cool discomfort for participant M1, a fact reflected in the mean of thermal sensation values recorded during the cool season of -0.3, which represents cool discomfort.

The operative temperature recorded during recorded 'neutral' thermal sensation was found to be 23.1°C and 24.3°C during cool and warm seasons, respectively. $T_{operative}$ was found to differ by 1.2°C between warm and cool season when the participant felt 'neutral'. Participant M1 recorded a different preference of operative temperature between cool and warm seasons. Reasons for this include difference in clothing insulation. Participant M1 was found to have clothing insulation of 0.3 clo in the warm season switching to 0.8 clo by the cool season. Increased clothing insulation in the cool season should lead to a decrease in the optimum $T_{operative}$. Change in hand skin temperature between seasons has not been noted in previous field study research, however thermal adaptability has been noted in field studies in which the human body adapts to cool and warm environments. It has long been known that an office can be kept cooler in winter and warmer in summer based on the outdoor temperature as humans make clothing choices primarily based on the outdoor conditions. It would be expected that cutaneous blood flow would remain the same in these changing conditions as the human is making thermal decisions, however results from participant M1 have shown a significant difference in hand skin temperature recorded between seasons.

Participant	Warm Season		Cool Season		Difference	
	T_{opis} (°C)	T_{index} (°C)	T_{opis} (°C)	T_{index} (°C)	T_{opis} (°C)	T_{index} (°C)
M1	34.0	34.1	32.5	33.2	1.5	0.9
M2	33.6	33.5	30.7	28.4	2.9	5.1
M3	31.3	31.1	30.0	29.7	1.3	1.4
F1	31.6	30.5	30.4	27.5	1.2	3.0
F2	-	-	29.6	26.9	-	-

Table 6-2 Table of mean hand skin temperatures for recorded thermal sensation of 'Neutral'

The other participants showed similar differences between hot and cool seasons. Table 6-2 shows the results for each participant of mean skin temperatures for both warm and cool seasons. The table shows the differences in T_{opis} and T_{index} measured between warm and cool seasons. Participant F2 did not participant in testing during a warm season. Every subject who participated in tests during warm and cool months showed a significant

difference in hand skin temperatures. Participant M2 showed the largest difference in hand skin temperatures recorded of 2.9°C for T_{opis} and 5.1°C for T_{index} . The room in which tests were carried out on M2 change between warm and cool seasons to a much cooler room according to the $T_{\text{operative}}$ data. This may account for the large difference in hand skin temperature recorded. M1 and M2 have similar hand skin temperatures in the warm season, participant M1 was found to have slightly higher mean T_{opis} and T_{index} than M2. In the cool season the difference between M1 and M2 was found to be large however the change in the room may account for the large variance in the recorded T_{opis} and T_{index} of M2.

F1, F2 and M3 were all found to have similar hand skin temperatures in the cool season with a range of 29.6°C to 30.4°C of T_{opis} and 26.9°C to 29.7°C of T_{index} . M3 and F1 had similar hand skin temperatures in the warm season and were found to be much different to those temperatures recorded by M1 and M2. F1 and F2 had very similar T_{index} in the cool season while M3 had a much higher T_{index} than the two females in the study. Human physiology shows that females need to maintain a tight range of body core temperatures. Male core temperatures do not occupy such a tight range [51]. Previous research has shown that females are more likely to have lower cutaneous blood flow in the extremities [80].

On looking at Table 6-1 it was found that M3, F1 and F2 had similar estimated basal metabolic rates (BMR) compared to participants M1 and M2. M1 and M2 shared similar BMR. Participants were grouped according to BMR and two groups were made in order to compare the differences of hand skin temperature and thermal sensation based on the differences in BMR. Participants M1 and M2 were grouped into a high BMR group while participants M3, F1 and F2 were grouped into a low BMR group.

Indraganti et al showed that gender differences correlated poorly with thermal sensation and age correlated poorly with thermal sensation [7]. Women were found to prefer a warmer environment and express greater thermal acceptance. In converse, Karjalainen et al found that males had greater thermal acceptance of the environment over women [79]. Clothing insulation and metabolic rate were found to have a greater impact on thermal sensation and preference than gender and age differences. In this study there were 3 male and 2 female participants. Since gender differences have little impact on thermal sensation according to previous research, it was proposed that estimated BMR would be the determining factor. Imbalance in the gender of participants would be accounted for in the different estimated BMR from the revised Harris-Benedict equations.

Participants show basal metabolic rate ranging from 698 kcal/day to 1259 kcal/day, see Table 6-1. There are two participants with BMR at the upper end of the range and three

participants at the lower end of the range. Participants F1, F2 and M3 have BMR values of 862, 836 and 778 kcal/day respectively. Participants M1 and M2 have BMR of 1259 and 1188 kcal/day respectively. By splitting these participants into two groups for assessment it is possible to see if differing BMR has an effect on hand skin temperatures.

Low BMR Statistics					
	Number of measurements, N	Min	Max	Mean	Standard Deviation
ASHRAE Scale	232	1.0	6.0	3.96	0.92
Preference Scale	232	1.0	5.0	2.79	0.70
Average Opisthenar Temperature(°C)	2680	23.4	35.5	30.3	2.25
Index Fingernail Temperature (°C)	2680	19.9	35.7	29.7	3.69
Operative Temperature (°C)	2680	16.0	25.0	22.3	1.46

Table 6-3 Statistical overview for low BMR participants

Table 6-3 shows the statistics of all the data gathered for the participants in the low BMR group. 2680 measurements of hand skin temperature and operative temperature were recorded in the low BMR group with 232 recordings of ASHRAE and preference scale.

High BMR Statistics					
	Number of measurements, N	Min	Max	Mean	Standard Deviation
ASHRAE Scale	385	1.0	7.0	3.86	1.20
Preference Scale	385	1.0	5.0	2.81	0.82
Average Opisthenar Temperature(°C)	2642	25.5	36.0	31.7	2.20
Index Fingernail Temperature (°C)	2642	18.5	37.1	31.0	3.73
Operative Temperature (°C)	2642	19.7	25.5	22.9	1.30

Table 6-4 Statistical overview for high BMR participants

Table 6-4 shows the statistics for data gathered for the participants in the high BMR group. The number of data points for hand skin temperatures and operative temperatures is similar for both high and low BMR groups. There are over 150 more data points for the high BMR group than low BMR group for values of ASHRAE and Preference scales. The mean of ASHRAE scale is 3.86 for high BMR group and 3.96 for the low BMR group. The mean of ASHRAE scale for both groups is close indicating that the data should compare well. The high BMR group shows more cool discomfort than the low BMR group however the mean T_{operative} is higher. The standard deviation of the high BMR group is higher than

the low BMR group indicating the high BMR group recorded a much greater range of ASHRAE scale than the other group.

The mean of operative temperature for low BMR group was found to be 22.3°C and for the high BMR group it was 22.9°C. The high BMR group experienced higher mean operative temperatures than the other group. Having a lower standard deviation which means the range of values experienced was narrower than those experienced by the low BMR group. The measured variables of indoor environment quality (IEQ) between the two groups set up appear to be comparable. The recorded mean values of each group are comparable for a number of IEQ variables. $T_{operative}$ was found to be within half a standard deviation for each group. ASHRAE and preference scale were found to be even closer, within a quarter of a standard deviation when comparing each group. Standard deviation for the IEQ variables ($T_{operative}$, ASHRAE scale and preference scale) are similar for each group. IEQ for each group shows good statistical similarity, therefore comparing the two groups for hand skin temperature should yield correct results which are not affected by bias in the data.

6.3.1. Average opisthenar temperature (T_{opis})

Average opisthenar temperature, T_{opis} , was measured for each test for each group and the standard deviation of T_{opis} for the low BMR group was found to be 2.25 and for the high BMR group was found to be 2.20. The standard deviation of the index fingernail temperatures was found to be 3.69 and 3.73 for low and high BMR groups, respectively. For each group the standard deviation was found to be very close in value meaning that the hand skin temperatures showed statistical similarity across the range in which they occupied. Mean values for T_{opis} were found to be 30.3°C and 31.7°C for low BMR and high BMR groups, respectively. The dissimilarity of the means calculated and the similarity of the standard deviation suggests that the hand skin temperatures of the low BMR group were lower on average and operated in a range similar to the high BMR group. This suggests that the hand skin temperature range was similar for both groups, however the upper and lower limits for each group were different based on the mean values calculated.

The mean of T_{index} was found to be 31.0°C and 29.7°C for high BMR and low BMR groups, respectively. The high BMR group was found to be 1.3°C higher than that of the low BMR group, while still maintaining a similar standard deviation much like that found for T_{opis} . T_{index} was found to be lower than the T_{opis} by 0.7°C and 0.6°C for high BMR and low BMR groups, respectively.

The lower mean fingernail temperatures compared to average opisthenar temperatures would suggest that fingernails operate at lower temperatures than opisthenar and that both groups seem to operate in the same way but with different mean values. The increased standard deviation of the fingernails compared to opisthenar was expected as the pilot study showed that fingernails ranged in greater values than opisthenar temperatures. This suggests that opisthenar skin has a regular blood flow compared to the blood flow to the finger.

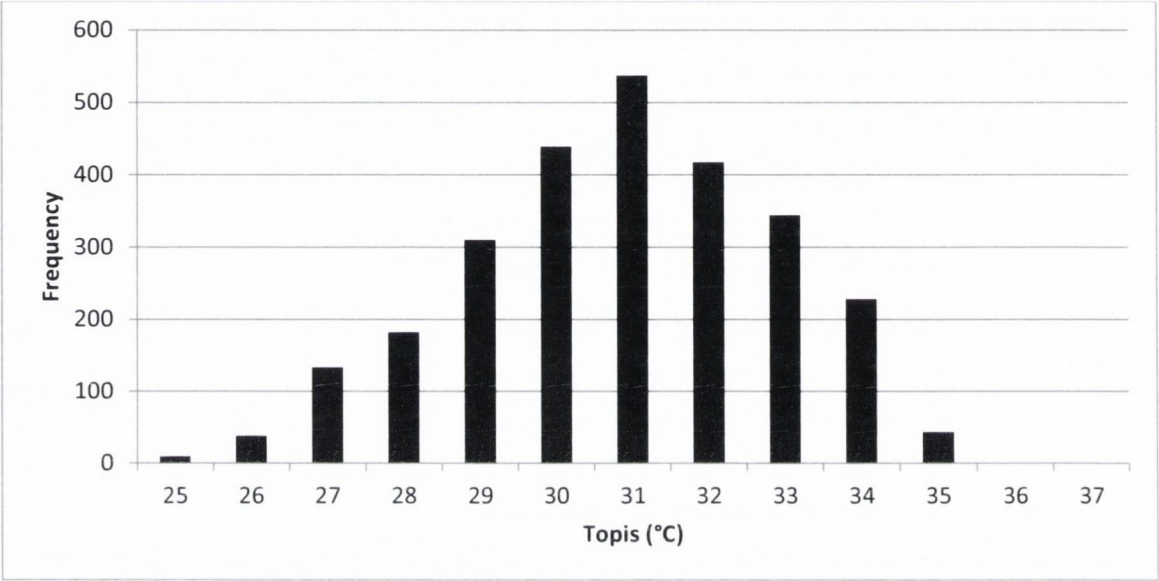


Fig. 6-2 Histogram of T_{opis} for low BMR group

In order to show the difference in hand skin temperatures recorded, the range of values recorded were plotted in a histogram type graph in which the frequency of a recorded value occurring is shown by the size of the columns. The more times a temperature is recorded the bigger the column will be. Fig. 6-2 shows a histogram of values of T_{opis} for all the participants in the low BMR group. The distribution appears to be normal with a skew towards the upper end of the range of values. There is a single peak in values at 31°C. The histogram shows the distribution of values for the entire study, however, because of the climate in Ireland most of the tests were performed on participants in the cool season.

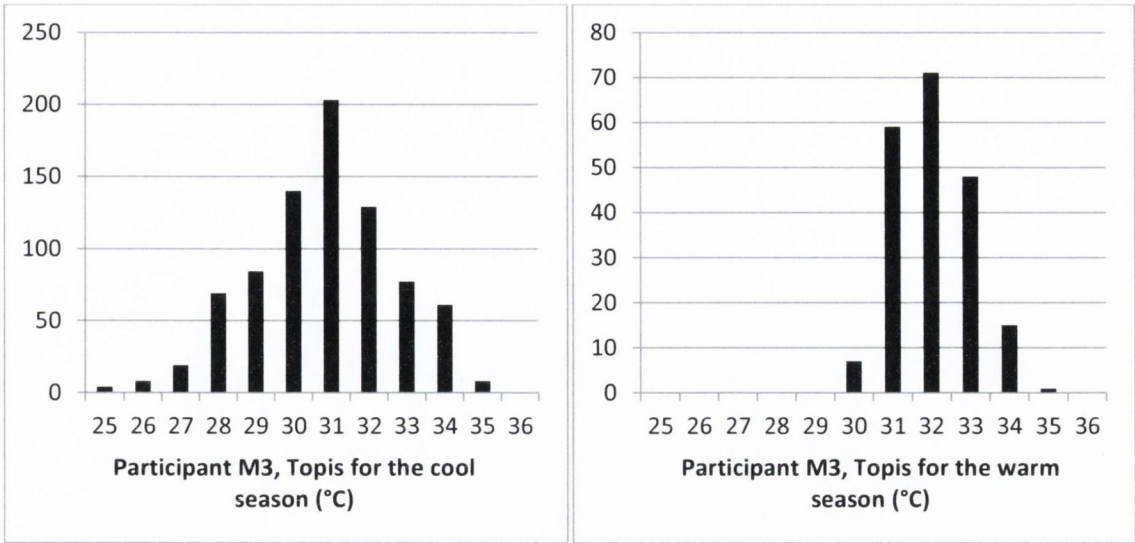


Fig. 6-3 Histogram of participant M3 T_{opis} , split by season

On splitting results of one participant on which tests were performed in both cool and warm seasons, it was clear that the response of the opisthenar skin temperature was different as shown in Fig. 6-3. In the cool season the distribution of T_{opis} was found to be a normal distribution in which there was a strong peak at 31°C, values range from 25°C to 35°C during this season, however the ends of the range are less likely to occur than the middle of the range. For the warm season tests the values of T_{opis} were found to be higher than those found in the cool season and also in a tighter range of values. A peak of 32°C was found however 31°C and 33°C show high occurrence of values also. This distribution is far from normal. The increased T_{opis} of participant M3 during the warm season was noted in participant M1 compared to the cool season. However M1 was found to have much higher T_{opis} in the warm season than M3 in the warm season.

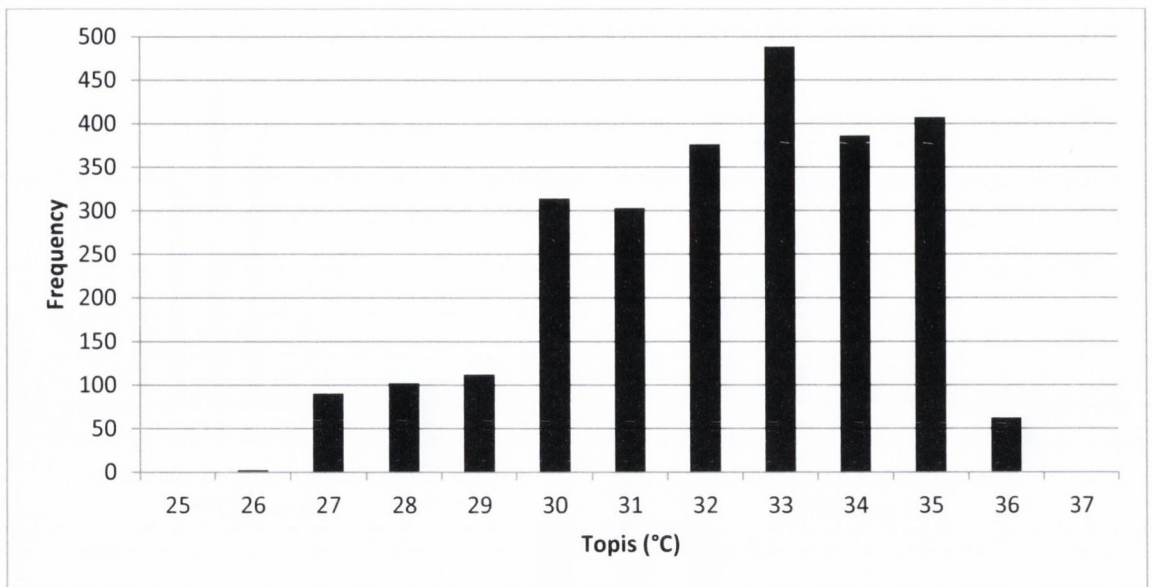


Fig. 6-4 Histogram of T_{opis} for high BMR group

The histogram of average opisthenar values is presented in Fig. 6-4 for the high BMR group. The distribution of values was found to be far from a normal distribution with a peak in values at 33°C. T_{opis} was found to range in value from 27°C to 35°C with some outliers from this range. The range was found to be higher than that of the low BMR group and was found to be heavily skewed toward the upper end of the range. A peak value at 33°C was found however the concentration of the values was more spread out across the range, and the peak was not found to be as significant as the strong peak of the low BMR group Fig. 6-2.

It is clear from the histograms of Fig. 6-2 and Fig. 6-4, that the range and peak values recorded by the high BMR group is significantly higher than those recorded by the low BMR group. Mean values of T_{opis} were found to be 30.3°C and 31.7°C for the low and high BMR groups, respectively. Mean values of T_{opis} are lower than the peaks of each distribution of T_{opis} . The lower mean temperature to the peak values in T_{opis} recorded means the data is skewed towards the upper end for both groups. That is, the number of occurrences above the peak is not the same as the number of occurrences below the peak. This skew is most likely due to the maximum skin temperature being controlled by the core temperature. Skin temperature cannot be higher than core temperatures of ~37°C.

The distribution of values for the high BMR group is clearly different to the low BMR group in that the peak is higher, the average is higher and the distribution is also dissimilar. The high BMR group was not found to have a strong peak but had a very strong range of values between 30°C and 35°C.

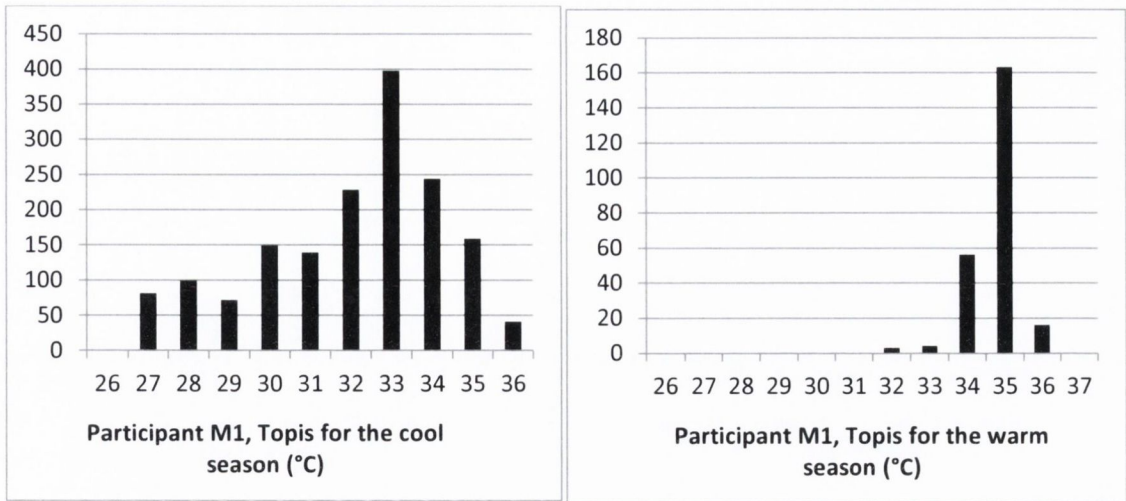


Fig. 6-5 Histogram of participant M1 T_{opis}, split by season

When the recorded values of T_{opis} of one participant in the high BMR group is split into cool and warm seasons, the distribution of each becomes easier to interpret as seen in Fig. 6-5. During the warm season the T_{opis} of participant M1 usually ranges between 34°C and 36°C while during the cool season the range was found to be much broader, between 27°C and 36°C. The peak in values for the warm season was found to be 35°C, while for the cool season it was found to be 33°C. During the warm season participant M1 did not record a thermal sensation of cool discomfort but recorded 'neutral' and warm discomfort. During the cool season, M1 recorded a range of thermal sensations including both warm and cool discomforts, which may account for the much broader range of recorded T_{opis}.

6.3.2. Index fingernail temperature (T_{index})

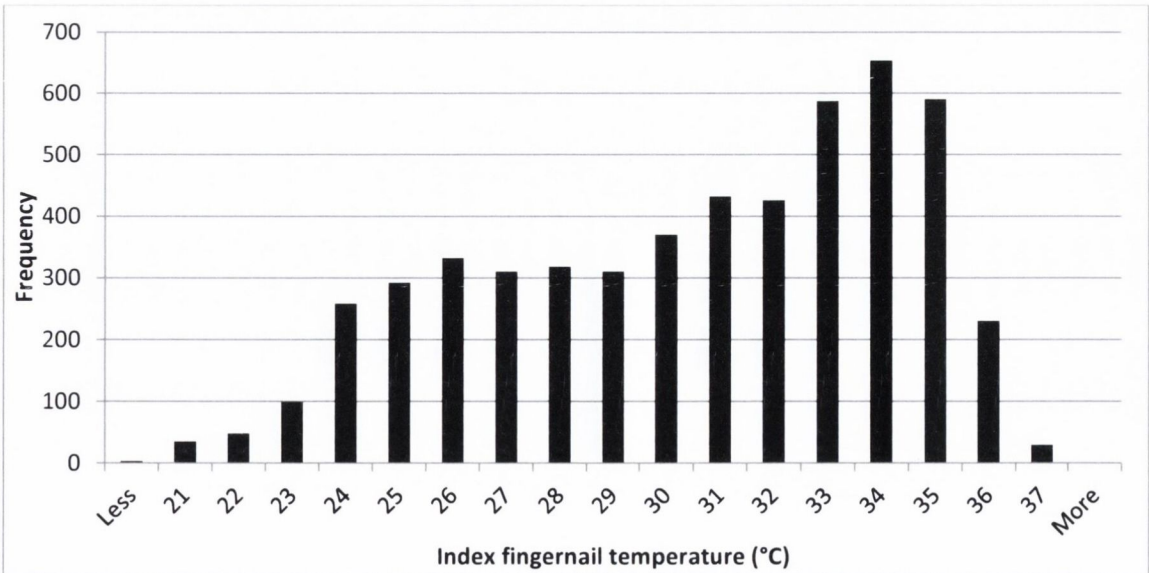


Fig. 6-6 Histogram of index fingernail temperature for entire study

The histogram for finger temperatures for the entire study in Fig. 6-6 shows a distribution much like a trimodal distribution with peaks at 34°C, 31°C and 26°C. The main peak in values is at 34°C with very slight secondary peaks at the other values. When data is split by group, high and low BMR as seen in Fig. 6-7 and Fig. 6-8, the secondary peaks became more pronounced and the peaks shifted in values. For the low BMR group a primary peak of 33°C is shown with strong secondary peaks at 24°C and 28°C. The response of the low BMR group is a stronger trimodal distribution. The high BMR group also shows a trimodal distribution of values with a primary peak at 35°C and weaker secondary peaks at 26°C and 31°C. The secondary peaks and primary peaks are in all cases 2°C or higher than those of the low BMR group. The low BMR group shows more frequency of value at the fingernail temperatures of the secondary peaks.

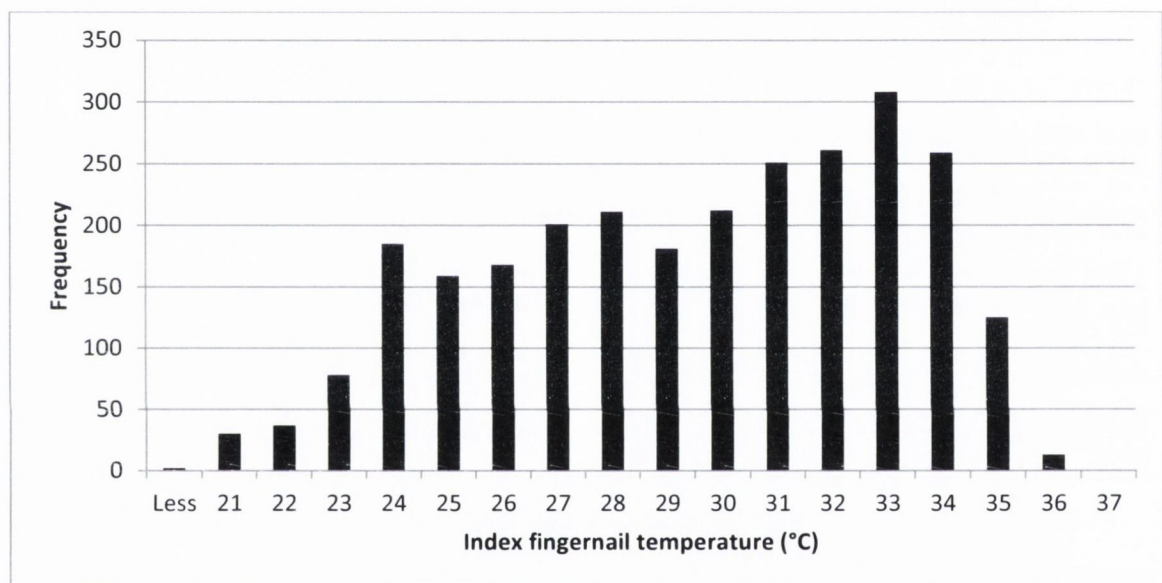


Fig. 6-7 Histogram of T_{index} for low BMR group

Fig. 6-7 presents the histogram of T_{index} recorded for the every test conducted for the low BMR group. It is clear that T_{index} was found to range in value widely and this range was found to be greater than that found of T_{opis} . A primary peak of 33°C was found while secondary peaks of 28°C and 24°C were found in the low BMR group. The pilot study was carried out in the warm season and for the participants in the low BMR group had a wider range than that of T_{opis} . The wide range of values was expected based on the pilot study data, however the lower end of the range was found to broaden to include lower temperatures and included temperatures close to the operative temperature.

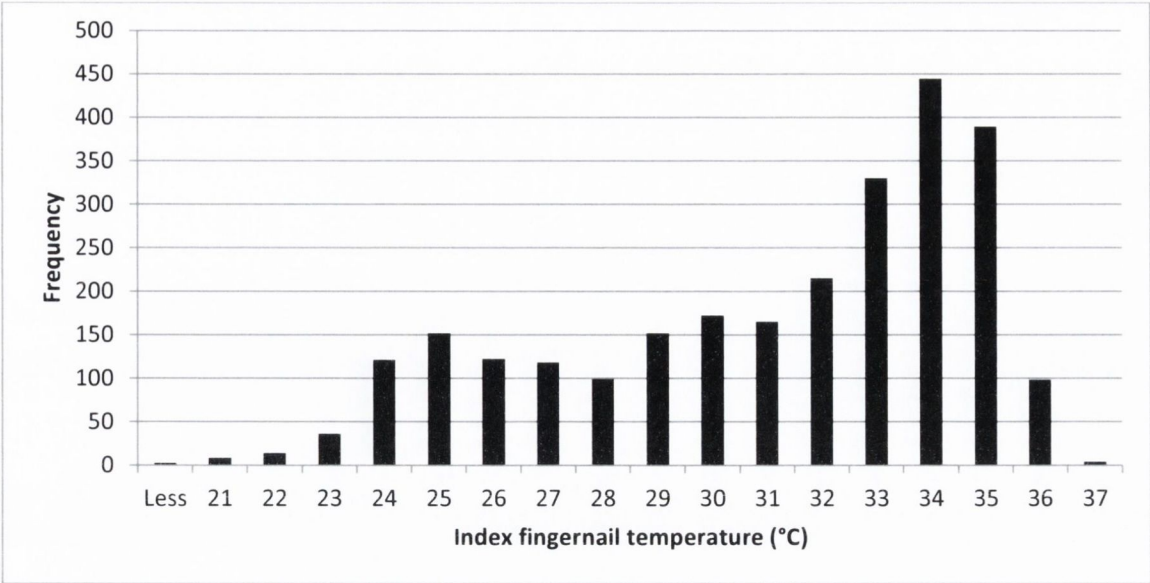


Fig. 6-8 Histogram of T_{index} for high BMR group

Fig. 6-8 graphs the distribution of T_{index} for the high BMR group for all tests conducted. Compared to the T_{index} distribution of the low BMR group the high BMR group was found to have much higher frequency of higher temperatures. A strong peak in values was found at 35°C. T_{index} was found to range higher, values of 37°C were recorded on occasion. For the low BMR group the maximum value of T_{index} was found to be 36°C. The high BMR group distribution of T_{index} was found to have secondary peaks in frequency at 30°C and 25°C.

A trimodal distribution of fingernail temperature has never been recorded. Humphreys et al recorded a bimodal distribution [68]. Humphreys took finger temperature measurements from 200 office workers with approximately 12 measurements per subject. In this research the number of subjects is much lower but the number of measurements is much greater. The trimodal response of a subject would be missed on looking at recorded temperatures of all the participants in the Humphreys study. The histogram of T_{index} in this study for all participants graphed in Fig. 6-6 shows distribution that is trimodal but very close to a bimodal response.

6.3.3. T_{opis} for thermal sensation scale vote of neutral (0)

The environment was monitored but not controlled. Tests were not carried out in the same room for some of the participants and not carried out concurrently. Therefore the environment in which the tests were carried out could be different from one participant to the next. If tests were carried out concurrently in the same room, it would not ensure that all participants were experiencing the same environment, as local thermal differences would occur as shown in ASHRAE standard 55 [31]. Local thermal differences would include draught from doors and windows and differing local radiant temperatures such as computer monitors.

In order to compare T_{opis} of each participant, a constant across every participant was needed. Operative temperature ($T_{\text{operative}}$) is used in industry and research applications to compare environmental variables [24], [81]. However in the pilot study $T_{\text{operative}}$ was not found to compare well to the hand skin temperature measured. ASHRAE scale votes are recorded and give a direct measurement of the participant comfort. The aim of this research is to investigate the relationship of thermal sensation and hand skin temperature, in the pilot study thermal sensation was shown to correlate well to the hand skin temperature recorded. Thermal sensation is directly comparable across participants, as it is a direct measurement of the thermal comfort felt at that time. Tests on each participant were performed across cool and warm months of the year, $T_{\text{operative}}$ was not found to be a significant factor in changes to hand skin temperature. To compare participants, the vote of neutral was selected, as this was the most common vote and the most desirable vote. A vote is desirable when the participant recorded a thermal preference of 'no change'. Research by Humphreys et al has shown that a vote of neutral is not always the most desirable vote, in summer months subjects have been shown to prefer to feel 'cool' or 'slightly cool', in winter months a feeling of warm is desirable [10]. When a vote of 'neutral' is made, thermal preference was for 'no change' in 95% of SCATs data and 84% of DeDear data. In this research when a TSV of 0 was recorded, over 90% (185 out of 204 recordings) of data points showed a thermal preference for 'no change'. For the purposes of this research which is carried out over the course of a year, a vote of neutral will be assumed to be the optimum. Data from all neutral votes were split according to the previous groupings by estimated BMR and graphed.

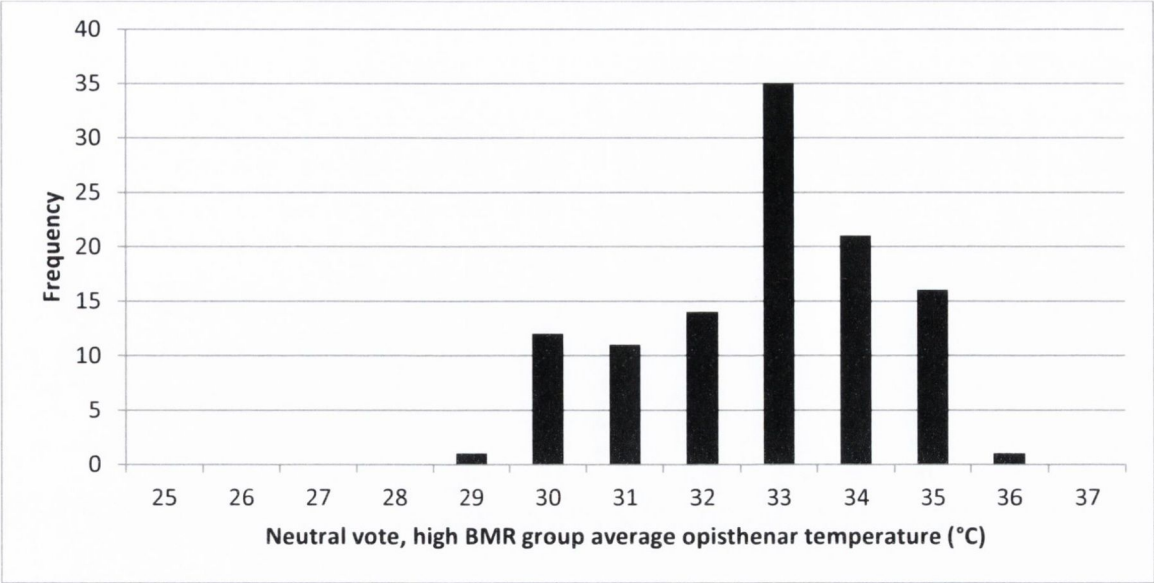


Fig. 6-9 Histogram of T_{opis} for high BMR group for ASHRAE scale values of 4, neutral

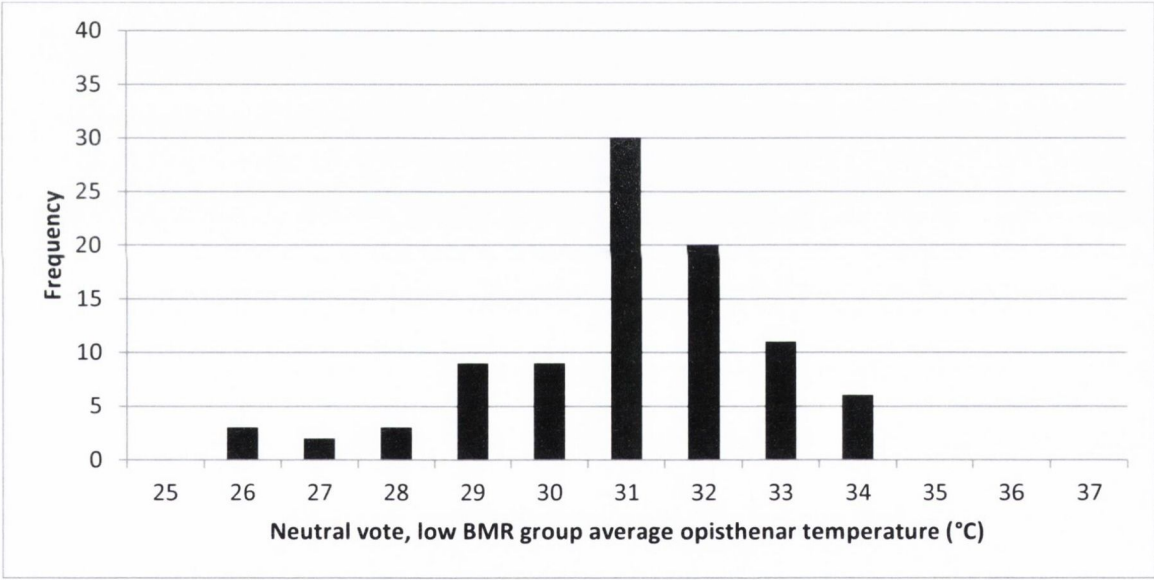


Fig. 6-10 Histogram of T_{opis} for low BMR group for ASHRAE scale values of 4, neutral

The recorded temperatures of average opisthenar temperature are seen in Fig. 6-9 and Fig. 6-10. The high BMR group was found to have a strong peak in T_{opis} at 33°C, while the low BMR group had a strong peak at 31°C. There is good similarity in the shape of the distribution of both groups. There is a difference of 2°C in peak values. Above the peak value recorded, frequency of T_{opis} decreases gradually. Below the peak values for both groups, the frequency of temperatures in this range is far lower than the peak.

This data shows that there is a significant difference in hand skin temperature between the subjects with high BMR and the subjects with low BMR. This suggests that participants with high estimated BMR have higher T_{opis} than those in with low estimated

BMR for the same conditions, feeling neutral. 111 recordings of neutral were made in the high BMR group while 93 recordings were made in the low BMR group. Participants in the high estimated BMR group have by definition a higher basal metabolic rate than those in the low BMR group. As a result, participants with a higher metabolic rate need to dissipate more heat than those in the other group. The human body needs to regulate core temperatures to ensure efficient operation of core systems. One mechanism for dissipation of excess heat is the cutaneous blood flow. In this case the high BMR group were shown to have higher skin temperatures leading to greater heat loss through the skin. The increased skin temperature substantiates the theory that the high BMR group dissipates more heat through the skin than the low BMR group. The difference in T_{opis} between groups for the same thermal sensation suggests that the high BMR group have larger cutaneous blood flow for the same feeling of neutral.

6.4.Distribution of Finger and Opisthenar Temperature for recorded values of thermal sensation vote

The pilot study showed that the distribution of finger and opisthenar temperatures largely followed the subject recordings thermal sensation vote (TSV) and preference scale. When hand skin temperatures (T_{skin}) were high the participant recorded a thermal sensation of feeling warm and when T_{skin} was low a vote for feeling thermally cool was recorded. The distribution of T_{skin} was not normal but T_{skin} for each category of TSV were within a defined range with peak values. Hand skin temperature values for each category of TSV overlapped on most occasions, meaning hand skin temperature was not a definitive measure of thermal sensation.

In the pilot study, T_{skin} was found to correlate well with TSV. In fact it was the leading variable showing a relationship with TSV. In further tests the number of data points is increased and participant numbers are also increased. Tests were carried out in summer months and winter months over the course of a few hours to a day in length. Tests were conducted at the participant's desk where the participant carried out elected work. Work was generally at a computer, reading or writing. The position of the infrared camera was such to encompass the predicted positions of the hand during the test period. The hand of the participant was generally found to be typing at a computer keyboard, controlling a computer mouse, writing or holding the paper while writing (dependent on laterality).

In further tests the tests were conducted in warm environments and cool environments. By testing the subject at the subject's desk the environment was not controllable. Previous research has been done in controlled environments where the environment can be altered

for the benefit of the test [30]. In further tests, the temperatures of the environment ranged lower in winter months than in the summer months.

6.4.1. Distribution of average opisthenar temperature (T_{opis}) for recorded thermal sensation vote (TSV)

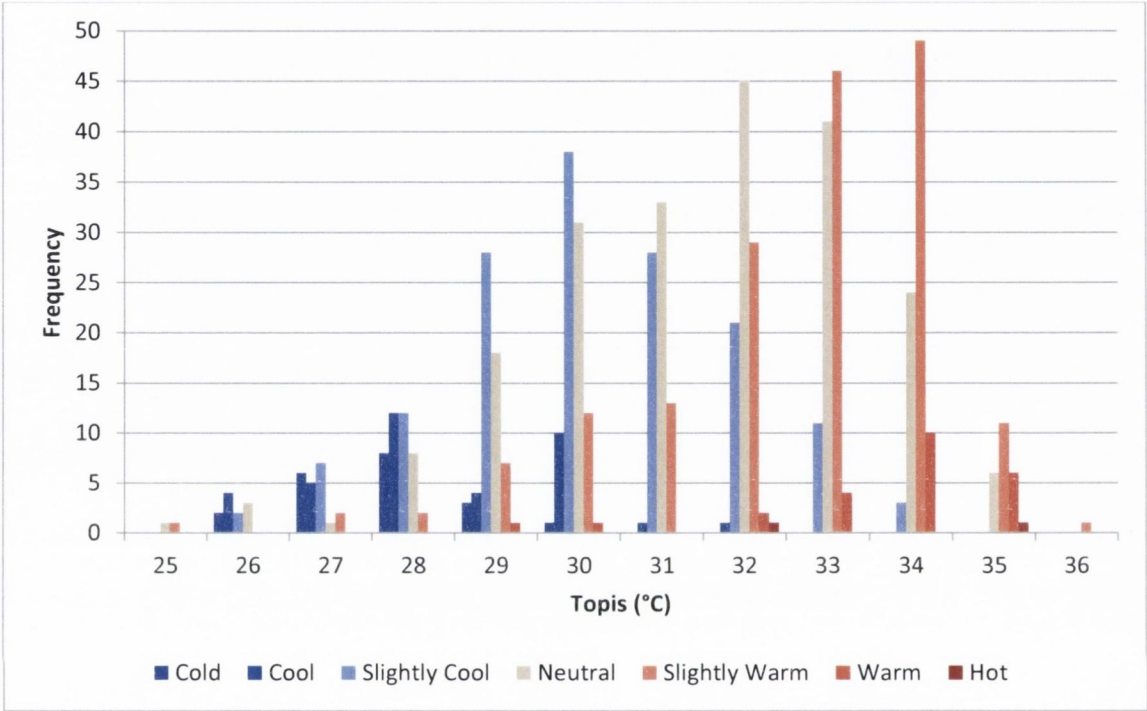


Fig. 6-11 Histogram of T_{opis} recorded for thermal sensation scale

The distribution of values of T_{opis} for recording of thermal sensation scale is shown in Fig. 6-11. The histogram shows each value of thermal sensation in a different distribution of T_{opis} coloured for clarity. The graph shows that broadly lower values of T_{opis} mean increased probability of colder thermal sensations, whereas higher T_{opis} means increased probability of warmer thermal sensation. A value of 32°C of T_{opis} showed high frequency of thermal sensation vote (TSV) of neutral at 45 recordings. TSV of ‘slightly warm’ and ‘slightly cool’ are also prevalent at this value of T_{opis} at 29 and 21 recordings, respectively. At this temperature there are few recordings of the other TSV categories. T_{opis} above this value produced higher frequency of ‘slightly warm’ and higher TSV and T_{opis} below produced higher frequency of ‘slightly cool’ and lower TSV. It should be noted that the number of recordings of T_{opis} above 32°C is 213 and number below 32°C 305. This implies that the data is skewed below 32°C, there are more values of T_{opis} below the 32°C level than above. Maximum and minimum values of T_{opis} recorded were 36.0°C and 23.6°C, the maximum being 4°C above 32°C the minimum 8.6°C below 32°C.

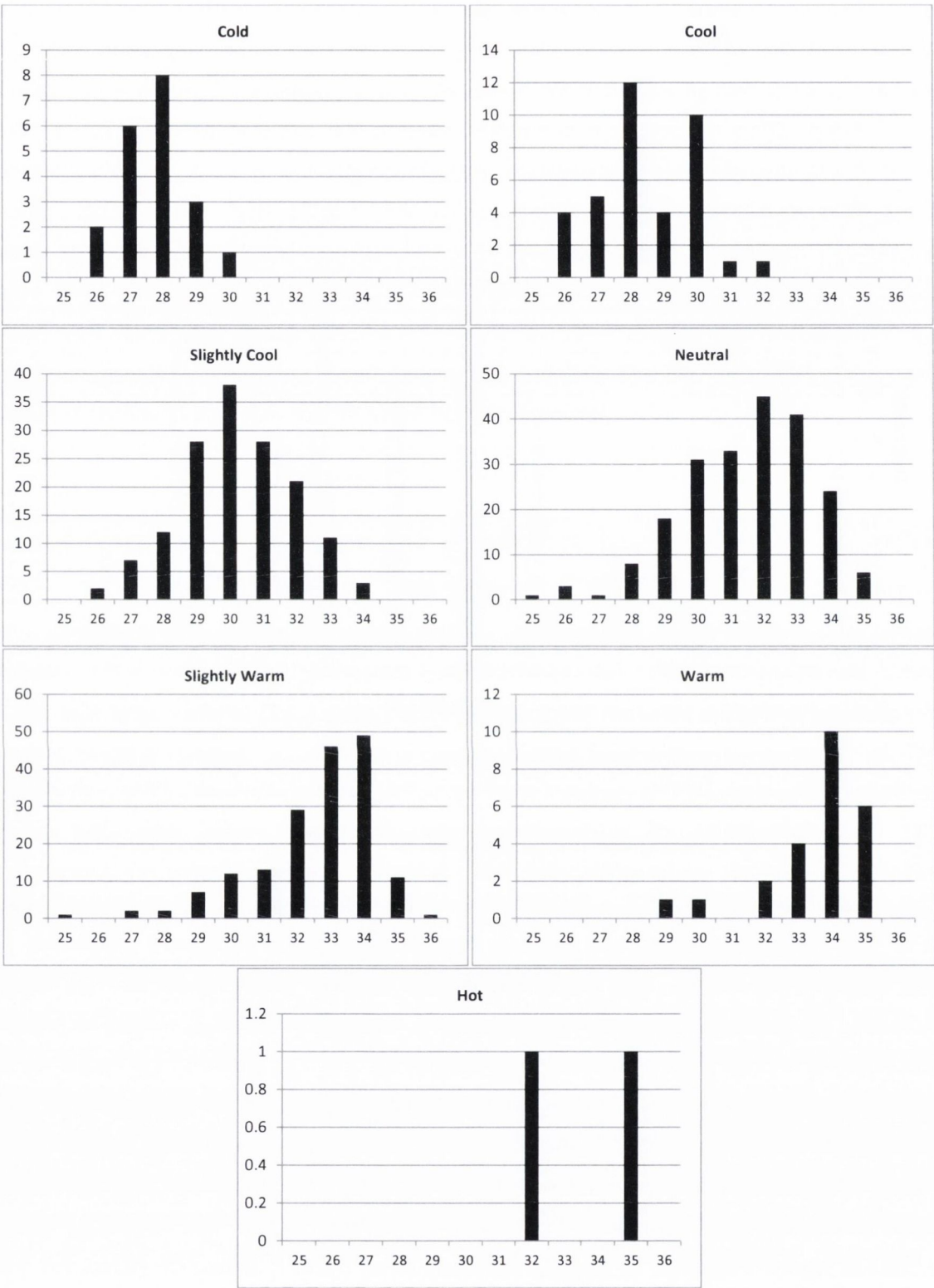


Fig. 6-12 Histograms of T_{opis} for each category of TSV

Fig. 6-12 is based on the same information as Fig. 6-11, but has a new plot for each category of TSV. It is clear from the graphs that lower values of T_{opis} produce a higher frequency of TSV of feeling 'slightly cool' or colder. The distribution of T_{opis} for 'slightly cool'

shows a normal type distribution with a peak at 30°C. Recordings of up to 34°C for T_{opis} were measured for TSV of 'slightly cool'. However the majority of T_{opis} values were found to be less than 32°C.

The corresponding graph for feeling 'neutral' shows data in which frequency was marginally skewed to the upper end of the range with a peak at 32°C. The skew of the distribution can be attributable to the upper limit of hand skin temperature of 37°C. The same was found for 'slightly warm' showing a strong skew to the upper end with a peak at 34°C. For T_{opis} of 34°C for all TSV categories, there are 3 instances of feeling 'slightly cool', 24 instances of feeling 'neutral', 49 instances of feeling 'slightly warm', and 10 instances of feeling 'warm'.

For T_{opis} 34°C or above, 68.6% of recorded TSV were for 'slightly warm' or higher. For the same T_{opis} , 96.5% of recorded TSV were for 'neutral' or higher. That is to say, when T_{opis} was found to be 34°C or above the most likely thermal sensation was found to be 'slightly warm' or higher. There were very few instances found in which a vote colder than 'neutral' occurred. For the entire dataset, the higher T_{opis} was recorded the more likely it was that a warm thermal sensation was recorded. This data fits in well with previous research in which higher finger, hand and forearm temperatures have shown higher thermal sensations [30], [68].

At T_{opis} of 29°C 67.9% of TSV were for 'slightly cool' or colder. For the same T_{opis} , 95.2% of TSV recorded 'neutral' or colder. The vast majority of values of T_{opis} below 29°C yielded a thermal sensation of 'slightly cool' or cooler votes and there were very rare occasions when a TSV of 'slightly warm' was found. This again fits in with previous research by Humphreys and Wang, which predicts lower hand skin temperatures for lower thermal sensation votes.

These thresholds, 29°C and 34°C for warm and cool discomfort does not explain the 5°C in between thresholds and the range of TSV recorded during these times. In fact, 60% of the values recorded for T_{opis} lie in the range 30°C to 33°C. It is difficult to use the T_{opis} recorded to predict the TSV in this range. At the lower end of the range TSV is more likely to be cooler and at the upper end of the range TSV is more likely to be warmer. Between 30°C and 33°C the most prevalent TSV is 'neutral'. As noted previously, the participant's hand skin temperature was found to be different across each participant and across seasons. By splitting up the data by participant and season it may become easier to predict the thermal sensation felt by each participant.

6.4.2. Distribution of index fingernail temperature (T_{index}) for recorded TSV

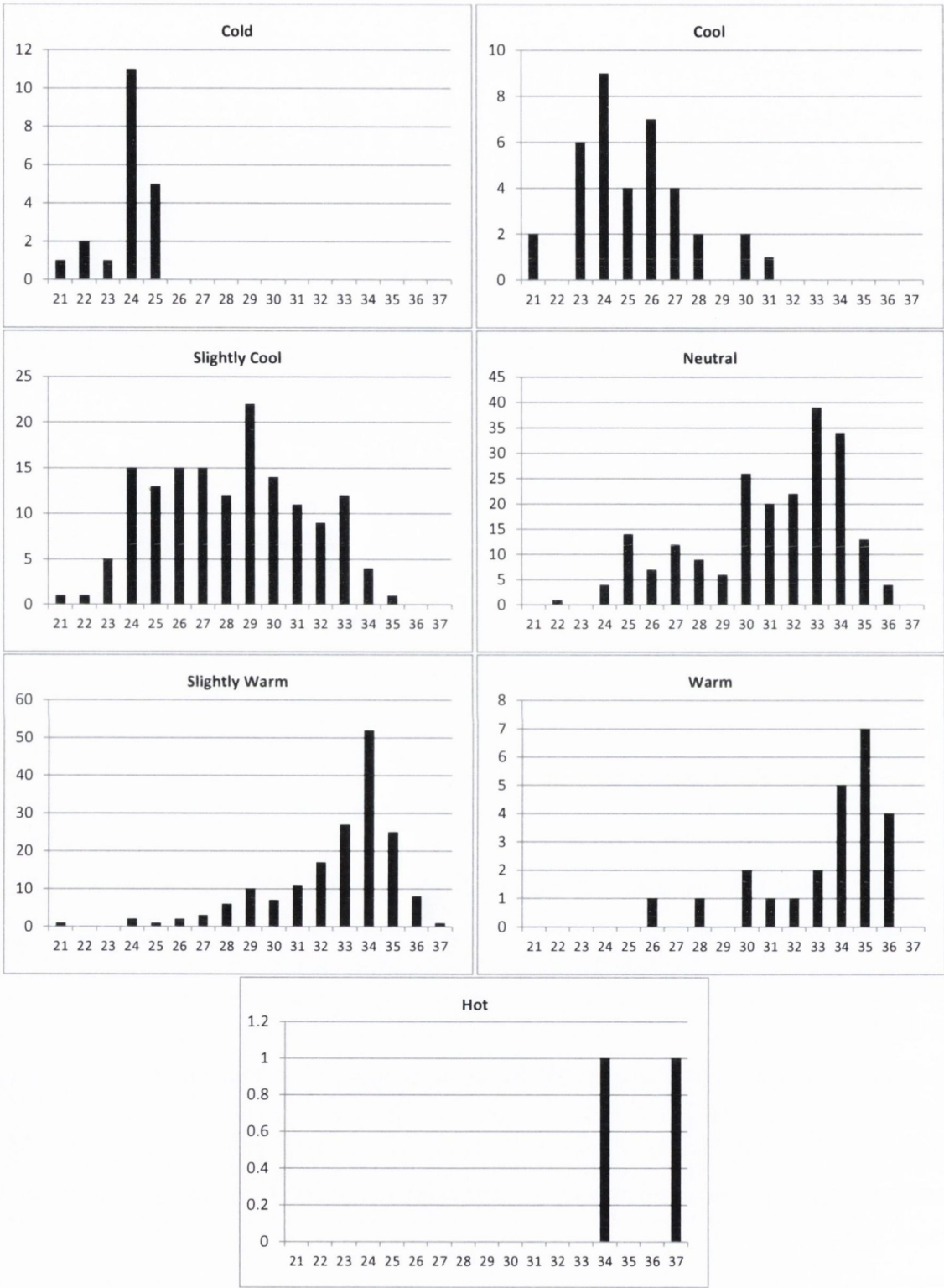


Fig. 6-13 Histograms of T_{index} for each category of TSV

The graphs of index fingernail temperatures split into each category of TSV are shown in Fig. 6-13. Index fingernail temperatures (T_{index}) range from 18.5°C to 37.1°C for all

participants in all the tests carried out. The lower end of the range is much lower than the T_{opis} measured of 23.4°C. The lower end of T_{index} was found to be lower than the operative temperature but there were very few recordings lower than 21°C, which was considered to be the lowest based on operative temperatures recorded. The reason for much lower T_{index} was that the participant had just come in from the outside where temperatures were far below indoor temperatures and the fingernails had dipped to this low temperature.

For values of T_{index} at 29°C or below, 65.7% of TSV recorded was found to be 'slightly cool' or colder, for the same T_{index} 88.4% of TSV recorded was found to be 'neutral' or colder. For values of T_{index} of 34°C or above, 65.0% of TSV was found to be 'slightly warm' or warmer while 96.9% of TSV was found to be 'neutral' or warmer. The same thresholds for T_{opis} were found however T_{opis} was found to have better prediction percentages. However, within the range 30°C to 33°C, only 42.5% of values of T_{index} were recorded compared to 60% of T_{opis} values. This means that while T_{index} does not predict the thermal sensation as accurately as T_{opis} there are less values lost in between the threshold values. When both T_{index} and T_{opis} are used to predict thermal sensation, only 31.9% of values are left in between the threshold values. That is to say, when T_{opis} or T_{index} is above 34.0°C or below 29.0°C the prediction is warm or cool discomfort, respectively. During the entire study 204 recordings of 'neutral' were found over 617 measurements, 33.1% of measurements.

When either of T_{index} and T_{opis} are beyond the two thresholds for warm and cool sensations 68.1% of recordings predict thermal sensation, the values in between these thresholds are then assumed to be a TSV of 0, 'neutral' in 31.9% of recordings. Which fits well with the 33.1% of measurements having a 'neutral' TSV. The prediction of thermal sensation could become more accurate by taking other factors such as seasonality and participant's estimated basal metabolic rate into consideration.

6.5. Seasonality of hand skin temperatures

Tests were carried out on willing participants throughout the year and comparison of hand skin temperature value based on the same environmental conditions was assessed. Monthly temperature data was gathered and mean outdoor air temperatures for each month a test carried out were recorded.

The monthly mean air temperature data was gathered from data supplied by Met Éireann. Mean air temperature was recorded at Dublin Airport which is less than 20km from all test sites and less than 10km from most test sites. The temperature data from Met Éireann in this research is used as a guide to the outdoor thermal environment during the tests. Mean monthly outdoor air temperatures ($T_{\text{mean,monthly}}$) are used and it would be expected that $T_{\text{mean,monthly}}$ at the test sites, considering proximity to Dublin Airport, would be similar especially considering that it is a mean of all temperatures recorded during a month so any localised difference would be negated.

The results from all the tests were split into two sets of data. Data was split based on $T_{\text{mean,monthly}}$ during the months in which tests were carried out. Mean monthly air temperature ranged from 4.2°C to 15.3°C during the testing period. During warm months of the year in Dublin, Ireland, $T_{\text{mean,monthly}}$ was found to be above 10.0°C, during the other months of the year $T_{\text{mean,monthly}}$ was found to range between 5.3°C and 8.3°C for an average year. The winter of 2012/2013 in Dublin was found to be much colder than the average with $T_{\text{mean,monthly}}$ as low as 4.2°C.

The data was split into $T_{\text{mean,monthly}}$ 10°C and above and those lower than 10°C. The data produced 4073 data points of lower $T_{\text{mean,monthly}}$ and 1250 points above this figure. The two sets of data were further split into groups of low and high estimated basal metabolic rate (BMR). The hypothesis that estimated BMR affects the hand skin temperatures recorded is supported by this research and the data was split to allow the full seasonal nature of each group to be investigated. On splitting the data into these groups low $T_{\text{mean,monthly}}$ produces 1810 data points for the low BMR group and 2260 data points for the high BMR group. For high $T_{\text{mean,monthly}}$, there were 868 data points for low BMR and 382 data points for high BMR. Clearly the data shows a skew toward the cold months of the year as only 3 months in the season July 2012 to June 2013 recorded $T_{\text{mean,monthly}}$ above 10°C. Months with $T_{\text{mean,monthly}}$ above 10°C shall be called warm months and those below 10°C shall be called cool months.

6.5.1. Hand skin temperatures for High BMR group

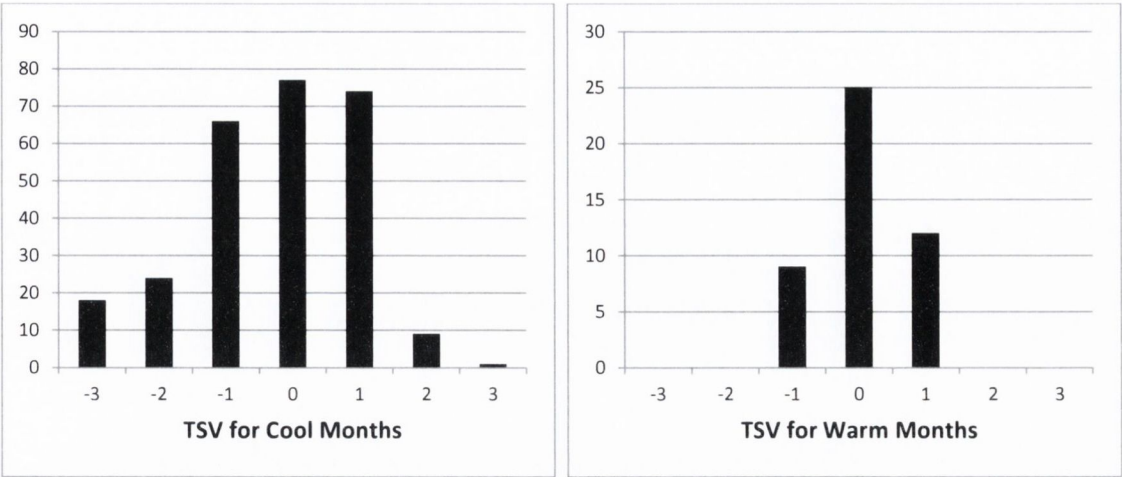


Fig. 6-14 Thermal sensation vote (TSV) distribution for Cool and Warm months for high BMR group

Fig. 6-14 shows the distribution of values of TSV noted split between warm and cool months for the high estimated BMR group. It is clear to see in the warm months the distribution of TSV is centred on a vote of 0, neutral. Votes of slightly warm and slightly cool are prevalent and no other TSV categories were noted. During the cool months for the same group, it is clear that votes of 'neutral' are prevalent however 1, 'slightly warm' and -1, 'slightly cool' were found to occur at almost the same frequency. In the building in which most tests were carried out the heating seasons stretches from October to May. There is very little control over the rooms required temperatures, therefore there are times when the building is too warm. This may explain the increased frequency of 'slightly warm' recordings compared with the recordings made during the warm months. Operative temperature recorded during this time may explain the increase in 'slightly warm' votes. In the cool months, there was increased frequency of recording a TSV of 'cool' or 'cold', as the outdoor temperatures were much lower than the warm months. It was expected that there would be a higher frequency of colder TSV, as heating systems struggle to heat an office on a Monday after two days of no heating during the weekend.

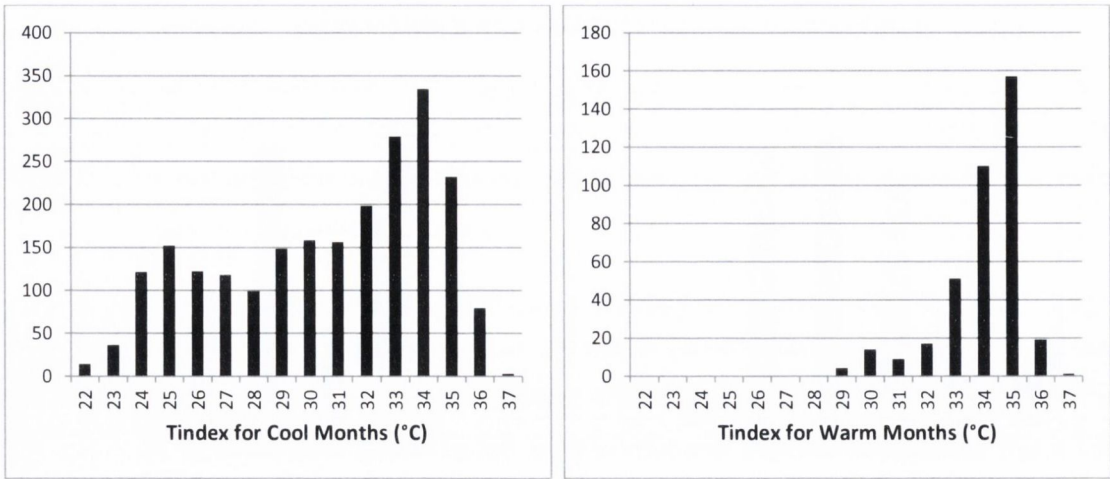


Fig. 6-15 Index fingernail temperature (T_{index}) distribution for high BMR group

The index fingernail temperatures (T_{index}) for the high estimated BMR group is shown in Fig. 6-15. For the warm months T_{index} was found to have a peak frequency of 35°C and there were only a few instances of T_{index} below 33°C. In contrast the T_{index} measured in the cool months ranges from 22°C to 37°C. The distribution during the cool months was found to be a trimodal distribution. There was a strong peak at 34°C with secondary peaks at 31°C and 25°C. A trimodal distribution of fingernail temperature has not been previously reported. Humphreys et al recorded a bimodal distribution of finger temperature which included all months of the year and a range of subjects. The trimodal distribution of T_{index} became more pronounced than that of the entire group after splitting the participants into groups and graphing for different seasons, Fig. 6-6.

6.5.2. Hand skin temperatures for Low BMR group

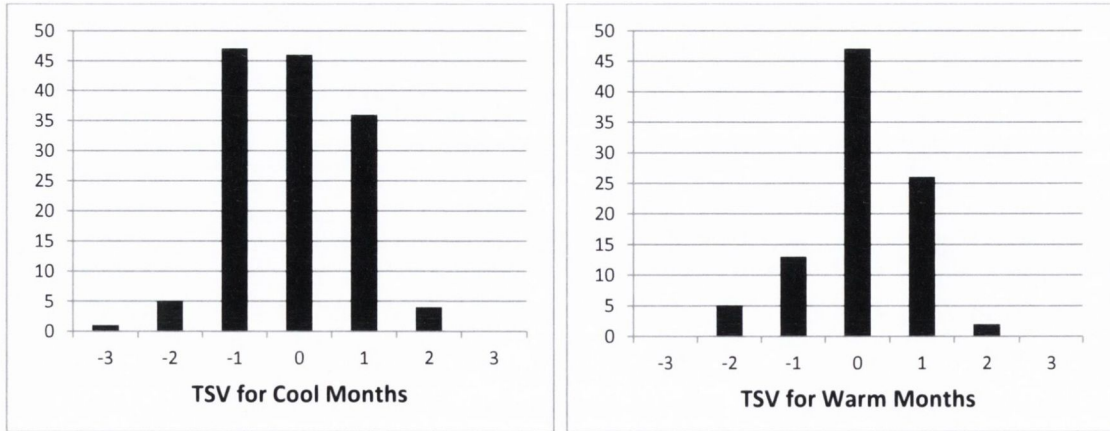


Fig. 6-16 TSV recorded for low estimated BMR group

For the low BMR group the number of data points split between warm and cool months is similar, therefore direct comparison is possible. In the cool months the TSV most recorded was found to be -1, slightly cool, however votes of 'slightly cool', 'neutral' and 'slightly

warm' occur with similar frequently, other votes rarely occur. In the warm months the TSV occurring most often was found to be 0, 'neutral'. TSV of 1, 'slightly warm' was found to have half the frequency of 'neutral' and 'slightly cool' has low frequency. Other categories of TSV were found to be rare.

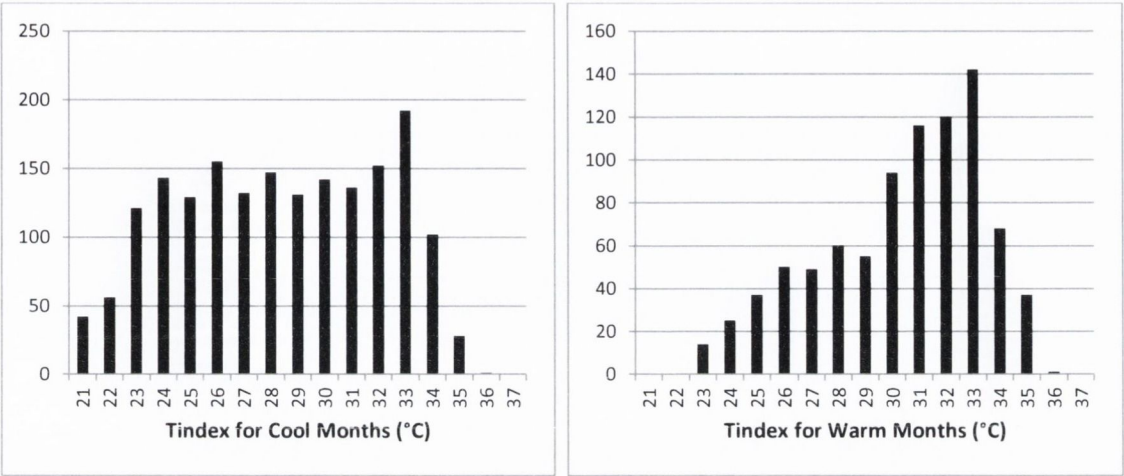


Fig. 6-17 Index Fingernail Temperatures for low BMR group

T_{index} for the low estimated BMR group is presented in Fig. 6-17 for both warm and cool months. In the cool months the values of T_{index} were recorded over a large range between 21°C and 35°C. Between 23°C and 33°C, inclusive, the number of recordings of T_{index} was found to be high. A weak peak at 33°C was found in T_{index}. There was no particular pattern found for T_{index} for this distribution except that T_{index} occupied a very wide range and had a similar frequency of occurrence across the range.

For T_{index} in the warm months the distribution was skewed toward the top end of the range of values, 23°C to 35°C. The minimum value recorded is 2°C higher than the values for the cool months. Peak frequency for values occurs at 33°C, generally the distribution is higher than that of the cool months. There was found to be a significant difference between the T_{index} recorded in cool and warm months. In warm months T_{index} was usually found to be higher than that of the cool months.

The data gathered on TSV for the low BMR group compares well to the data for the high BMR group. In the warm months for the high BMR group a TSV of 'neutral' was found to be prevalent, while other votes were much less prevalent, which is the same as that recorded for the low BMR group in the warm months. In the cool months for the high BMR group equal frequency of -1, 0 and +1 TSV was recorded. For the low BMR group this was found to be the same, however the high BMR group recorded more instances of -2 and -3 TSV. When TSV is the same for the groups, it means that a comparison can easily be drawn between groups. For the purposes of the seasonal split of warm and cool months it

is clear that there isn't the same pattern of TSV recorded for either BMR group. In order to compare the seasonal split based on hand skin temperatures a TSV with values prevalent in both warm and cool seasons was chosen, a TSV of 0, 'neutral' was chosen. The TSV of 'neutral' has the added benefit in that it is the desired thermal sensation on most occasions, as discussed in 6.3.3.

6.5.3. Seasonality of Hand Skin Temperatures for TSV of 0 ('neutral')

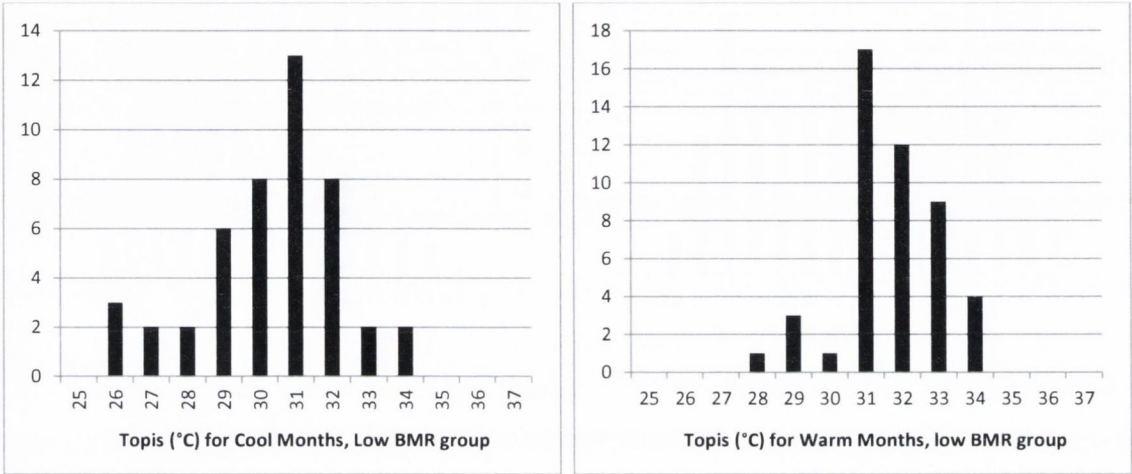


Fig. 6-18 Distribution of T_{opis} for TSV 0 ('neutral') for low BMR group

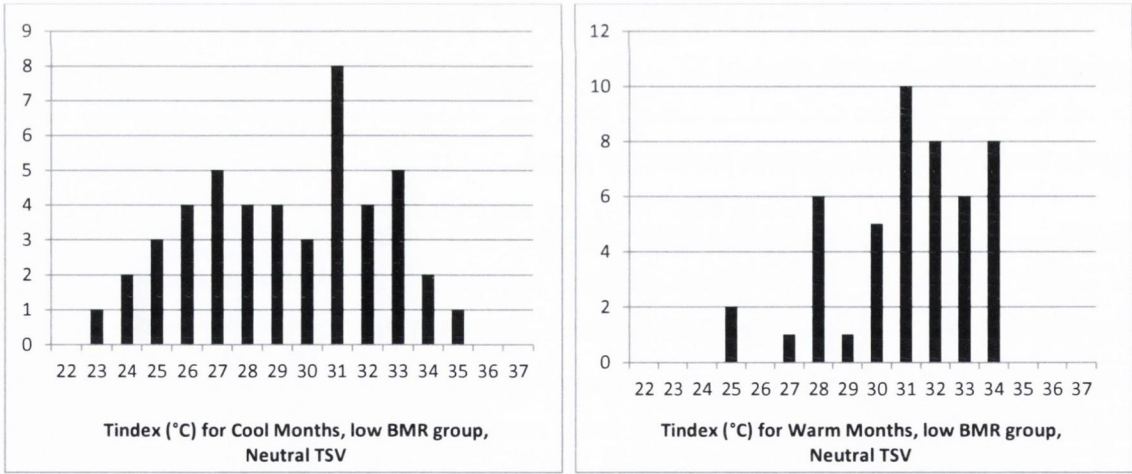


Fig. 6-19 Distribution of T_{index} for TSV 0 ('neutral') for low BMR group

Fig. 6-18 graphs the distribution of T_{opis} for the low BMR group when a TSV of 0 was recorded, split by season. It is clear there is a difference between warm and cool months. The mean recorded T_{opis} in the cool months was found to be 29.9°C while for the warm months was found to be 31.2°C. The distribution in the warm months shows a much higher frequency of T_{opis} recorded above the peak value of 31°C. The comparison of these two distributions which model the same thermal sensation suggest there is significant seasonality in T_{opis} for this group.

Fig. 6-19 graphs T_{index} when a TSV of 0 was recorded, split for warm and cool months. It backs up the suggestion that T_{opis} displays seasonality in temperature. The mean value of T_{index} recorded in the cool months was found to be 28.7°C, while in the warm months it was found to be 30.5°C, which is a larger difference (1.8°C) than that recorded of T_{opis} (1.3°C). The distribution of T_{index} in the warm months is usually between 30°C and 34°C, however in the cool months it was found to predominantly range between 25°C and 34°C.

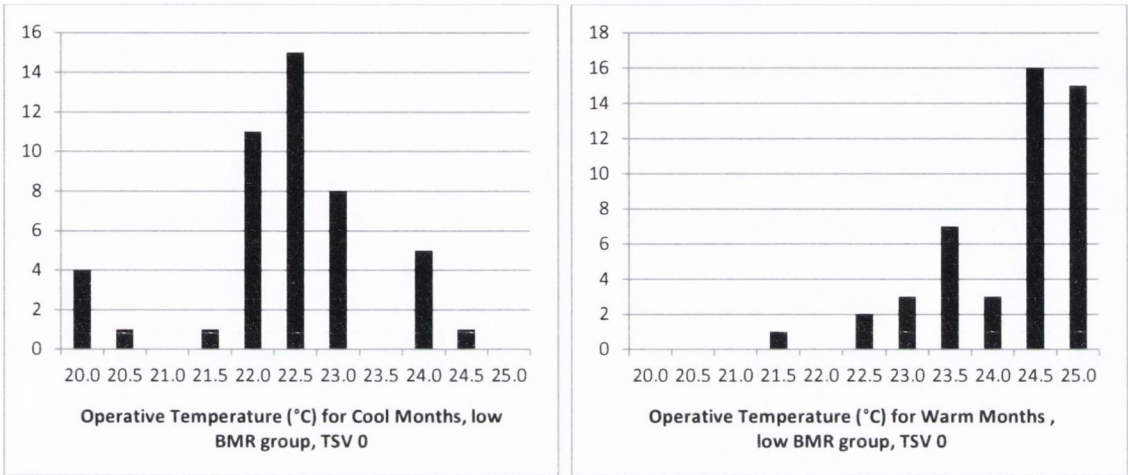


Fig. 6-20 Operative temperature distribution for ASHRAE scale vote of 4, Neutral for low BMR group

The operative temperature distribution is shown in Fig. 6-20 for both warm and cool months. Peak values of 22.5°C were recorded from the cool months whereas the peak value for warm months was found to be 24.5°C. The operative temperatures recorded show a difference in the preferred thermal environment by 2.0°C. This has long been established to be true [7] and cost benefits have been applied to buildings which can be left cooler in winter and warmer in summer. The participant appears to be more accepting of lower operative temperatures during the cool months. Hand skin temperatures recorded were found to be much lower in the cool months. T_{index} was found to have a larger difference in mean values recorded. This may be due to the larger range in which T_{index} operates compared to T_{opis} and the relative effect of decreased operative temperature on an extremity like the finger.

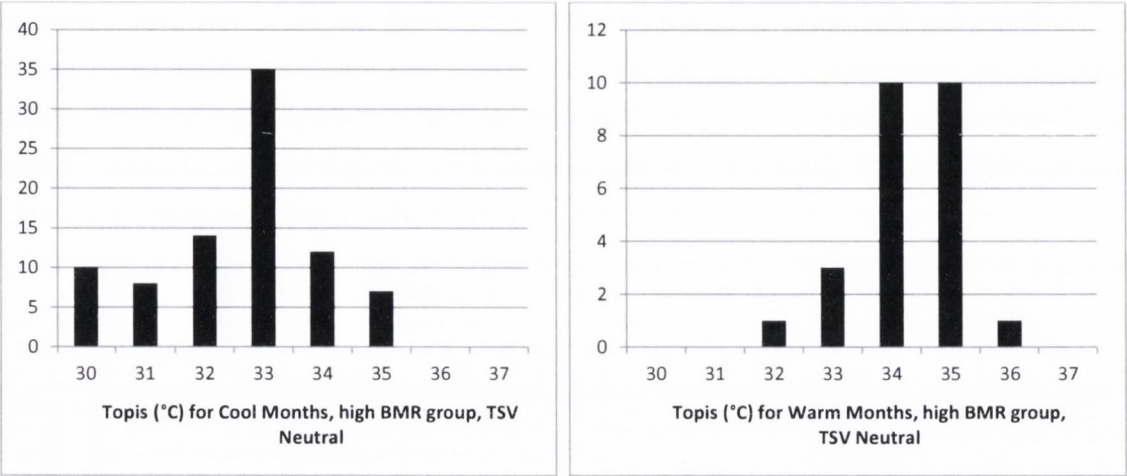


Fig. 6-21 Distribution of T_{opis} for TSV 0 ('neutral') for high BMR group

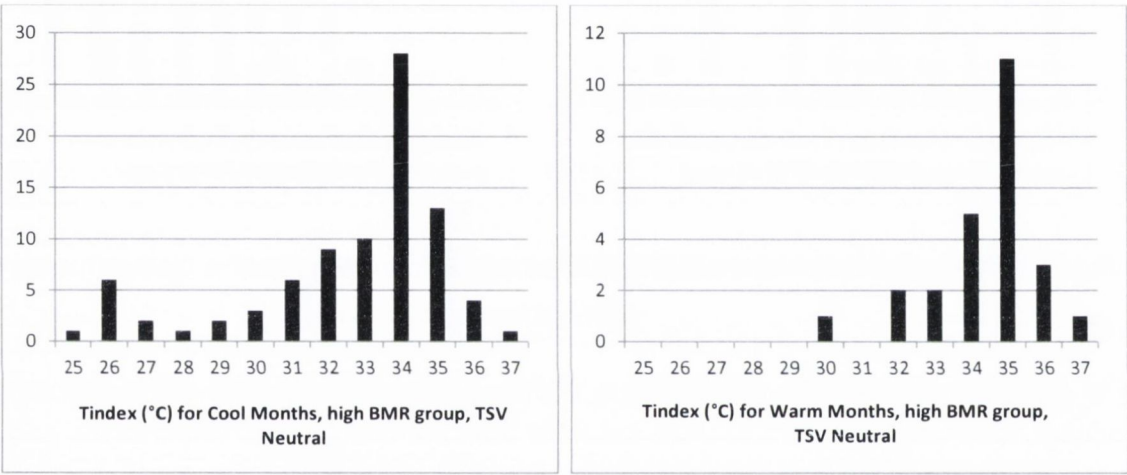


Fig. 6-22 Distribution of T_{index} for TSV 0 ('neutral') for high BMR group

Fig. 6-21 graphs the distribution of T_{opis} for the high BMR group when a TSV of 0 ('neutral') was recorded. Peak values for T_{opis} were found to be 33°C and a shared peak of 34°C and 35°C for cool and warm months, respectively. There was found to be a clear difference between those T_{opis} recorded during cool months and those from warm months for the high BMR group. In the cool months when a TSV of 0 was recorded there were found to be much lower T_{opis} recorded compared to the warm months. The mean of T_{opis} recorded in the warm months was found to be 33.8°C while in the cool months it was found to be 32.1°C, a difference of 1.7°C. This difference was found to be larger than that recorded by the low BMR group. The means of both warm and cool months for the high BMR group were found to be higher than those recorded by the low BMR group. Differences of 2.2°C and 2.6°C were found between the mean of T_{opis} for the low and high BMR groups across the cool and warm months, respectively.

Fig. 6-22 shows the distribution of T_{index} for the high BMR group. Peak values for T_{index} were found to be 34°C for the cool months and 35°C for the warm months. T_{index} was rarely recorded below 33°C in the warm months but was recorded between 25°C and 37°C in the cool months. The mean of T_{index} recorded in the warm months was found to be 33.8°C while in the cool months was found to be 32.1°C, a difference of 1.7°C. It is clear from looking at the distribution of T_{index} for high and low BMR groups in the cool months, that there is a significant difference between the two groups. The high BMR group has a much higher mean value of T_{index} and there is a lower frequency of lower T_{index} temperatures being recorded. By splitting the data into the high and low BMR group the trend of higher hand skin temperatures for the high BMR group emerges which the pilot study highlighted.

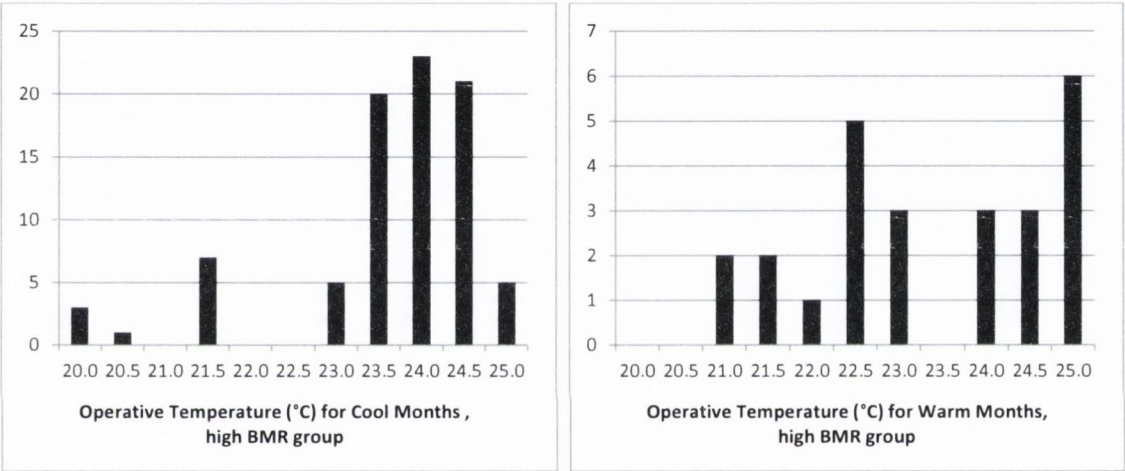


Fig. 6-23 Operative temperature distribution for TSV 0 ('neutral') for high BMR group

Mean of operative temperature in the warm months for the high BMR group were found to be 23.07°C and in the cool months it was 23.4°C for TSV 0 ('neutral'). There was 86 recorded data points of TSV 0, ('neutral') in cool months and 25 data points in warm months. The raised operative temperature during the warm months provided an environment in which the participant rarely recorded a feeling of 'neutral' but was more likely to record a hotter vote. Only 25 votes of TSV 0 were recorded during the warm months. However the differences in operative temperature appear to be negligible considering that mean $T_{operative}$ was higher for the cool months than the warm months. An explanation for this may be changes in clothing insulation. The clothing difference for the low BMR group between warm and cool months testing was insignificant, however the high BMR group participants were noted to be wearing lower insulation value ensembles in warm months than those recorded in cool months. Increased clothing insulation means lower heat transfer from the body and should result in increased cutaneous blood flow. The increased blood flow results in increased skin temperatures.

6.6.Overview

	N	Min	Max	Mean	Standard Deviation
ASHRAE Scale	617	1.0	7.0	3.9	1.1
Preference Scale	617	1.0	5.0	2.8	0.7
Average Opisthenar Temperature(°C)	5322	23.4	36.0	31.0	2.3
Index Fingernail Temperature (°C)	5322	18.5	37.1	30.0	3.8
Operative Temperature (°C)	5322	16.0	25.5	22.7	1.4

Table 6-5 Summary statistics for the entire dataset

Table 6-5 shows the summary statistics for the data recorded in the entire dataset. It also includes the data from the pilot study. The data recorded from the pilot study was reassessed using the recommendations from the pilot study. The pilot study data contains data for the months of July and August and was added to the range of months of testing in further tests carried out. ASHRAE scale votes for the entire data recorded have a mean of 3.9 and standard deviation of 1.1. For the pilot study data the mean was found to be 4.0 and standard deviation of 0.8. The increased standard deviation shows the range of values of ASHRAE scale recorded increased compared with pilot study data. The drop in mean values shows the recorded values tended toward the cooler end of the ASHRAE scale. The recordings of ASHRAE scale used the full range of the scale, in the pilot study the entire scale wasn't used. This indicates that the participants experienced a greater range of thermal environments covering full range of thermal sensation.

The preference scale, much like the ASHRAE scale, shows lower mean values and a slightly increased standard deviation compared to the pilot study. Preference scale vote used the full range of values. The mean in the pilot study was 3.1 and in the further tests it was 2.8, indicating the increased preference for a warmer environment. This is a symptom of the environment in which most of the testing took place. Operative temperature values were much lower in the winter months than summer months, leading to increased cool discomfort.

The mean opisthenar temperatures (T_{opis}) and index fingernail temperatures (T_{index}) recorded show a drop in mean values from the pilot study. Mean values of T_{index} and T_{opis} for the pilot study were measured as 32.2°C and 32.6°C, respectively, while mean values for the entire study were measured as 30.0°C and 31.0°C, respectively. There was a drop of 2.2°C of T_{index} in mean values. A drop in mean ASHRAE scale votes would explain the drop in T_{index} recorded. The drop in T_{opis} wasn't as pronounced at 1.6°C. Standard deviation for both hand skin temperature measures increased compared with the pilot study data.

The operative temperature ($T_{operative}$) from the pilot study recorded a mean value of 23.7°C and standard deviation of 1.1. For data from the entire study the $T_{operative}$ mean decreased to 22.7°C a drop of 1°C, the standard deviation increased by 0.3 to 1.4. Increased standard deviation means the range of values was wider and the lower mean indicates that $T_{operative}$ was much reduced compared to the data recorded in the pilot study. The minimum value of $T_{operative}$ recorded was 19.7°C and the maximum was 25.5°C. Compared to the pilot study the maximum and minimum $T_{operative}$ increased and decreased by less than 0.6°C, respectively, for the entire study, however the drop in mean temperature and increased standard deviation indicate that $T_{operative}$ had a greater frequency of values at the lower end of the range compared with the pilot study.

	ASHRAE Scale	Preference Scale	T_{opis}	T_{index}	$T_{operative}$
ASHRAE Scale	1	0.808	0.609	0.643	0.339
Preference Scale	0.808	1	0.617	0.650	0.371
T_{opis}	0.609	0.617	1	0.850	0.422
T_{index}	0.643	0.650	0.850	1	0.421
$T_{operative}$	0.339	0.371	0.422	0.421	1

Table 6-6 Correlation matrix for the entire dataset

Table 6-6 shows the correlation of values recorded in the entire dataset. Compared to the pilot study data there were increases in most correlations. Data analysis has shown that by increasing the range of values, the correlation equation improves. Data from the pilot study was limited in thermal sensation and preference scale recordings. Further test carried out included a greater range of values of ASHRAE and preference scale, therefore the correlation of the values compared would be expected to be higher.

T_{index} has the highest correlation to ASHRAE scale at 0.643, correlation to preference scale is ignored. The correlation of T_{index} to preference scale was found to be higher at 0.650. T_{opis} was found to correlate well to the ASHRAE and preference scales with values of 0.609 and 0.617, respectively. T_{index} and T_{opis} correlations were better than those found in the pilot study. T_{opis} showed a significant increase in correlation. T_{opis} was generally found to have a smaller range of values compared to T_{index} . T_{opis} showed an increased range of values in further tests over those recorded in the pilot study. An increased range of values usual indicates a higher correlation figure. Given that the pilot study was conducted on one day for most participants, a broader range of T_{opis} throughout the year would be expected.

Operative temperature showed increased correlation to preference scale but reduced correlation to ASHRAE scale. In the pilot study $T_{operative}$ showed negative correlation to

values of hand skin temperature. However, in the further tests the correlation of T_{opis} and T_{index} to $T_{operative}$ was significantly increased to 0.422 and 0.421, respectively.

In this research the relationship of hand skin temperature to thermal sensation is investigated. Hand skin temperature has been shown to depend on the human physiology and the season in which the measurement is taking place. In order to investigate the correlation of hand skin temperature to thermal sensation across participants and season, the data collected was analysed for correlation based on the previous group split.

	T_{opis}	T_{index}
TSV, Low BMR group, Warm Months	0.46	0.60
TSV, High BMR group, Warm Months	0.44	0.44
TSV, Low BMR group, Cool Months	0.43	0.50
TSV, High BMR group, Cool Months	0.78	0.76

Table 6-7 Correlation of thermal sensation to noted hand skin temperature

Table 6-7 presents the correlation factors of each of 4 groups split by estimated BMR and season in which the test was carried out. T_{index} offers good correlation for the most part but dips for the high BMR group in the warm months. For values of T_{opis} recorded, the correlation was not found to be as high as T_{index} . For the high BMR group T_{opis} was found to be similar if not better in correlation to thermal sensation. For the low BMR group, T_{index} was found to correlate better to thermal sensation. It is interesting to note that the high BMR group in the cool months recorded a correlation of 0.78 and 0.76 for T_{opis} and T_{index} , respectively. This high correlation factor does not translate to the low BMR group for the same months, but the low BMR group shows higher correlation of T_{index} in the warm months than in the cool months

Participant	T_{opis}	T_{index}
M1	0.83	0.83
M2	0.52	0.56
M3	0.50	0.57
F1	0.55	0.57
F2	0.49	0.62

Table 6-8 Correlation of thermal sensation to hand skin temperature for each participant

Table 6-8 shows the correlation of T_{opis} and T_{index} to thermal sensation for each participant. Participant M1 was found to have the highest correlation of both T_{opis} and T_{index} at 0.83 for each. The other participants were found to have similar correlations in the range 0.49 to 0.62. For each participant T_{index} was found to have the same or better correlation than T_{opis} . T_{index} was found to have a much broader range which was found to have less error than a tighter range. The measurement of T_{index} was found to be more difficult as the fingernail area in the infrared imagery was much smaller than the area of the opisthenar.

Seasons have been shown to have an effect on T_{index} recorded. Basal metabolic rate (BMR) has been found to have a similar effect on hand skin temperature. For the groups split by BMR and season, differing results in prediction of thermal sensation felt were found.

	Cool Months		Warm Months	
	T_{index} for Cool Discomfort	T_{index} for Warm Discomfort	T_{index} for Cool Discomfort	T_{index} for Warm Discomfort
High BMR group	29°C and lower	33°C and higher	30°C and lower	34°C and Higher
Low BMR group	27°C and lower	32°C and Higher	29°C and lower	33°C and Higher

Table 6-9 Table of predicted discomfort thresholds for values of T_{index}

Table 6-9 presents the predicted threshold values of T_{index} when warm or cool discomfort is the most likely event. The data gathered in the entire dataset was analysed statistically to determine at what threshold temperature of T_{index} thermal discomfort is most likely to occur. The event was considered most likely to occur when 60% or higher of measured data points were of that thermal discomfort. For example, at T_{index} of 27°C for the low BMR group, thermal sensation of 'slightly cool' or cooler was found for 60.3% of data points collected. Therefore T_{index} at this threshold or lower is likely to lead to a thermal sensation of 'slightly cool' or colder. Each category was found to present a different threshold value of T_{index} to indicate discomfort. In each category the difference between a prediction of cool and warm discomfort was found to be 4°C, except for the low BMR group in the cool months, where the gap was found to be 5°C.

The prediction using the entire dataset without splitting into groups yielded a result that cool discomfort is experienced for T_{index} values 29°C or below while warm discomfort is predicted when T_{index} values reach 34°C or higher. This table presents a similar picture but with different ranges. For example, in the cool months for the high BMR group, T_{index} 29°C or below predicted cool discomfort much like the prediction using the entire dataset, however when T_{index} was found to be 33°C or higher, warm discomfort was predicted. Another example, again in the cool months, was that the low BMR group was found to experience a lower T_{index} , 27°C, before cool discomfort was predicted. The upper threshold for warm discomfort was found to be 32°C. For this group in the cool months the range of values for which a neutral vote can be expected is 2°C lower than that predicted by the entire dataset, which means that for this group the accuracy of the prediction rises once the season and participant information is known.

7. Conclusions

7.1. Summary of Work Done

Upon completion of a review of the relevant literature, the response of the human hand skin to the environment was determined to be the greatest interest in this research. In particular whether infrared images can be used to extract the temperature data from the hand and be compared successfully to thermal comfort data also collected. Initially steps were taken to investigate using infrared images of hands to determine temperature and the possibility of automatic recognition of hands using MATLAB image processing software and bespoke software designed by the author.

After this, a pilot study was set up to investigate a number of parameters regarding the human response to the thermal environment. These parameters were direct measurements of thermal sensation and preference and also included measurement of variables used in the current approximation of thermal comfort, such as air temperature, mean radiant temperature and predicted mean vote.

Previous work on hand skin temperature measurements used thermocouples taped to the skin or held between finger and thumb to measure hand skin temperature and showed some success in prediction of thermal comfort. The pilot study was designed to find the optimum area of the hand for measuring hand skin temperature with a view to determining thermal comfort. The hand on a computer mouse was considered the most exposed hand and generally in the same place in an office situation. Measuring hand skin temperature in various places on the hand was achieved using an infrared camera set up with emissivity data to measure the temperature of skin. The infrared camera was a non-intrusive way of measuring hand skin temperature and could be used to monitor the hand position during the test.

The pilot study was conducted on 4 willing participants during the summer of 2012 in Ireland. The test bed used for this research was a Georgian building recently refurbished. The type of study was a field study in which the environment was not controlled. This research was concerned with the real world response of humans in the normal environment. Participants in the pilot study were asked to proceed as normal during the test period and completed work at the desk and computer at which the participant was normally seated. Infrared images of the participant hand were taken while the participant filled in a thermal sensation survey at intervals. A number of environmental variables were measured during the test in order to calculate equations of thermal comfort.

Results from the pilot study were used to determine the design of further tests and it was designed to investigate the results of the pilot study further. Intervals of recording of

variables were lengthened. Test periods were extended to cover a whole day and included tests in warm and cool conditions. One more female participant was added to investigate the possibility of gender differences in hand skin temperature. The literature review showed very little difference between males and females. However, this research found differences in participants based on Basal Metabolic Rate (BMR). Further tests carried out focused on the differences between metabolic rates of participants.

7.2.Principle Conclusions

The following observations and conclusions have been identified following the research presented in this thesis:

- Initial study into using infrared images: The initial image processing using sample pictures from the FLIR infrared camera showed that hands could be readily identified using the automatic software without much input from the user. Other objects in the field of view could be accurately deleted leaving only the hands in the image for temperature processing. During the pilot study some images of cold hands became increasingly common and identification of the entire hand by the program was difficult and in some cases impossible. Images were found where the tips of the fingers were the same or almost the same as the temperature of the surroundings and the program struggled to identify the full finger. With some adjustments using the threshold factors more of the finger could be identified. However, some images did not contain data which distinguished the finger and background and therefore could not be used in automatic hand recognition. Infrared cameras are not appropriate for use in situations where the hand could be near the same temperature of the surroundings. In an office case where the hand is warm, identification is achievable in cases where the hand is cold and close to the temperature of the room identification is not possible with any certainty using an automatic method without employing another type of camera to pick up position of the hands.
- Pilot study environmental variables: The variables measured during the pilot study test were used to work out known thermal comfort assessment tools such as Operative temperature ($T_{operative}$) and Predicted Mean Vote (PMV). PMV and $T_{operative}$ for participant were not found to correlate well with the thermal sensation recorded by each participant. The method of calculating PMV used several variables in which a large amount of error existed, due to the use of these variables. $T_{operative}$ was used in the place of PMV as a current measure of thermal comfort using environment variables as there was less error associated with its calculation. Correlation of $T_{operative}$ to the measured thermal sensation (ASHRAE

scale) was found to be 0.36 for the pilot study data. $T_{\text{operative}}$ was not found to correlate to hand skin temperature measured. In some cases $T_{\text{operative}}$ was a poor measure of thermal comfort as it predicted a warmer comfort than what was measured by the thermal sensation survey.

- Pilot study hand skin temperature: Hand skin temperature measured during the pilot study showed a better correlation to thermal sensation than any environmental variable measured or calculated. For participant F1, the correlation of T_{opis} to thermal sensation was found to be 0.57, however on including all participants from the pilot study this factor dropped to 0.40. Differences in hand skin temperature were noted between participants in the study. Participants M1 and M2 had higher mean hand skin temperatures over the test periods than the other participants. Participant M3 and F1 were found to have lower mean hand skin temperatures by over 1.5°C compared to participants M1 and M2. There was no gender difference between these two groups as M3, found to have lower hand skin temperature, was male. Other differences in physiology were investigated and it was found that M1 and M2 had much higher body mass than M3 and F1.
- Changes to hand skin temperature between seasons: T_{index} and T_{opis} were found to change with the change of mean monthly outdoor temperature. In warm months hand skin temperature was higher for each participant in the study than in the cool months. The difference noted ranged from 0.9°C to 5.1°C for each participant between seasons for recorded thermal sensation of 'neutral'.
- Differences in participants in entire study: the data showed that each participant had a different range of hand skin temperature. Some participants recorded much higher T_{index} and T_{opis} than others. The difference between these participants was found to be body mass. Estimated basal metabolic rate (BMR) equations were used to measure the difference in metabolic rate between participants. BMR was found to match well with the increase in hand skin temperatures noted. Participants were split into high and low BMR groups. The distribution of hand skin temperatures for both groups did not match, the high BMR group recorded much higher T_{opis} and T_{index} . When the data for a 'neutral' vote was graphed (Fig. 6-9, Fig. 6-10) it was shown that the high BMR group had higher T_{opis} than the low BMR group. 'neutral' thermal sensation was assumed to be the desired sensation and was used to compare the two groups
- Distribution of hand skin temperatures: for the entire dataset T_{opis} was linked to thermal sensation (Fig. 6-11). For values of T_{opis} 29°C and below it was predicted that the thermal sensation would be 'slightly cool' or lower. For values 34°C and

above it was predicted that thermal sensation would be 'slightly warm' or higher. In between these thresholds a vote of 'neutral' would be expected. However, the accuracy of these thresholds found to be 68.6% at maximum.

- Seasonality of hand skin temperature: when the participants were split into high and low BMR groups and data was split by warm and cool months, a pattern of differing hand skin temperature arose. For the high BMR group, for 'neutral' thermal sensation recordings, the mean value of T_{opis} in the cool months was found to be 32.1°C while in the warm months was found to be 1.7°C higher. Also T_{index} was found have the same mean values and differences. Further to this, $T_{\text{operative}}$ was found to have very little impact on the thermal sensation experienced. For the low BMR group in 'neutral' thermal sensation conditions, mean values of T_{opis} in cool months was found to be 29.9°C while in the warm months it was found to be 31.2°C. T_{index} in the cool months was found to be 28.7°C while in the warm months was found to be 30.5°C. Both groups showed much higher hand skin temperatures in the warm months than in the cool months. The high BMR group was found to have mean values of T_{opis} and T_{index} 2°C above the low BMR group in both cool and warm months.
- Correlation of hand skin temperature to thermal sensation: Humphreys et al reported that finger temperature had a better correlation to thermal sensation than globe temperature with a factor reported of 0.37. Globe temperature was found to have a correlation factor of 0.31 to thermal sensation. In this research the correlation of the entire dataset of T_{opis} to thermal sensation was found to be 0.61 while for T_{index} it was found to be 0.64. $T_{\text{operative}}$ which is similar to globe temperature had a factor of 0.34 to thermal sensation.
- The Infrared camera used to measure skin temperature had an accuracy range of $\pm 2^\circ\text{C}$. In some tests, changes in hand skin temperatures were found to be less than 4°C. Distinguishing between thermal comfort votes using skin temperature, given the low accuracy of the camera, will never give a definite answer. Each participant recorded a range of skin temperature for each thermal comfort vote but every range overlaps the next and determination of the thermal comfort by skin temperature is based on probability.

7.3.Recommended Future Work

This study has made a significant contribution to the research required to use hand skin temperature to assess thermal comfort. The infrared camera used in this research suffered from a low accuracy. Hand skin temperature was found to vary in some test by a little as 4°C and hand skin temperatures were found to be close in range for each thermal sensation or thermal preference recorded. Further work would benefit from a more accurate measuring device.

Factors highlighted such as basal metabolic rate and mean monthly temperature have been shown to impact on the interpretation of thermal comfort from hand skin temperature alone. This study involved 5 participants of the same age range. Further work into this assessment process should include for a larger group of subjects in which age and physiological attributes are investigated further. A larger group of subjects will allow for the definite formation of the theory formed in this in-depth research. Future studies could include for the effect of thermal comfort assessment in different countries. This research has been carried out in Ireland. Future studies should concentrate on the effects of outdoor temperature and time of day to improve the accuracy even further of the assessment technique using hand skin temperature.

A new technology of highly accurate ultra-thin devices can be attached to the skin to measure temperature has recently been published [82]. The given application was in the medical field. The work in this thesis could be used to set up a system which uses this technology for thermal comfort assessment through hand skin temperature and would avoid the use of low accuracy infrared imagers.

A system which determines thermal comfort through assessment of hand skin temperature, taking account for the physiology of the subject and mean monthly temperature, could be developed in future studies in order to relay information to the building management system which in turn could improve thermal comfort, productivity and possibly save energy in heating and cooling of the building.

8. References

- [1] CEN, ISO 7730;2005 Ergonomics of the thermal environment — Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. 2006.
- [2] M. A. Humphreys and J. Fergus Nicol, "The validity of ISO-PMV for predicting comfort votes in every-day thermal environments," *Energy and Buildings*, vol. 34, no. 6, pp. 667–684, Jul. 2002.
- [3] R. Yao, B. Li, and J. Liu, "A theoretical adaptive model of thermal comfort - Adaptive Predicted Mean Vote (aPMV)," *Building and Environment*, vol. 44, no. 10, pp. 2089–2096, Oct. 2009.
- [4] P. O. Fanger, *Thermal comfort: analysis and applications in environmental engineering*. New York,: McGraw-Hill, 1972.
- [5] W. L. Paul and P. A. Taylor, "A comparison of occupant comfort and satisfaction between a green building and a conventional building," *Building and Environment*, vol. 43, no. 11, pp. 1858–1870, Nov. 2008.
- [6] N. Baker and M. Standeven, "Thermal comfort for free-running buildings," *Energy and Buildings*, vol. 23, no. 3, pp. 175–182, Mar. 1996.
- [7] M. Indraganti and K. D. Rao, "Effect of age, gender, economic group and tenure on thermal comfort: A field study in residential buildings in hot and dry climate with seasonal variations," *Energy and Buildings*, vol. 42, no. 3, pp. 273–281, Mar. 2010.
- [8] R. de Dear and G. S. Brager, "Developing an adaptive model of thermal comfort and preference," Jan. 1998.
- [9] G. Platt, J. Li, R. Li, G. Poulton, G. James, and J. Wall, "Adaptive HVAC zone modeling for sustainable buildings," *Energy and Buildings*, vol. 42, no. 4, pp. 412–421, Apr. 2010.
- [10] Humphreys, Michael A.; Nicol, J. Fergus, "Do People Like to Feel 'Neutral'? Response to the ASHRAE Scale of Subjective Warmth in Relation to Thermal Preference, Indoor and Outdoor Temperature," *SOURCE ASHRAE Transactions*;2004, Vol. 110 Issue 2, p569, Oct. 2004.
- [11] F. Haldi and D. Robinson, "On the unification of thermal perception and adaptive actions," *Building and Environment*, vol. 45, no. 11, pp. 2440–2457, Nov. 2010.
- [12] F. De Oliveira, S. Moreau, C. Gehin, and A. Dittmar, "Infrared Imaging Analysis for Thermal Comfort Assessment," in *Engineering in Medicine and Biology Society, 2007. EMBS 2007. 29th Annual International Conference of the IEEE, 2007*, pp. 3373–3376.
- [13] D. Vrecko, N. Vodopivec, and S. Strmcnik, "An algorithm for calculating the optimal reference temperature in buildings," *Energy and Buildings*, vol. 41, no. 2, pp. 182–189, Feb. 2009.
- [14] W. Huang and H. N. Lam, "Using genetic algorithms to optimize controller parameters for HVAC systems," *Energy and Buildings*, vol. 26, no. 3, pp. 277–282, 1997.
- [15] M. He, W.-J. Cai, and S.-Y. Li, "Multiple fuzzy model-based temperature predictive control for HVAC systems," *Information Sciences*, vol. 169, no. 1–2, pp. 155–174, Jan. 2005.
- [16] S. K. Szokolay, *Introduction to architectural science: the basis of sustainable design*. Amsterdam ; Oxford: Architectural Press, 2004.
- [17] R. Niemelä, M. Hannula, S. Rautio, K. Reijula, and J. Railio, "The effect of air temperature on labour productivity in call centres—a case study," *Energy and Buildings*, vol. 34, no. 8, pp. 759–764, Sep. 2002.
- [18] L. Lan, Z. Lian, and L. Pan, "The effects of air temperature on office workers' well-being, workload and productivity-evaluated with subjective ratings," *Applied Ergonomics*, vol. 42, no. 1, pp. 29–36, Dec. 2010.
- [19] Gagge and Nevins, "Effect of energy conservation guidelines on comfort, acceptability and health." 1976.

- [20] K. Pantavou, G. Theoharatos, A. Mavrakakis, and M. Santamouris, "Evaluating thermal comfort conditions and health responses during an extremely hot summer in Athens," *Building and Environment*, vol. 46, no. 2, pp. 339–344, Feb. 2011.
- [21] CEN, "ISO 7726:2001 Ergonomics of the thermal environment - Instruments for measuring physical quantities." 2001.
- [22] CEN, "ISO 8996:2004 Ergonomics of the thermal environment -- Determination of metabolic rate." 2004.
- [23] J. A. Orosa, "Research on the origins of thermal comfort," *European Journal of Scientific Research*, vol. 34, no. 4, pp. 561–567, 2009.
- [24] A. Simone and B. W. Olesen, "An experimental study of thermal comfort at different combinations of air and mean radiant temperature," in *9th International Healthy Buildings Conference and Exhibition, HB 2009*, September 13, 2009 - September 17, 2009, 2009, p. National Grid; Syracuse University; Carrier; Corning; IBM.
- [25] J. Palonen, O. Seppanen, and J. J. K. Jaakkola, "The Effects Of Air Temperature And Relative Humidity On Thermal Comfort In The Office Environment," *Indoor Air*, vol. 3, no. 4, pp. 391–397, Dec. 1993.
- [26] A. Mahdavi and S. Kumar, "Implications of indoor climate control for comfort, energy and environment," *Energy and Buildings*, vol. 24, no. 3, pp. 167–177, Oct. 1996.
- [27] J. L. M. Hensen, "Literature review on thermal comfort in transient conditions," *Building and Environment*, vol. 25, no. 4, pp. 309–316, 1990.
- [28] R.-L. Hwang and S.-Y. Shu, "Building envelope regulations on thermal comfort in glass facade buildings and energy-saving potential for PMV-based comfort control," *Building and Environment*, vol. In Press, Accepted Manuscript.
- [29] D. H. Kang, P. H. Mo, D. H. Choi, S. Y. Song, M. S. Yeo, and K. W. Kim, "Effect of MRT variation on the energy consumption in a PMV-controlled office," *Building and Environment*, vol. 45, no. 9, pp. 1914–1922, Sep. 2010.
- [30] D. Wang, H. Zhang, E. Arens, and C. Huizenga, "Observations of upper-extremity skin temperature and corresponding overall-body thermal sensations and comfort," *Building and Environment*, vol. 42, no. 12, pp. 3933–3943, Dec. 2007.
- [31] ASHRAE, ANSI ASHRAE Standard 55, Thermal environmental conditions for human occupancy. ASHRAE, 2003.
- [32] W. Cui, G. Cao, J. H. Park, Q. Ouyang, and Y. Zhu, "Influence of indoor air temperature on human thermal comfort, motivation and performance," *Building and Environment*, vol. 68, pp. 114–122, Oct. 2013.
- [33] S. C. Sekhar, "Higher space temperatures and better thermal comfort — a tropical analysis," *Energy and Buildings*, vol. 23, no. 1, pp. 63–70, Oct. 1995.
- [34] M. Sherman, "A simplified model of thermal comfort," *Energy and Buildings*, vol. 8, no. 1, pp. 37–50, Feb. 1985.
- [35] Chartered Institution of Building Services Engineers, *Environmental design: CIBSE guide A*, 7th ed. London: Chartered Institution of Building Services Engineers, 2006.
- [36] S. Carlucci and L. Pagliano, "A review of indices for the long-term evaluation of the general thermal comfort conditions in buildings," *Energy and Buildings*, vol. 53, pp. 194–205, Oct. 2012.
- [37] F. Jazizadeh, F. M. Marin, and B. Becerik-Gerber, "A thermal preference scale for personalized comfort profile identification via participatory sensing," *Building and Environment*, vol. 68, pp. 140–149, Oct. 2013.
- [38] A. Melikov, T. Ivanova, and G. Stefanova, "Seat headrest-incorporated personalized ventilation: Thermal comfort and inhaled air quality," *Building and Environment*, vol. 47, pp. 100–108, Jan. 2012.
- [39] H. Zhang, E. Arens, D. Kim, E. Buchberger, F. Bauman, and C. Huizenga, "Comfort, perceived air quality, and work performance in a low-power task–ambient conditioning system," *Building and Environment*, vol. 45, no. 1, pp. 29–39, Jan. 2010.
- [40] A. Simone, S. Della Crociata, and F. Martellotta, "The influence of clothing distribution and local discomfort on the assessment of global thermal comfort," *Building and Environment*, vol. 59, pp. 644–653, Jan. 2013.

- [41] P. S. Curtiss, J. F. Kreider, and M. J. Brandemuehl, "Adaptive control of HVAC processes using predictive neural networks," in *ASHRAE Transactions*, 1993, vol. 99, pp. 496–504.
- [42] G. Fraisse, J. Virgone, and J. J. Roux, "Thermal control of a discontinuously occupied building using a classical and a fuzzy logic approach," *Energy and Buildings*, vol. 26, no. 3, pp. 303–316, 1997.
- [43] S. E. Bassett and MyiLibrary, *Anatomy & physiology*. Hoboken, N.J: Wiley, 2005.
- [44] J. A. Harris and F. G. Benedict, "A Biometric Study of Human Basal Metabolism," *Proc Natl Acad Sci U S A*, vol. 4, no. 12, pp. 370–373, Dec. 1918.
- [45] A. M. Roza and H. M. Shizgal, "The Harris Benedict equation reevaluated: resting energy requirements and the body cell mass," *Am J Clin Nutr*, vol. 40, no. 1, pp. 168–182, Jul. 1984.
- [46] A. M. Johnstone, S. D. Murison, J. S. Duncan, K. A. Rance, and J. R. Speakman, "Factors influencing variation in basal metabolic rate include fat-free mass, fat mass, age, and circulating thyroxine but not sex, circulating leptin, or triiodothyronine," *Am. J. Clin. Nutr.*, vol. 82, no. 5, pp. 941–948, Nov. 2005.
- [47] H. S. L. C. Hens, "Thermal comfort in office buildings: Two case studies commented," *Building and Environment*, vol. 44, no. 7, pp. 1399–1408, Jul. 2009.
- [48] J. Garcia and C. Quintana-Domeque, "The evolution of adult height in Europe: a brief note," *Econ Hum Biol*, vol. 5, no. 2, pp. 340–349, Jul. 2007.
- [49] "DocuBase Article: Anthropometric Reference Data for Children and Adults: United States, 2003-2006." [Online]. Available: <http://web.docuticker.com/go/docubase/27257>. [Accessed: 11-Apr-2013].
- [50] W. A. Government, "Welsh Health Survey, 2009," 15-Sep-2010. [Online]. Available: <http://wales.gov.uk/topics/statistics/headlines/health2010/100915/?lang=en>. [Accessed: 11-Apr-2013].
- [51] S. I. Fox, *Human Physiology*, 9 edition. McGraw-Hill Science/Engineering/Math, 2006.
- [52] N. Charkoudian, "Skin Blood Flow in Adult Human Thermoregulation: How It Works, When It Does Not, and Why," *Mayo Clinic Proceedings*, vol. 78, no. 5, pp. 603–612, May 2003.
- [53] D. M. Anderson and W. A. N. Dorland, *Dorland's illustrated medical dictionary*. Philadelphia [u.a.]: Saunders, 2000.
- [54] C. Elachi and J. J. van Zyl, *Introduction To The Physics and Techniques of Remote Sensing*, 2nd ed. Wiley-Interscience, 2006.
- [55] J. M. Palmer, *The art of radiometry*. Bellingham, Wash: SPIE Press, 2010.
- [56] T. Binzoni, T. Leung, D. T. Delpy, M. A. Fauci, and D. Rüfenacht, "Mapping human skeletal muscle perforator vessels using a quantum well infrared photodetector (QWIP) might explain the variability of NIRS and LDF measurements," *Phys Med Biol*, vol. 49, no. 12, pp. N165–173, Jun. 2004.
- [57] D. M. Savastano, A. M. Gorbach, H. S. Eden, S. M. Brady, J. C. Reynolds, and J. A. Yanovski, "Adiposity and human regional body temperature," *Am J Clin Nutr*, vol. 90, no. 5, pp. 1124–1131, Nov. 2009.
- [58] T. Astarita, G. Cardone, G. M. Carlomagno, and C. Meola, "A survey on infrared thermography for convective heat transfer measurements," *Optics & Laser Technology*, vol. 32, no. 7–8, pp. 593–610, Oct. 2000.
- [59] C. Huizenga, H. Zhang, E. Arens, and D. Wang, "Skin and core temperature response to partial and whole-body heating and cooling," *Journal of Thermal Biology*, vol. 29, no. 7–8, pp. 549–558, 2004.
- [60] S. D. Burch, V. Hassani, T. R. Penney, and N. R. E. L. (US), *Use of infra-red thermography for automotive climate control analysis*. National Renewable Energy Laboratory, 1994.
- [61] M. Ö. Korukçu and M. Kilic, "The usage of IR thermography for the temperature measurements inside an automobile cabin," *International Communications in Heat and Mass Transfer*, vol. 36, no. 8, pp. 872–877, Oct. 2009.
- [62] C. K. Eveland, D. A. Socolinsky, and L. B. Wolff, "Tracking human faces in infrared video," *Image and Vision Computing*, vol. 21, no. 7, pp. 579–590, Jul. 2003.

- [63] Y. V. Gulyaev, A. G. Markov, L. G. Koreneva, and P. V. Zakharov, "Dynamical infrared thermography in humans," *Engineering in Medicine and Biology Magazine*, IEEE, vol. 14, no. 6, pp. 766–771, 1995.
- [64] R. G. Gordon, R. B. Roemer, and S. M. Horvath, "A Mathematical Model of the Human Temperature Regulatory System - Transient Cold Exposure Response," *Biomedical Engineering, IEEE Transactions on*, vol. BME-23, no. 6, pp. 434–444, 1976.
- [65] A. Al-Habaibeh and R. Parkin, "An autonomous low-Cost infrared system for the on-line monitoring of manufacturing processes using novelty detection," *The International Journal of Advanced Manufacturing Technology*, vol. 22, no. 3–4, pp. 249–258, Sep. 2003.
- [66] I. J. Amin, A. J. Taylor, and R. Parkin, "In-cabin occupant tracking using a low-cost infrared system," *Proceedings Mechatronics and Robotics 2004*, pp. 259–264.
- [67] W. Liu, Z. Lian, Q. Deng, and Y. Liu, "Evaluation of Calculation Methods of Mean Skin Temperature for Use in Thermal Comfort Study," *Building and Environment*, 2010.
- [68] M. A. Humphreys and F. Nicol, "An analysis of some observations of the finger temperature and thermal comfort of office workers.," *Proceeding of Indoor Air*, pp. 602–7, 1999.
- [69] B. H. Hahn and D. T. Valentine, "CHAPTER 1 - Introduction," in *Essential Matlab for Engineers and Scientists (Fourth Edition)*, B. H. Hahn and D. T. Valentine, Eds. Boston: Academic Press, 2010, pp. 3–21.
- [70] M. A. Humphreys, "The Optimum Diameter for a Globe Thermometer for Use Indoors," *Ann Occup Hyg*, vol. 20, no. 2, pp. 135–140, Oct. 1977.
- [71] J. L. Purswell and J. D. Davis, "Construction of a Low-Cost Black Globe Thermometer.," *Applied Engineering in Agriculture*, vol. 24, no. 3, pp. 379–381, 2008.
- [72] "ISO 7243:1989 Hot environments -- Estimation of the heat stress on working man, based on the WBGT-index (wet bulb globe temperature)." .
- [73] E. Kähkönen, E. Nykyri, E. Tammela, R. Ilmarinen, and T. Seppälä, "The accuracy of estimating the thermal insulation of clothing ensembles — the effect of appraisers," *Applied Ergonomics*, vol. 21, no. 4, pp. 325–330, Dec. 1990.
- [74] thermal environmental conditions thermal comfort, "Thermal Comfort for Office Work : OSH Answers." [Online]. Available: http://www.ccohs.ca/oshanswers/phys_agents/thermal_comfort.html. [Accessed: 26-Jun-2013].
- [75] "A comprehensive database for estimating clothing insulation."
- [76] G. S. Brager and R. J. de Dear, "Thermal adaptation in the built environment: a literature review," *Energy and Buildings*, vol. 27, no. 1, pp. 83–96, Feb. 1998.
- [77] ISO, "Ergonomics of the thermal environment - analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria." [Online]. Available: <http://www.ihsti.com/IRISHCISPLUS/Doc.aspx?AuthCode=25A59B0&DocNum=278220&sc=pg%3dIRPLUS%3bany%3dEN+ISO+7730&Loc=sea>. [Accessed: 15-Oct-2010].
- [78] M. D. Mifflin, S. T. S. Jeor, L. A. Hill, B. J. Scott, S. A. Daugherty, and Y. O. Koh, "A new predictive equation for resting energy expenditure in healthy individuals.," *Am J Clin Nutr*, vol. 51, no. 2, pp. 241–247, Feb. 1990.
- [79] S. Karjalainen, "Gender differences in thermal comfort and use of thermostats in everyday thermal environments," *Building and Environment*, vol. 42, no. 4, pp. 1594–1603, Apr. 2007.
- [80] J. P. Cooke, M. A. Creager, P. J. Osmundson, and J. T. Shepherd, "Sex differences in control of cutaneous blood flow," *Circulation*, vol. 82, no. 5, pp. 1607–1615, Nov. 1990.
- [81] T. H. Karyono, "Report on thermal comfort and building energy studies in Jakarta—Indonesia," *Building and Environment*, vol. 35, no. 1, pp. 77–90, Jan. 2000.

- [82] R. C. Webb, A. P. Bonifas, A. Behnaz, Y. Zhang, K. J. Yu, H. Cheng, M. Shi, Z. Bian, Z. Liu, Y.-S. Kim, W.-H. Yeo, J. S. Park, J. Song, Y. Li, Y. Huang, A. M. Gorbach, and J. A. Rogers, "Ultrathin conformal devices for precise and continuous thermal characterization of human skin," *Nat Mater*, vol. advance online publication, Sep. 2013.

9. Appendix

9.1.Environment and Skin Temperature and Infrared Data Sample

Participant	Date	Time	Opisthenar Temperature	Fingernail Temperature	Thermal Sensation	Thermal Preference	Air Temperature	Relative Humidity	Globe Temperature	Mean Radiant Temperature	Predicted Mean Vote
M1	14/12/2012	13:56	33.7	35.6	5.0	3.0	23.6	37.7	23.4	23.3	0.3
M1	14/12/2012	14:06	33.5	34.4	5.0	4.0	22.7	39.0	23.5	23.9	0.3
M1	14/12/2012	14:16	33.4	35.0	5.0	4.0	22.4	39.4	23.5	23.9	0.3
M1	14/12/2012	14:26	33.5	34.7	5.0	4.0	22.4	39.7	23.7	24.3	0.3
M1	14/12/2012	14:36	33.1	34.4	5.0	3.0	22.4	39.9	23.9	24.6	0.3
M1	14/12/2012	14:46	33.6	34.5	5.0	4.0	22.4	40.0	23.9	24.6	0.4
M1	14/12/2012	14:56	33.1	34.2	5.0	4.0	22.4	40.0	24.1	24.8	0.4
M1	14/12/2012	15:06	33.1	34.4	5.0	4.0	22.5	40.2	24.1	24.8	0.4
M1	14/12/2012	15:16	33.4	34.4	5.0	3.0	22.5	40.4	24.1	24.9	0.4
M1	14/12/2012	15:26	32.9	34.1	5.0	3.0	22.6	40.5	24.2	24.9	0.4
M1	14/12/2012	15:36	31.8	33.4	5.0	4.0	22.6	40.3	24.2	25.0	0.4
M1	14/12/2012	15:46	32.0	34.1	5.0	3.0	22.7	40.4	24.3	25.0	0.4
M1	14/12/2012	15:56	32.3	33.4	5.0	3.0	22.7	40.4	24.4	25.1	0.4
M1	14/12/2012	16:06	32.7	34.7	5.0	3.0	22.7	40.4	24.4	25.1	0.4
M1	14/12/2012	16:16	32.9	33.7	4.0	3.0	22.8	40.4	24.4	25.1	0.4
M2	23/10/2012	11:55	35.4	36.7	5.0	3.0	22.2	55.9	23.2	23.6	0.3
M2	23/10/2012	12:05	33.7	34.1	5.0	3.0	22.4	55.7	23.0	23.2	0.3
M2	23/10/2012	12:15	32.8	32.1	5.0	3.0	22.6	55.5	23.1	23.3	0.3
M2	23/10/2012	12:25	31.8	30.0	4.0	3.0	22.8	55.1	23.2	23.4	0.4
M2	23/10/2012	12:44	31.5	29.4	5.0	4.0	23.0	54.8	23.4	23.6	0.4
M2	23/10/2012	12:54	30.4	28.9	4.0	3.0	23.1	54.7	23.5	23.7	0.4
M2	23/10/2012	13:05	30.7	32.2	5.0	4.0	23.1	54.6	23.6	23.7	0.4
M2	23/10/2012	13:14	31.8	31.1	4.0	3.0	23.2	54.5	23.6	23.8	0.5
M2	23/10/2012	13:27	32.1	27.5	4.0	3.0	23.3	54.5	23.5	23.6	0.4
M2	23/10/2012	13:34	30.0	25.2	4.0	3.0	23.3	54.5	23.6	23.7	0.5
M2	23/10/2012	13:44	29.9	25.9	4.0	3.0	23.4	54.2	23.8	23.9	0.5
M2	23/10/2012	13:54	29.6	25.9	4.0	3.0	23.5	54.1	23.9	24.0	0.5
M2	23/10/2012	14:04	29.6	30.8	4.0	3.0	23.5	54.0	24.0	24.1	0.5
M2	23/10/2012	14:14	29.3	26.9	4.0	2.0	23.6	54.4	23.9	23.9	0.5
M2	23/10/2012	14:24	29.0	26.1	4.0	2.0	23.7	54.5	23.9	23.9	0.5
F1	01/08/2012	11:20	34.0	34.6	5.0	4.0	22.8	60.2	23.1	23.2	-0.5
F1	01/08/2012	11:25	33.9	34.1	5.0	4.0	22.8	59.7	23.2	23.3	-0.4

Participant	Date	Time	Opisthenar Temperature	Fingernail Temperature	Thermal Sensation	Thermal Preference	Air Temperature	Relative Humidity	Globe Temperature	Mean Radiant Temperature	Predicted Mean Vote
F1	01/08/2012	11:30	33.6	33.6	4.0	3.0	22.9	59.2	23.2	23.3	-0.4
F1	01/08/2012	11:35	33.2	33.3	4.0	3.0	23.0	58.6	23.3	23.3	-0.4
F1	01/08/2012	11:38	33.0	32.5	3.0	2.0	23.0	58.6	23.3	23.3	-0.4
F1	01/08/2012	11:45	31.6	31.0	3.0	2.0	23.1	57.6	23.4	23.4	0.2
F1	01/08/2012	11:51	31.8	31.0	4.0	3.0	23.2	57.4	23.4	23.5	0.2
F1	01/08/2012	11:55	31.6	30.0	4.0	3.0	23.3	57.1	23.5	23.6	0.2
F1	01/08/2012	12:00	31.4	30.1	4.0	3.0	23.3	56.7	23.6	23.7	0.2
F1	01/08/2012	12:05	30.9	28.8	3.0	2.0	23.4	56.3	23.6	23.6	0.2
F1	01/08/2012	12:10	30.6	29.2	3.0	2.0	23.4	56.3	23.6	23.7	0.2
F1	01/08/2012	12:15	30.4	27.8	2.0	2.0	23.5	56.2	23.7	23.7	0.2
F1	01/08/2012	12:20	30.3	27.7	2.0	2.0	23.6	55.8	23.8	23.8	0.3
F1	01/08/2012	12:25	30.4	26.5	2.0	2.0	23.6	55.5	23.7	23.7	0.2
F1	01/08/2012	12:30	30.4	26.6	2.0	2.0	23.6	55.3	23.7	23.7	0.3
F1	01/08/2012	12:35	30.1	25.6	2.0	2.0	23.7	55.4	23.7	23.7	0.3
F1	01/08/2012	12:40	30.0	25.6	3.0	3.0	23.7	55.5	23.7	23.7	0.3
F1	01/08/2012	12:44	29.5	25.7	3.0	3.0	23.7	55.4	23.7	23.7	0.3
F1	01/08/2012	12:55	28.8	26.5	4.0	3.0	23.8	55.5	23.8	23.8	0.3
F1	01/08/2012	13:00	28.9	27.4	4.0	3.0	23.8	55.4	23.8	23.8	0.3
F1	01/08/2012	13:05	29.2	27.1	4.0	3.0	23.8	55.5	23.8	23.8	0.3
F1	01/08/2012	14:10	31.5	27.5	4.0	3.0	24.1	55.6	24.0	24.0	0.3
F1	01/08/2012	14:15	30.9	30.5	4.0	3.0	24.1	55.7	24.1	24.0	0.4
F1	01/08/2012	14:20	32.4	33.2	4.0	3.0	24.2	55.7	24.1	24.1	0.4
F1	01/08/2012	14:26	32.9	33.3	4.0	3.0	24.2	55.7	24.1	24.1	0.4

9.2.ASHRAE and Thermal Preference Survey

Name: Arinob O. Haden

Session: Tuesday 16/04/13

Time	How do you feel at this time?							I would prefer to be:				
	Cold	Cool	Slightly Cool	Neutral	Slightly warm	Warm	Hot	Much cooler	A bit cooler	No change	A bit warmer	Much warmer
17.53	1	2	3	4	5	6	7	5	4	3	2	1
14.02	1	2	3	4	5	6	7	5	4	3	2	1
14.05	1	2	3	4	5	6	7	5	4	3	2	1
15.21	1	2	3	4	5	6	7	5	4	3	2	1
15.31	1	2	3	4	5	6	7	5	4	3	2	1
15.48	1	2	3	4	5	6	7	5	4	3	2	1
15.54	1	2	3	4	5	6	7	5	4	3	2	1
16.05	1	2	3	4	5	6	7	5	4	3	2	1
16.18	1	2	3	4	5	6	7	5	4	3	2	1
16.29	1	2	3	4	5	6	7	5	4	3	2	1
16.38	1	2	3	4	5	6	7	5	4	3	2	1
16.53	1	2	3	4	5	6	7	5	4	3	2	1
17.17	1	2	3	4	5	6	7	5	4	3	2	1
17.45	1	2	3	4	5	6	7	5	4	3	2	1
17.48	1	2	3	4	5	6	7	5	4	3	2	1
18.06	1	2	3	4	5	6	7	5	4	3	2	1
18.08	1	2	3	4	5	6	7	5	4	3	2	1
18.40	1	2	3	4	5	6	7	5	4	3	2	1
18.56	1	2	3	4	5	6	7	5	4	3	2	1
19.02	1	2	3	4	5	6	7	5	4	3	2	1
19.17	1	2	3	4	5	6	7	5	4	3	2	1
19.47	1	2	3	4	5	6	7	5	4	3	2	1
19.56	1	2	3	4	5	6	7	5	4	3	2	1
20.01	1	2	3	4	5	6	7	5	4	3	2	1
20.21	1	2	3	4	5	6	7	5	4	3	2	1
20.42	1	2	3	4	5	6	7	5	4	3	2	1
21.00	1	2	3	4	5	6	7	5	4	3	2	1
21.10	1	2	3	4	5	6	7	5	4	3	2	1
21.18	1	2	3	4	5	6	7	5	4	3	2	1
21.43	1	2	3	4	5	6	7	5	4	3	2	1
21.57	1	2	3	4	5	6	7	5	4	3	2	1
22.54	1	2	3	4	5	6	7	5	4	3	2	1
23.06	1	2	3	4	5	6	7	5	4	3	2	1
23.15	1	2	3	4	5	6	7	5	4	3	2	1
23.23	1	2	3	4	5	6	7	5	4	3	2	1
23.42	1	2	3	4	5	6	7	5	4	3	2	1
23.55	1	2	3	4	5	6	7	5	4	3	2	1
24.10	1	2	3	4	5	6	7	5	4	3	2	1
24.18	1	2	3	4	5	6	7	5	4	3	2	1
24.43	1	2	3	4	5	6	7	5	4	3	2	1
24.57	1	2	3	4	5	6	7	5	4	3	2	1
25.54	1	2	3	4	5	6	7	5	4	3	2	1
26.06	1	2	3	4	5	6	7	5	4	3	2	1
26.15	1	2	3	4	5	6	7	5	4	3	2	1
26.23	1	2	3	4	5	6	7	5	4	3	2	1
26.42	1	2	3	4	5	6	7	5	4	3	2	1
26.55	1	2	3	4	5	6	7	5	4	3	2	1
27.10	1	2	3	4	5	6	7	5	4	3	2	1
27.18	1	2	3	4	5	6	7	5	4	3	2	1
27.43	1	2	3	4	5	6	7	5	4	3	2	1
27.57	1	2	3	4	5	6	7	5	4	3	2	1
28.06	1	2	3	4	5	6	7	5	4	3	2	1
28.15	1	2	3	4	5	6	7	5	4	3	2	1
28.23	1	2	3	4	5	6	7	5	4	3	2	1
28.42	1	2	3	4	5	6	7	5	4	3	2	1
28.55	1	2	3	4	5	6	7	5	4	3	2	1
29.10	1	2	3	4	5	6	7	5	4	3	2	1
29.18	1	2	3	4	5	6	7	5	4	3	2	1
29.43	1	2	3	4	5	6	7	5	4	3	2	1
29.57	1	2	3	4	5	6	7	5	4	3	2	1

Alsh

Thurs 18th April

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Session: 2nd MAY

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1/5/13

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38/4/13

[illegible]

Kary

29/4/13

[illegible]

Name:

SIM

Session:

14th Feb 2013

Time	How do you feel at this time?							I would prefer to be:				
	Cold	Cool	Slightly Cool	Neutral	Slightly warm	Warm	Hot	Much cooler	A bit cooler	No change	A bit warmer	Much warmer
10:48	1	2	3	4	5	6	7	5	4	3	2	1
10:51	1	2	3	4	5	6	7	5	4	3	2	1
10:53	1	2	3	4	5	6	7	5	4	3	2	1
10:55	1	2	3	4	5	6	7	5	4	3	2	1
10:59	1	2	3	4	5	6	7	5	4	3	2	1
11:01	1	2	3	4	5	6	7	5	4	3	2	1
11:05	1	2	3	4	5	6	7	5	4	3	2	1
11:11	1	2	3	4	5	6	7	5	4	3	2	1
11:16	1	2	3	4	5	6	7	5	4	3	2	1
11:19	1	2	3	4	5	6	7	5	4	3	2	1
11:19	1	2	3	4	5	6	7	5	4	3	2	1
11:25	1	2	3	4	5	6	7	5	4	3	2	1
11:27	1	2	3	4	5	6	7	5	4	3	2	1
11:30	1	2	3	4	5	6	7	5	4	3	2	1
11:32	1	2	3	4	5	6	7	5	4	3	2	1
11:40	1	2	3	4	5	6	7	5	4	3	2	1
11:41	1	2	3	4	5	6	7	5	4	3	2	1
11:45	1	2	3	4	5	6	7	5	4	3	2	1
11:50	1	2	3	4	5	6	7	5	4	3	2	1
11:57	1	2	3	4	5	6	7	5	4	3	2	1
12:02	1	2	3	4	5	6	7	5	4	3	2	1
12:11	1	2	3	4	5	6	7	5	4	3	2	1
12:21	1	2	3	4	5	6	7	5	4	3	2	1
12:25	1	2	3	4	5	6	7	5	4	3	2	1
12:29	1	2	3	4	5	6	7	5	4	3	2	1
13:28	1	2	3	4	5	6	7	5	4	3	2	1
14:01	1	2	3	4	5	6	7	5	4	3	2	1
14:14	1	2	3	4	5	6	7	5	4	3	2	1
14:15	1	2	3	4	5	6	7	5	4	3	2	1
14:20	1	2	3	4	5	6	7	5	4	3	2	1
14:25	1	2	3	4	5	6	7	5	4	3	2	1
14:30	1	2	3	4	5	6	7	5	4	3	2	1
14:36	1	2	3	4	5	6	7	5	4	3	2	1
14:40	1	2	3	4	5	6	7	5	4	3	2	1
14:45	1	2	3	4	5	6	7	5	4	3	2	1
14:50	1	2	3	4	5	6	7	5	4	3	2	1
14:55	1	2	3	4	5	6	7	5	4	3	2	1
15:03	1	2	3	4	5	6	7	5	4	3	2	1
15:05	1	2	3	4	5	6	7	5	4	3	2	1
15:08	1	2	3	4	5	6	7	5	4	3	2	1
15:10	1	2	3	4	5	6	7	5	4	3	2	1
15:11	1	2	3	4	5	6	7	5	4	3	2	1
15:14	1	2	3	4	5	6	7	5	4	3	2	1
15:17	1	2	3	4	5	6	7	5	4	3	2	1
	1	2	3	4	5	6	7	5	4	3	2	1

Name:

S in

Session:

7/Feb

Time	How do you feel at this time?							I would prefer to be:				
	Cold	Cool	Slightly Cool	Neutral	Slightly warm	Warm	Hot	Much cooler	A bit cooler	No change	A bit warmer	Much warmer
11:36	1	2	3	4	5	6	7	5	4	3	2	1
11:42	1	2	3	4	5	6	7	5	4	3	2	1
11:45	1	2	3	4	5	6	7	5	4	3	2	1
11:50	1	2	3	4	5	6	7	5	4	3	2	1
11:55	1	2	3	4	5	6	7	5	4	3	2	1
12:00	1	2	3	4	5	6	7	5	4	3	2	1
12:05	1	2	3	4	5	6	7	5	4	3	2	1
12:10	1	2	3	4	5	6	7	5	4	3	2	1
12:15	1	2	3	4	5	6	7	5	4	3	2	1
12:20	1	2	3	4	5	6	7	5	4	3	2	1
12:25	1	2	3	4	5	6	7	5	4	3	2	1
12:30	1	2	3	4	5	6	7	5	4	3	2	1
12:35	1	2	3	4	5	6	7	5	4	3	2	1
12:40	1	2	3	4	5	6	7	5	4	3	2	1
12:45	1	2	3	4	5	6	7	5	4	3	2	1
13:10	1	2	3	4	5	6	7	5	4	3	2	1
13:15	1	2	3	4	5	6	7	5	4	3	2	1
13:20	1	2	3	4	5	6	7	5	4	3	2	1
13:25	1	2	3	4	5	6	7	5	4	3	2	1
13:30	1	2	3	4	5	6	7	5	4	3	2	1
13:35	1	2	3	4	5	6	7	5	4	3	2	1
13:40	1	2	3	4	5	6	7	5	4	3	2	1
13:45	1	2	3	4	5	6	7	5	4	3	2	1
13:50	1	2	3	4	5	6	7	5	4	3	2	1
13:55	1	2	3	4	5	6	7	5	4	3	2	1
14:00	1	2	3	4	5	6	7	5	4	3	2	1
14:05	1	2	3	4	5	6	7	5	4	3	2	1
14:10	1	2	3	4	5	6	7	5	4	3	2	1
14:15	1	2	3	4	5	6	7	5	4	3	2	1
14:20	1	2	3	4	5	6	7	5	4	3	2	1
14:25	1	2	3	4	5	6	7	5	4	3	2	1
14:30	1	2	3	4	5	6	7	5	4	3	2	1
14:35	1	2	3	4	5	6	7	5	4	3	2	1
14:40	1	2	3	4	5	6	7	5	4	3	2	1
14:45	1	2	3	4	5	6	7	5	4	3	2	1
14:50	1	2	3	4	5	6	7	5	4	3	2	1
14:55	1	2	3	4	5	6	7	5	4	3	2	1
15:00	1	2	3	4	5	6	7	5	4	3	2	1
15:05	1	2	3	4	5	6	7	5	4	3	2	1
15:10	1	2	3	4	5	6	7	5	4	3	2	1
15:15	1	2	3	4	5	6	7	5	4	3	2	1
15:20	1	2	3	4	5	6	7	5	4	3	2	1
15:25	1	2	3	4	5	6	7	5	4	3	2	1
15:30	1	2	3	4	5	6	7	5	4	3	2	1
15:35	1	2	3	4	5	6	7	5	4	3	2	1
15:40	1	2	3	4	5	6	7	5	4	3	2	1
15:45	1	2	3	4	5	6	7	5	4	3	2	1
15:50	1	2	3	4	5	6	7	5	4	3	2	1
15:55	1	2	3	4	5	6	7	5	4	3	2	1
16:00	1	2	3	4	5	6	7	5	4	3	2	1
16:05	1	2	3	4	5	6	7	5	4	3	2	1
16:10	1	2	3	4	5	6	7	5	4	3	2	1
16:15	1	2	3	4	5	6	7	5	4	3	2	1
16:20	1	2	3	4	5	6	7	5	4	3	2	1
16:25	1	2	3	4	5	6	7	5	4	3	2	1
16:30	1	2	3	4	5	6	7	5	4	3	2	1
16:35	1	2	3	4	5	6	7	5	4	3	2	1
16:40	1	2	3	4	5	6	7	5	4	3	2	1
16:45	1	2	3	4	5	6	7	5	4	3	2	1
16:50	1	2	3	4	5	6	7	5	4	3	2	1
16:55	1	2	3	4	5	6	7	5	4	3	2	1
17:00	1	2	3	4	5	6	7	5	4	3	2	1
17:05	1	2	3	4	5	6	7	5	4	3	2	1
17:10	1	2	3	4	5	6	7	5	4	3	2	1
17:15	1	2	3	4	5	6	7	5	4	3	2	1

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13/2/13

[illegible]

9.3. Appendix of Thermal Comfort Indices

- [A.1] J.S. Haldane, The influence of high air temperature, *The Journal of Hygiene* 5 (1905) 494–513.
- [A.2] L. Hill, O. Griffith, M. Flack, The measurement of the rate of heat loss at body temperature by convection, radiation and evaporation, *Philosophical Transaction of the Royal Society* 207(B) (1916) 183–220.
- [A.3] F.C. Houghton, C.P. Yaglou, Determining equal comfort lines, *Journal of American Society of Heat Ventilation Engineers* 29 (1923) 165–176.
- [A.4] A.F. Dufton, The eupatheostat, *Journal of Scientific Instruments* 6 (1929) 249–251.
- [A.5] H.M. Vernon, *Journal of Physiology, London*, 70 (1930) XV.
- [A.6] H.M. Vernon, C.G. Warner, The influence of the humidity of the air on capacity for work at high temperatures, *The Journal of Hygiene* 32 (1932) 431–462.
- [A.7] C.E.A. Winslow, A.P. Gagge, L. Greenburg, I.M. Moriyama, E.J. Rodee, *American Journal of Hygiene*, 22 (1935) 137.
- [A.8] C.E.A. Winslow, L.P. Herrington, A.P. Gagge, Physiological reactions and sensations of pleasantness under varying atmospheric conditions, *Trans ASHVE* 44 (1937) 179–196.
- [A.9] O.F. Hevener, *All about humiture, Weatherwise* (1937).
- [A.10] A.P. Gagge, Man, his environment, his comfort, *Federal Proceedings* (1941).
- [A.11] M. Ionides, J. Plummer, P.A. Siple, The thermal acceptance ratio. Interm report No. 1, *Climatology and envelope, Fed Proc* 9 (1945) 26.
- [A.12] S. Robinson, E.S. Turrell, S.D. Gerking, Physiologically equivalent conditions of air temperature and humidity, *Am J Physiol* 143 (1945) 21–32.
- [A.13] P.A. Siple, C.F. Passel, Measurement of dry atmospheric cooling in subfreezing temperatures, *Proc. Am. Phil. Soc.* 89 (1945) 177–199.
- [A.14] T. Bedford, *Environmental warmth and its measurement, Med Res Council Memo* 17. HMSO, London, 1946.
- [A.15] B. McArdle, W. Dunham, H.E. Holling, W.S.S. Ladel, J.W. Scott, M.L. Thomson, J.S. Weiner, The prediction of the physiological effects of warm and hot environments, *Med Res Council, London RNP Report* 47/391, London, 1947.
- [A.16] A. Missenard, A thermique des ambiances: équivalences de passage, équivalences de séjours, *Chaleur Indust* 276 (1948) 159–72 (in French).
- [A.17] Craig, *Relation between heat balance and physiological strain in walking men clad in ventilated impermeable*, 1950.
- [A.18] H.S. Belding, T.F. Hatch, Index for evaluating heat stress in terms of resulting physiological strain, *Heat Pip Air Condit* 27 (1955) 129–136.
- [A.19] C.P. Yaglou, D. Minard, Control of heat casualties at military training centers, *Am Med Ass Arch Ind Hlth* 16 (1957) 302–316.
- [A.20] A.R. Lind, R.F. Hallon, Assessment of physiologic severity of hot climate, *J Appl Physiol* 11 (1957) 35–40.
- [A.21] D.H.K. Lee, Proprioclimates of man and domestic animals, in: *Climatology, Arid Zone Research—X, UNESCO, Paris*, 1958, pp. 102–125.
- [A.22] E.C. Thom, The discomfort index, *Weatherwise* 12 (1959) 57–60.
- [A.23] C.G. Webb An analysis of some observations of thermal comfort in an equatorial climate, *Brit J of Industrial Medicine*, 16 (3) (1959) 297–310.
- [A.24] J.F.K. Hall, W. Polte, Physiological index of strain and body heat storage in

hyperthermia, *J Appl Physiol* 15 (1960) 1027–1030.

[A.25] V.E. Lally, B.F. Watson, Humiture revisited, *Weatherwise*, 13 (1960) 254–256.

[A.26] J. Tennenbaum, E. Sohar, R. Adar, T. Gilat, D. Yaski, The physiological significance of the cumulative discomfort index (Cum DI), *Harefuah* 60 (1961) 315–319.

[A.27] E. Sohar, D.J. Tennenbaum, N. Robinson, A comparison of the cumulative discomfort index (Cum DI) and cumulative effective temperature (Cum ET), as obtained by meteorological data, in: S.W. Tromp (Ed.), *Biometeorology*, Pergamon Press, Oxford, 1962, pp. 395–400.

[A.28] B. Givoni, The influence of work and environmental conditions on the physiological responses and thermal equilibrium of man, in: *Proceedings of UNESCO Symposium on Environmental Physiology and Psychology in Arid Conditions*, Lucknow, 1962, pp. 199–204.

[A.29] J.S. McKarns, R.S. Brief, Nomographs give refined estimate of heat stress index, *Heat Pip Air Cond* 38 (1966) 113–6.60.

[A.30] F.H. Fuller, L. Brouha, New engineering methods for evaluating the job environment, *ASHRAE J* 8 (1966) 39–52.

[A.31] A.P. Gagge, G.M. Rapp, J.D. Hardy, Effective radiant field and operative temperature necessary for comfort with radiant heating, *ASHRAE Trans* 73 (1967) 2.1–9.

[A.32] P.O. Fanger, *Thermal Comfort*, Danish Technical Press, Copenhagen, DK, 1970.

[A.33] A.R. Lind, Effect of individual variation on upper limit of perspective zone of climates, *J Appl Physiol* 28 (1970) 57–62.

[A.34] A. Gagge, A. Stolwijk, Y. Nishi, An effective temperature scale based on a simple model of human physiological regulatory response, *ASHRAE Trans* 77 (1971) 247–257.

[A.35] J.H. Botsford, A wet globe thermometer for environmental heat measurement, *Am Ind Hyg Assoc J* 32 (1971) 1–10.

[A.36] Y. Nishi, A.P. Gagge Humid operative temperature. A biophysical index of thermal sensation and discomfort, *J Physiol (Paris)* 63 (1971) 365–368.

[A.37] R.G. Steadman, Indices of wind chill of clothed persons, *J. Appl. Meteor.*, 10 (1971) 674–683.

[A.38] B. Givoni, R.F. Goldman, Predicting rectal temperature response to work, environment, and clothing, *J Appl Physiol* 32 (1972) 812–822.

[A.39] D.M. Kerslake, *The Stress of Hot Environment*, Cambridge University Press, Cambridge, 1972.

[A.40] B. Givoni, R.R. Pandolf, Predicting heart rate response to work, environment and clothing, *J Appl Physiol* 34 (1973) 201–204.

[A.41] R.R. Gonzalez, Y. Nishi, A.P. Gagge, Experimental evaluation of standard effective temperature: a new biometeorological index of man's thermal discomfort, *Int J Biometeorol* 18 (1974) 1–15.

[A.42] R.R. Gonzalez, L.G. Berglund, A.P. Gagge, Indices of thermoregulatory strain for moderate exercise in the heat, *J Appl Physiol* 44 (1978) 889–899.

[A.43] S.H. Nunneley, F. Stribley, Fighter index of thermal stress (FITS): guidance for hot-weather aircraft operations, *Aviat Space Environ Med* 50 (1979) 639–642.

[A.44] J.M. Masterton, F.A. Richardson, Humidex, a method of quantifying human discomfort due to excessive heat and humidity, *CLI* 1–79, Environment Canada, Atmospheric Environment Service, Downsview, Ontario, 1979.

[A.45] R.G. Steadman, The Assessment of Sultriness. Part I: A Temperature-Humidity Index Based on Human Physiology and Clothing Science, *J. Appl. Meteor.*, 18 (1979) 861–873.

- [A.46] W.O. Wray, A simple procedure for assessing thermal comfort in passive solar heated buildings, *Solar Energy*, vol. 25, Pergamon Press Ltd. 1980, pp. 327–333.
- [A.47] E. Kamon, C. Ryan, Effective heat strain index using pocket computer, *Am Ind Hyg Assoc J* 42 (1981) 611–615.
- [A.48] Y. Shapiro, K.B. Pandolf, R.F. Goldman, Predicting sweat loss response to exercise, environment and clothing, *Eur J Appl Physiol Occup Physiol* 48 (1982) 83–96.
- [A.49] M. Weiss, The humisery and other measures of summer discomfort, *Nat. Wea. Dig.*, 7:2 (1982) 10–18.
- [A.50] P. Höppe, *Die Energiebilanz des Menschen* (dissertation), Wiss Mitt Meteorological Institute, University of München, 1984, p. 49
- [A.51] C.R. De Freitas, Assessment of human bioclimate based on thermal response, *International Journal of Biometeorology*, 29 (1985) 97–119.
- [A.52] A.P. Gagge, A.P. Fobelets, L.G. Berglund, A standard predictive index of human response to the thermal environment, *ASHRAE Trans* 92 (1986) 709–731.
- [A.53] C.R. De Freitas, L.V. Symon, A bioclimatic index of human survival times in the Antarctic, *Polar Record*, 23 (1987) 651–659.
- [A.54] Bureau of Indian Standards, *Handbook of Functional Requirements of Buildings (Other than Industrial Buildings)*, 1987, SP:41.
- [A.55] W.J. Pepi, The Summer Simmer Index, *Weatherwise*, 40 (June (3)) (1987).
- [A.56] M.Y. Beshir, J.D. Ramsey, Heat stress indices: a review paper, *International Journal of Industrial Ergonomics*, 3 (1988) 89–102.
- [A.57] ISO 7933, Hot environments—analytical determination and interpretation of thermal stress using calculation of required sweat rate, ISO, Geneva, 1989, *Industrial Health* 2006, 44, 388–398.
- [A.58] K. Blazejczyk, New climatological-and-physiological model of human heat balance outdoor (MENEX) and its applications in bioclimatological studies in different scales, in: K. Blazejczyk, B. Krawczyk (Eds.), *Bioclimatic Research of the Human Heat Balance*. Polish Academy of Sciences, Institute of Geography and Spatial Organization, Warsaw, 1994, pp. 27–58.
- [A.59] A. Frank, D. Moran, Y. Epstein, M. Belokopytov, Y. Shapiro, The estimation of heat tolerance by a new cumulative heat strain index, in: Y. Shapiro, D. Moran, Y. Epstein (Eds.), *Environmental Ergonomics: Recent Progress and New Frontiers*, Freund Pub House, London, 1996, pp. 194–197.
- [A.60] D.S. Moran, A. Shitzer, K.B. Pandolf, A physiological strain index to evaluate heat stress, *Am J Physiol* 275 (1998) R129–134.
- [A.61] D.S. Moran, Y. Shapiro, Y. Epstein, W. Matthew, K.B. Pandolf, A modified discomfort index (MDI) as an alternative to the wet bulb globe temperature (WBGT), in: J.A. Hodgdon, J.H. Heaney, M.J. Buono (Eds.), *Environmental Ergonomics VIII*, Int Conf Environ Ergo, San Diego, 1998, pp. 77–80.
- [A.62] W.J. Pepi, The New Summer Simmer Index, International Audience at the 80th Annual Meeting of the AMS at Long Beach, California, on January 11, 2000.
- [A.63] D.S. Moran, K.B. Pandolf, Y. Shapiro, Y. Heled, Y. Shani, W.T. Matthew, R.R. Gonzales, An environmental stress index (ESI) as a substitute for the wet bulb globe temperature (WBGT), *J Thermal Biol* 26 (2001) 427–431.
- [A.64] Chartered Institution of Building Services Engineers, *Guide J: Weather, Solar and Illuminance Data*, London, UK, 2002, 8.1–8.6, pp. 1–4.
- [A.65] R.F. Wallace, D. Kriebel, L. Punnett, D.H. Wegman, C.B. Wenger, J.W. Gardner, R.R. Gonzales, The effects of continuous hot weather training on risk of exertional heat

illness, Med Sci Sports Exerc 37 (2005) 84–90.

[A.66] International Standard Organization, ISO 7730: Ergonomics of the thermal environment—analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria, 3rd version, Geneva, 15/11/2005, 2005.

[A.67] Chartered Institution of Building Services Engineers, CIBSE Guide A Chapter 1: Environmental Criteria for Design, CIBSE, London, 2006.

[A.68] European Committee for Standardization, EN 15251: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics, Brussels, March 2007.

[A.69] D. Robinson, F. Haldi (2007) Model to predict overheating risk based on an electrical capacitor analogy. Energy and Buildings 40(2007) 1240–1245.

[A.70] F. Nicol, J. Hacker, B. Spires, H. Davies, Suggestion for new approach to overheating diagnostics, in: Proceedings of Conference: Air Conditioning and the Low Carbon Cooling Challenge, Cumberland Lodge, Windsor, UK, 27–29 July 2008, 2008.

[A.71] S. Borgeson, G.S. Brager, Comfort standards and variations in exceedance for mixed-mode buildings, Building Research & Information 39 (2) (2010) 118–133.

9.4.Globe thermometer calibration results

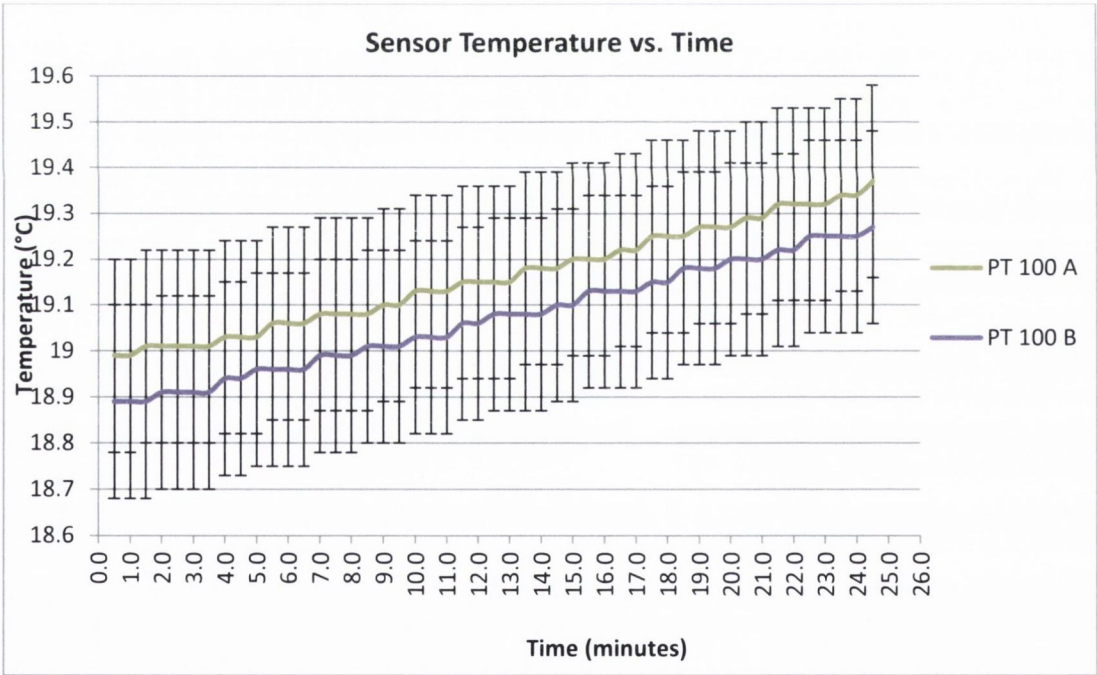


Fig. 9-1 Calibration of PT-100 Sensors - Temperature Recorded vs. Time

9.5.C++ Programming Code for Infrared Camera Image Capture

9.5.1. FormMain.h Header File

```
#pragma once

#include "..\Shared Files\IPCSample.h"
#include "..\Shared Files\IPC2.h"
#include "stdafx.h"

namespace IPCSample
{
    using namespace System;
    using namespace System::ComponentModel;
    using namespace System::Collections;
    using namespace System::Windows::Forms;
    using namespace System::Data;
    using namespace System::Drawing;

    /// <summary>
    /// Zusammenfassung für FormMain
    ///
    /// Warnung: Wenn Sie den Namen dieser Klasse ändern, müssen Sie
    auch
    /// die Ressourcendateiname-Eigenschaft für das Tool zur
    Kompilierung verwalteter Ressourcen ändern,
    /// das allen RESX-Dateien zugewiesen ist, von denen diese
    Klasse abhängt.
    /// Anderenfalls können die Designer nicht korrekt mit den
    lokalisierten Ressourcen
    /// arbeiten, die diesem Formular zugewiesen sind.
    /// </summary>
    public ref class FormMain : public System::Windows::Forms::Form
    {
    public:
        FormMain(HWND hostHandle);

    private: System::Windows::Forms::GroupBox^ groupBoxFlag;
    private: System::Windows::Forms::Button^ buttonFlagClose;
    private: System::Windows::Forms::CheckBox^ checkBoxColors;
    private: System::Windows::Forms::GroupBox^ groupBoxVideo;
    private: System::Windows::Forms::GroupBox^ groupBoxMeasureAreas;
    private: System::Windows::Forms::ComboBox^ comboBoxOptics;

    private: System::Windows::Forms::TextBox^ textBoxInstanceName;
    private: System::Windows::Forms::Label^ labelInstanceName;
    private: System::Windows::Forms::Button^ buttonKill;
    private: System::Windows::Forms::Button^ buttonFlagRenew;
    private: System::Windows::Forms::ProgressBar^ progressBarInit;
    private: System::Windows::Forms::CheckBox^ checkBoxDock;
    private: System::Windows::Forms::GroupBox^ groupBoxHostAppl;
    private: System::Windows::Forms::Label^ labelHW;
    private: System::Windows::Forms::Label^ labelFW;
    private: System::Windows::Forms::Button^ button1;

    private: System::Windows::Forms::GroupBox^ groupBoxFile;
    private: System::Windows::Forms::ToolStrip^ toolStripFile;

    private:
        System::Windows::Forms::ToolStripButton^
```

```

toolStripButtonSnapshot;
    private: System::Windows::Forms::ToolStripButton^
toolStripButtonOpen;
    private: System::Windows::Forms::ToolStripButton^
toolStripButtonPlay;
    private: System::Windows::Forms::ToolStripButton^
toolStripButtonPause;
    private: System::Windows::Forms::ToolStripButton^
toolStripButtonStop;
    private: System::Windows::Forms::ToolStripButton^
toolStripButtonRecord;
    private: System::Windows::Forms::Label^ labelFrameCounter;

    private: System::Windows::Forms::Label^ labelPIF;
    private: System::Windows::Forms::NumericUpDown^
numericUpDownEmissivity;

    private: System::Windows::Forms::Label^ labelEmissivity;
    private: System::Windows::Forms::Label^ labelTempAmbient;
    private: System::Windows::Forms::NumericUpDown^
numericUpDownTempAmbient;
    private: System::Windows::Forms::Label^ labelFlag1;
    private: System::Windows::Forms::Label^ labelFlag;

private: System::Windows::Forms::ComboBox^ comboBoxTempRange;

property System::Version^ Version
{
    System::Version^ get()
    {
        Reflection::Assembly^ assembly =
Reflection::Assembly::GetExecutingAssembly();
        return assembly->GetName()->Version;
    }
}

protected:
    /// <summary>
    /// Verwendete Ressourcen bereinigen.
    /// </summary>
    ~FormMain();
    void GetBitmap(Bitmap^ Bmp, array<short>^values);
    void GetBitmap_Limits(array<short>^Values, short *min, short
    *max);

    short FrameWidth, FrameHeight, FrameDepth;
    double FrameRatio;
    int FrameSize;
    IPC^ ipc;
    bool ipcInitialized;
    int FrameCounter0, FrameCounter1, LastFrameCounter, FC0, FC1;
    System::DateTime LastFrameTime;
    System::Collections::ArrayList^ List;
    double Tmax;
    Bitmap^ bmp;

```

```

Device Dev;
bool Connected;
bool AppendLog;
bool ResetPending;
int takeSnap; //initialise value for taking snapshot at timed
intervals

array<Byte>^rgbValues;
array<short>^Values;

int MainTimerDivider;
bool Painted;
bool Old_CorrEnable;
USHORT Old_FlagMode;
USHORT MeasureAreaCount;
Drawing::Size Margin;
Drawing::Rectangle^ OldApplRect;
bool OldEmbeddedState;

private: System::Windows::Forms::Label^ label1;
private: System::Windows::Forms::Label^ label2;
private: System::Windows::Forms::Label^ labelFramerate;

private: System::Windows::Forms::Timer^ timer1;
private: System::Windows::Forms::Label^ labelTempChip;
private: System::Windows::Forms::Label^ labelTempFlag;
private: System::Windows::Forms::PictureBox^ pictureBox;
private: System::Windows::Forms::GroupBox^ groupBoxOptics;

private: System::Windows::Forms::Label^ labelVersionAppl;
private: System::Windows::Forms::Timer^ timer2;
private: System::Windows::Forms::Label^ labelVersionIPC;
private: System::Windows::Forms::Label^ labelTempTarget;
private: System::Windows::Forms::Label^ labelTempBox;
private: System::Windows::Forms::Button^ buttonFlagOpen;
private: System::Windows::Forms::GroupBox^ groupBoxRangeMode;
private: System::Windows::Forms::RadioButton^
radioButtonRangeMinMax;
private: System::Windows::Forms::RadioButton^
radioButtonRange3Sigma;
private: System::Windows::Forms::RadioButton^
radioButtonRange1Sigma;
private: System::Windows::Forms::Label^ labelOpticsFOV;

private: System::Windows::Forms::Label^ labelTempRange;
private: System::ComponentModel::IContainer^ components;
private:
    /// <summary>
    /// Erforderliche Designervariable.
    /// </summary>

#pragma region Windows Form Designer generated code
    /// <summary>
    /// Erforderliche Methode für die Designerunterstützung.
    /// Der Inhalt der Methode darf nicht mit dem Code-Editor
geändert werden.
    /// </summary>
    void InitializeComponent(void)
    {
        this->components = (gcnew
System::ComponentModel::Container());
        System::ComponentModel::ComponentResourceManager^

```



```

resources                                     =                                     (gcnew
System::ComponentModel::ComponentResourceManager(FormMain::typeid));
    this->label1 = (gcnew System::Windows::Forms::Label());
    this->label2 = (gcnew System::Windows::Forms::Label());
    this->labelFramerate                       =                                     (gcnew
System::Windows::Forms::Label());
    this->timer1                               =                                     (gcnew
System::Windows::Forms::Timer(this->components));
    this->labelTempChip                       =                                     (gcnew
System::Windows::Forms::Label());
    this->labelTempFlag                       =                                     (gcnew
System::Windows::Forms::Label());
    this->pictureBox                         =                                     (gcnew
System::Windows::Forms::PictureBox());
    this->groupBoxOptics                     =                                     (gcnew
System::Windows::Forms::GroupBox());
    this->labelTempAmbient                   =                                     (gcnew
System::Windows::Forms::Label());
    this->labelEmissivity                    =                                     (gcnew
System::Windows::Forms::Label());
    this->numericUpDownTempAmbient           =                                     (gcnew
System::Windows::Forms::NumericUpDown());
    this->numericUpDownEmissivity            =                                     (gcnew
System::Windows::Forms::NumericUpDown());
    this->comboBoxTempRange                  =                                     (gcnew
System::Windows::Forms::ComboBox());
    this->comboBoxOptics                     =                                     (gcnew
System::Windows::Forms::ComboBox());
    this->labelTempRange                     =                                     (gcnew
System::Windows::Forms::Label());
    this->labelOpticsFOV                     =                                     (gcnew
System::Windows::Forms::Label());
    this->labelVersionAppl                    =                                     (gcnew
System::Windows::Forms::Label());
    this->timer2                             =                                     (gcnew
System::Windows::Forms::Timer(this->components));
    this->labelVersionIPC                     =                                     (gcnew
System::Windows::Forms::Label());
    this->labelTempTarget                     =                                     (gcnew
System::Windows::Forms::Label());
    this->labelTempBox                       =                                     (gcnew
System::Windows::Forms::Label());
    this->buttonFlagOpen                     =                                     (gcnew
System::Windows::Forms::Button());
    this->groupBoxRangeMode                   =                                     (gcnew
System::Windows::Forms::GroupBox());
    this->checkBoxColors                      =                                     (gcnew
System::Windows::Forms::CheckBox());
    this->radioButtonRangeMinMax              =                                     (gcnew
System::Windows::Forms::RadioButton());
    this->radioButtonRange3Sigma              =                                     (gcnew
System::Windows::Forms::RadioButton());
    this->radioButtonRange1Sigma              =                                     (gcnew
System::Windows::Forms::RadioButton());
    this->groupBoxFlag                       =                                     (gcnew
System::Windows::Forms::GroupBox());
    this->buttonFlagRenew                     =                                     (gcnew
System::Windows::Forms::Button());
    this->buttonFlagClose                     =                                     (gcnew
System::Windows::Forms::Button());
    this->groupBoxVideo                       =                                     (gcnew
System::Windows::Forms::GroupBox());
    this->groupBoxMeasureAreas                =                                     (gcnew
System::Windows::Forms::GroupBox());

```

```

        this->textBoxInstanceName = (gcnew
System::Windows::Forms::TextBox());
        this->labelInstanceName = (gcnew
System::Windows::Forms::Label());
        this->buttonKill = (gcnew
System::Windows::Forms::Button());
        this->progressBarInit = (gcnew
System::Windows::Forms::ProgressBar());
        this->checkBoxDock = (gcnew
System::Windows::Forms::CheckBox());
        this->groupBoxHostAppl = (gcnew
System::Windows::Forms::GroupBox());
        this->labelHW = (gcnew
System::Windows::Forms::Label());
        this->labelFW = (gcnew
System::Windows::Forms::Label());
        this->button1 = (gcnew
System::Windows::Forms::Button());
        this->groupBoxFile = (gcnew
System::Windows::Forms::GroupBox());
        this->toolStripFile = (gcnew
System::Windows::Forms::ToolStrip());
        this->toolStripButtonOpen = (gcnew
System::Windows::Forms::ToolStripButton());
        this->toolStripButtonPlay = (gcnew
System::Windows::Forms::ToolStripButton());
        this->toolStripButtonPause = (gcnew
System::Windows::Forms::ToolStripButton());
        this->toolStripButtonStop = (gcnew
System::Windows::Forms::ToolStripButton());
        this->toolStripButtonRecord = (gcnew
System::Windows::Forms::ToolStripButton());
        this->toolStripButtonSnapshot = (gcnew
System::Windows::Forms::ToolStripButton());
        this->labelFrameCounter = (gcnew
System::Windows::Forms::Label());
        this->labelPIF = (gcnew
System::Windows::Forms::Label());
        this->labelFlag1 = (gcnew
System::Windows::Forms::Label());
        this->labelFlag = (gcnew
System::Windows::Forms::Label());

        (cli::safe_cast<System::ComponentModel::ISupportInitialize^
>(this->pictureBox))->BeginInit();
        this->groupBoxOptics->SuspendLayout();

        (cli::safe_cast<System::ComponentModel::ISupportInitialize^
>(this->numericUpDownTempAmbient))->BeginInit();

        (cli::safe_cast<System::ComponentModel::ISupportInitialize^
>(this->numericUpDownEmissivity))->BeginInit();
        this->groupBoxRangeMode->SuspendLayout();
        this->groupBoxFlag->SuspendLayout();
        this->groupBoxVideo->SuspendLayout();
        this->groupBoxFile->SuspendLayout();
        this->toolStripFile->SuspendLayout();
        this->SuspendLayout();
        //
        // label1
        //
        this->label1->AutoSize = true;
        this->label1->Location = System::Drawing::Point(21,
58);

```

```

this->label1->Name = L"label1";
this->label1->Size = System::Drawing::Size(16, 13);
this->label1->TabIndex = 0;
this->label1->Text = L"---";
//
// label2
//
this->label2->AutoSize = true;
this->label2->Location = System::Drawing::Point(21,
94);

this->label2->Name = L"label2";
this->label2->Size = System::Drawing::Size(16, 13);
this->label2->TabIndex = 1;
this->label2->Text = L"---";
//
// labelFramerate
//
this->labelFramerate->AutoSize = true;
this->labelFramerate->Location =
System::Drawing::Point(21, 135);
this->labelFramerate->Name = L"labelFramerate";
this->labelFramerate->Size = System::Drawing::Size(16,
13);

this->labelFramerate->TabIndex = 4;
this->labelFramerate->Text = L"---";
//
// timer1
//
this->timer1->Tick += gcnew System::EventHandler(this,
&FormMain::timer1_Tick);
//
// labelTempChip
//
this->labelTempChip->AutoSize = true;
this->labelTempChip->ForeColor =
System::Drawing::Color::Red;
this->labelTempChip->Location =
System::Drawing::Point(21, 180);
this->labelTempChip->Name = L"labelTempChip";
this->labelTempChip->Size = System::Drawing::Size(61,
13);

this->labelTempChip->TabIndex = 5;
this->labelTempChip->Text = L"Chip-Temp";
//
// labelTempFlag
//
this->labelTempFlag->AutoSize = true;
this->labelTempFlag->ForeColor =
System::Drawing::Color::Green;
this->labelTempFlag->Location =
System::Drawing::Point(21, 195);
this->labelTempFlag->Name = L"labelTempFlag";
this->labelTempFlag->Size = System::Drawing::Size(60,
13);

this->labelTempFlag->TabIndex = 6;
this->labelTempFlag->Text = L"Flag-Temp";
//
// pictureBox
//
this->pictureBox->Dock =
System::Windows::Forms::DockStyle::Fill;
this->pictureBox->Location = System::Drawing::Point(3,
16);

this->pictureBox->Name = L"pictureBox";

```



```

        this->pictureBox->Size = System::Drawing::Size(194,
121);
        this->pictureBox->TabIndex = 8;
        this->pictureBox->TabStop = false;
        this->pictureBox->Paint += gcnew
System::Windows::Forms::PaintEventHandler(this,
&FormMain::pictureBox_Paint);
        //
        // groupBoxOptics
        //
        this->groupBoxOptics->Controls->Add(this-
>labelTempAmbient);
        this->groupBoxOptics->Controls->Add(this-
>labelEmissivity);
        this->groupBoxOptics->Controls->Add(this-
>numericUpDownTempAmbient);
        this->groupBoxOptics->Controls->Add(this-
>numericUpDownEmissivity);
        this->groupBoxOptics->Controls->Add(this-
>comboBoxTempRange);
        this->groupBoxOptics->Controls->Add(this-
>comboBoxOptics);
        this->groupBoxOptics->Controls->Add(this-
>labelTempRange);
        this->groupBoxOptics->Controls->Add(this-
>labelOpticsFOV);
        this->groupBoxOptics->Location =
System::Drawing::Point(281, 289);
        this->groupBoxOptics->Name = L"groupBoxOptics";
        this->groupBoxOptics->Size = System::Drawing::Size(200,
102);
        this->groupBoxOptics->TabIndex = 13;
        this->groupBoxOptics->TabStop = false;
        //
        // labelTempAmbient
        //
        this->labelTempAmbient->AutoSize = true;
        this->labelTempAmbient->Location =
System::Drawing::Point(92, 69);
        this->labelTempAmbient->Name = L"labelTempAmbient";
        this->labelTempAmbient->Size =
System::Drawing::Size(41, 13);
        this->labelTempAmbient->TabIndex = 84;
        this->labelTempAmbient->Text = L"TAmb.";
        //
        // labelEmissivity
        //
        this->labelEmissivity->AutoSize = true;
        this->labelEmissivity->Location =
System::Drawing::Point(6, 69);
        this->labelEmissivity->Name = L"labelEmissivity";
        this->labelEmissivity->Size = System::Drawing::Size(31,
13);
        this->labelEmissivity->TabIndex = 84;
        this->labelEmissivity->Text = L"Eps.";
        //
        // numericUpDownTempAmbient
        //
        this->numericUpDownTempAmbient->DecimalPlaces = 1;
        this->numericUpDownTempAmbient->Increment =
System::Decimal(gcnew cli::array< System::Int32 >(4) {1, 0, 0, 65536});
        this->numericUpDownTempAmbient->Location =
System::Drawing::Point(134, 67);
        this->numericUpDownTempAmbient->Maximum =

```

```

System::Decimal(gcnew cli::array< System::Int32 >(4) {200, 0, 0, 0});
    this->numericUpDownTempAmbient->Minimum =
System::Decimal(gcnew cli::array< System::Int32 >(4) {40, 0, 0,
System::Int32::MinValue});
    this->numericUpDownTempAmbient->Name =
L"numericUpDownTempAmbient";
    this->numericUpDownTempAmbient->Size =
System::Drawing::Size(60, 20);
    this->numericUpDownTempAmbient->TabIndex = 83;
    this->numericUpDownTempAmbient->Value =
System::Decimal(gcnew cli::array< System::Int32 >(4) {23, 0, 0, 0});
    this->numericUpDownTempAmbient->ValueChanged += gcnew
System::EventHandler(this,
&FormMain::numericUpDownTempAmbient_ValueChanged);
    //
    // numericUpDownEmissivity
    //
    this->numericUpDownEmissivity->DecimalPlaces = 3;
    this->numericUpDownEmissivity->Increment =
System::Decimal(gcnew cli::array< System::Int32 >(4) {1, 0, 0, 196608});
    this->numericUpDownEmissivity->Location =
System::Drawing::Point(43, 67);
    this->numericUpDownEmissivity->Maximum =
System::Decimal(gcnew cli::array< System::Int32 >(4) {11, 0, 0, 65536});
    this->numericUpDownEmissivity->Minimum =
System::Decimal(gcnew cli::array< System::Int32 >(4) {1, 0, 0, 65536});
    this->numericUpDownEmissivity->Name =
L"numericUpDownEmissivity";
    this->numericUpDownEmissivity->Size =
System::Drawing::Size(48, 20);
    this->numericUpDownEmissivity->TabIndex = 83;
    this->numericUpDownEmissivity->Value =
System::Decimal(gcnew cli::array< System::Int32 >(4) {10, 0, 0, 65536});
    this->numericUpDownEmissivity->ValueChanged += gcnew
System::EventHandler(this,
&FormMain::numericUpDownEmissivity_ValueChanged);
    //
    // comboBoxTempRange
    //
    this->comboBoxTempRange->FormattingEnabled = true;
    this->comboBoxTempRange->Location =
System::Drawing::Point(81, 40);
    this->comboBoxTempRange->Name = L"comboBoxTempRange";
    this->comboBoxTempRange->Size =
System::Drawing::Size(113, 21);
    this->comboBoxTempRange->TabIndex = 67;
    this->comboBoxTempRange->SelectedIndexChanged += gcnew
System::EventHandler(this,
&FormMain::comboBoxTempRange_SelectedIndexChanged);
    //
    // comboBoxOptics
    //
    this->comboBoxOptics->FormattingEnabled = true;
    this->comboBoxOptics->Location =
System::Drawing::Point(81, 13);
    this->comboBoxOptics->Name = L"comboBoxOptics";
    this->comboBoxOptics->Size = System::Drawing::Size(113,
21);
    this->comboBoxOptics->TabIndex = 67;
    this->comboBoxOptics->SelectedIndexChanged += gcnew
System::EventHandler(this,
&FormMain::comboBoxOptics_SelectedIndexChanged);
    //
    // labelTempRange

```

```

//
this->labelTempRange->AutoSize = true;
this->labelTempRange->Location
System::Drawing::Point(6, 43);
this->labelTempRange->Name = L"labelTempRange";
this->labelTempRange->Size = System::Drawing::Size(70,
13);

this->labelTempRange->TabIndex = 60;
this->labelTempRange->Text = L"Temp. range:";
//
// labelOpticsFOV
//
this->labelOpticsFOV->AutoSize = true;
this->labelOpticsFOV->Location
System::Drawing::Point(6, 16);
this->labelOpticsFOV->Name = L"labelOpticsFOV";
this->labelOpticsFOV->Size = System::Drawing::Size(40,
13);

this->labelOpticsFOV->TabIndex = 59;
this->labelOpticsFOV->Text = L"Optics:";
//
// labelVersionAppl
//
this->labelVersionAppl->AutoSize = true;
this->labelVersionAppl->Location
System::Drawing::Point(23, 240);
this->labelVersionAppl->Name = L"labelVersionAppl";
this->labelVersionAppl->Size
System::Drawing::Size(59, 13);
this->labelVersionAppl->TabIndex = 27;
this->labelVersionAppl->Text = L"Host-Appl.";
//
// timer2
//
this->timer2->Enabled = true;
this->timer2->Interval = 200;
this->timer2->Tick += gcnew System::EventHandler(this,
&FormMain::timer2_Tick);
//
// labelVersionIPC
//
this->labelVersionIPC->AutoSize = true;
this->labelVersionIPC->Location
System::Drawing::Point(23, 255);
this->labelVersionIPC->Name = L"labelVersionIPC";
this->labelVersionIPC->Size = System::Drawing::Size(40,
13);

this->labelVersionIPC->TabIndex = 29;
this->labelVersionIPC->Text = L"IPC-dll:";
//
// labelTempTarget
//
this->labelTempTarget->AutoSize = true;
this->labelTempTarget->Font = (gcnew
System::Drawing::Font(L"Microsoft Sans Serif", 8.25F,
System::Drawing::FontStyle::Regular,
System::Drawing::GraphicsUnit::Point,
static_cast<System::Byte>(0)));
this->labelTempTarget->ForeColor
System::Drawing::Color::Blue;
this->labelTempTarget->Location
System::Drawing::Point(21, 225);
this->labelTempTarget->Name = L"labelTempTarget";
this->labelTempTarget->Size = System::Drawing::Size(71,

```



```

13);
    this->labelTempTarget->TabIndex = 32;
    this->labelTempTarget->Text = L"Target-Temp:";
    //
    // labelTempBox
    //
    this->labelTempBox->AutoSize = true;
    this->labelTempBox->ForeColor
System::Drawing::Color::Magenta;
    this->labelTempBox->Location
System::Drawing::Point(21, 210);
    this->labelTempBox->Name = L"labelTempBox";
    this->labelTempBox->Size = System::Drawing::Size(58,
13);
    this->labelTempBox->TabIndex = 30;
    this->labelTempBox->Text = L"Box-Temp:";
    //
    // buttonFlagOpen
    //
    this->buttonFlagOpen->Location
System::Drawing::Point(16, 16);
    this->buttonFlagOpen->Name = L"buttonFlagOpen";
    this->buttonFlagOpen->Size = System::Drawing::Size(48,
23);
    this->buttonFlagOpen->TabIndex = 34;
    this->buttonFlagOpen->Text = L"Open";
    this->buttonFlagOpen->UseVisualStyleBackColor = true;
    this->buttonFlagOpen->Click += gcnew
System::EventHandler(this, &FormMain::buttonFlagOpen_Click);
    //
    // groupBoxRangeMode
    //
    this->groupBoxRangeMode->Controls->Add(this-
>checkBoxColors);
    this->groupBoxRangeMode->Controls->Add(this-
>radioButtonRangeMinMax);
    this->groupBoxRangeMode->Controls->Add(this-
>radioButtonRange3Sigma);
    this->groupBoxRangeMode->Controls->Add(this-
>radioButtonRange1Sigma);
    this->groupBoxRangeMode->Location
System::Drawing::Point(281, 153);
    this->groupBoxRangeMode->Name = L"groupBoxRangeMode";
    this->groupBoxRangeMode->Size
System::Drawing::Size(200, 75);
    this->groupBoxRangeMode->TabIndex = 57;
    this->groupBoxRangeMode->TabStop = false;
    this->groupBoxRangeMode->Text = L"Display range";
    //
    // checkBoxColors
    //
    this->checkBoxColors->AutoSize = true;
    this->checkBoxColors->Location
System::Drawing::Point(16, 47);
    this->checkBoxColors->Name = L"checkBoxColors";
    this->checkBoxColors->Size = System::Drawing::Size(55,
17);
    this->checkBoxColors->TabIndex = 1;
    this->checkBoxColors->Text = L"Colors";
    this->checkBoxColors->UseVisualStyleBackColor = true;
    //
    // radioButtonRangeMinMax
    //
    this->radioButtonRangeMinMax->AutoSize = true;

```

```

        this->radioButtonRangeMinMax->Location =
System::Drawing::Point(16, 16);
        this->radioButtonRangeMinMax->Name =
L"radioButtonRangeMinMax";
        this->radioButtonRangeMinMax->Size =
System::Drawing::Size(48, 17);
        this->radioButtonRangeMinMax->TabIndex = 0;
        this->radioButtonRangeMinMax->TabStop = true;
        this->radioButtonRangeMinMax->Text = L"< / >";
        this->radioButtonRangeMinMax->UseVisualStyleBackColor =
true;

        //
        // radioButtonRange3Sigma
        //
        this->radioButtonRange3Sigma->AutoSize = true;
        this->radioButtonRange3Sigma->Location =
System::Drawing::Point(134, 16);
        this->radioButtonRange3Sigma->Name =
L"radioButtonRange3Sigma";
        this->radioButtonRange3Sigma->Size =
System::Drawing::Size(63, 17);
        this->radioButtonRange3Sigma->TabIndex = 0;
        this->radioButtonRange3Sigma->TabStop = true;
        this->radioButtonRange3Sigma->Text = L"3 Sigma";
        this->radioButtonRange3Sigma->UseVisualStyleBackColor =
true;

        //
        // radioButtonRange1Sigma
        //
        this->radioButtonRange1Sigma->AutoSize = true;
        this->radioButtonRange1Sigma->Location =
System::Drawing::Point(70, 16);
        this->radioButtonRange1Sigma->Name =
L"radioButtonRange1Sigma";
        this->radioButtonRange1Sigma->Size =
System::Drawing::Size(63, 17);
        this->radioButtonRange1Sigma->TabIndex = 0;
        this->radioButtonRange1Sigma->TabStop = true;
        this->radioButtonRange1Sigma->Text = L"1 Sigma";
        this->radioButtonRange1Sigma->UseVisualStyleBackColor =
true;

        //
        // groupBoxFlag
        //
        this->groupBoxFlag->Controls->Add(this-
>buttonFlagRenew);
        this->groupBoxFlag->Controls->Add(this-
>buttonFlagClose);
        this->groupBoxFlag->Controls->Add(this-
>buttonFlagOpen);
        this->groupBoxFlag->Location =
System::Drawing::Point(281, 232);
        this->groupBoxFlag->Name = L"groupBoxFlag";
        this->groupBoxFlag->Size = System::Drawing::Size(200,
51);

        this->groupBoxFlag->TabIndex = 65;
        this->groupBoxFlag->TabStop = false;
        this->groupBoxFlag->Text = L"Flag";
        //
        // buttonFlagRenew
        //
        this->buttonFlagRenew->Location =
System::Drawing::Point(124, 16);
        this->buttonFlagRenew->Name = L"buttonFlagRenew";

```

```

        this->buttonFlagRenew->Size = System::Drawing::Size(60,
23);
        this->buttonFlagRenew->TabIndex = 35;
        this->buttonFlagRenew->Text = L"Renew";
        this->buttonFlagRenew->UseVisualStyleBackColor = true;
        this->buttonFlagRenew->Click += gcnnew
System::EventHandler(this, &FormMain::buttonFlagRenew_Click);
        //
        // buttonFlagClose
        //
        this->buttonFlagClose->Location =
System::Drawing::Point(70, 16);
        this->buttonFlagClose->Name = L"buttonFlagClose";
        this->buttonFlagClose->Size = System::Drawing::Size(48,
23);
        this->buttonFlagClose->TabIndex = 34;
        this->buttonFlagClose->Text = L"Close";
        this->buttonFlagClose->UseVisualStyleBackColor = true;
        this->buttonFlagClose->Click += gcnnew
System::EventHandler(this, &FormMain::buttonFlagClose_Click);
        //
        // groupBoxVideo
        //
        this->groupBoxVideo->Controls->Add(this->pictureBox);
        this->groupBoxVideo->Location =
System::Drawing::Point(281, 7);
        this->groupBoxVideo->Name = L"groupBoxVideo";
        this->groupBoxVideo->Size = System::Drawing::Size(200,
140);
        this->groupBoxVideo->TabIndex = 66;
        this->groupBoxVideo->TabStop = false;
        //
        // groupBoxMeasureAreas
        //
        this->groupBoxMeasureAreas->Location =
System::Drawing::Point(24, 329);
        this->groupBoxMeasureAreas->Name =
L"groupBoxMeasureAreas";
        this->groupBoxMeasureAreas->Size =
System::Drawing::Size(130, 30);
        this->groupBoxMeasureAreas->TabIndex = 67;
        this->groupBoxMeasureAreas->TabStop = false;
        this->groupBoxMeasureAreas->Text = L"Measure areas:";
        //
        // textBoxInstanceName
        //
        this->textBoxInstanceName->Location =
System::Drawing::Point(107, 20);
        this->textBoxInstanceName->Name =
L"textBoxInstanceName";
        this->textBoxInstanceName->Size =
System::Drawing::Size(168, 20);
        this->textBoxInstanceName->TabIndex = 71;
        this->textBoxInstanceName->TextChanged += gcnnew
System::EventHandler(this, &FormMain::textBoxInstanceName_TextChanged);
        //
        // labelInstanceName
        //
        this->labelInstanceName->AutoSize = true;
        this->labelInstanceName->Location =
System::Drawing::Point(21, 23);
        this->labelInstanceName->Name = L"labelInstanceName";
        this->labelInstanceName->Size =
System::Drawing::Size(80, 13);

```



```

        this->labelInstanceName->TabIndex = 70;
        this->labelInstanceName->Text = L"Instance name:";
        //
        // buttonKill
        //
        this->buttonKill->Location =
System::Drawing::Point(182, 46);
        this->buttonKill->Name = L"buttonKill";
        this->buttonKill->Size = System::Drawing::Size(93, 27);
        this->buttonKill->TabIndex = 72;
        this->buttonKill->Text = L"Close Host-Appl.";
        this->buttonKill->UseVisualStyleBackColor = true;
        this->buttonKill->Click += gcnew
System::EventHandler(this, &FormMain::buttonKill_Click);
        //
        // progressBarInit
        //
        this->progressBarInit->Location =
System::Drawing::Point(24, 163);
        this->progressBarInit->Name = L"progressBarInit";
        this->progressBarInit->Size =
System::Drawing::Size(251, 14);
        this->progressBarInit->TabIndex = 74;
        this->progressBarInit->Visible = false;
        //
        // checkBoxDock
        //
        this->checkBoxDock->AutoSize = true;
        this->checkBoxDock->Location =
System::Drawing::Point(281, 455);
        this->checkBoxDock->Name = L"checkBoxDock";
        this->checkBoxDock->Size = System::Drawing::Size(133,
17);
        this->checkBoxDock->TabIndex = 75;
        this->checkBoxDock->Text = L"Dock Main Application";
        this->checkBoxDock->UseVisualStyleBackColor = true;
        this->checkBoxDock->CheckedChanged += gcnew
System::EventHandler(this, &FormMain::checkBoxDock_CheckedChanged);
        //
        // groupBoxHostAppl
        //
        this->groupBoxHostAppl->Location =
System::Drawing::Point(487, 12);
        this->groupBoxHostAppl->Name = L"groupBoxHostAppl";
        this->groupBoxHostAppl->Size =
System::Drawing::Size(360, 379);
        this->groupBoxHostAppl->TabIndex = 76;
        this->groupBoxHostAppl->TabStop = false;
        this->groupBoxHostAppl->Text = L"Host application";
        //
        // labelHW
        //
        this->labelHW->AutoSize = true;
        this->labelHW->Location = System::Drawing::Point(179,
240);
        this->labelHW->Name = L"labelHW";
        this->labelHW->Size = System::Drawing::Size(29, 13);
        this->labelHW->TabIndex = 27;
        this->labelHW->Text = L"HW:";
        //
        // labelFW
        //
        this->labelFW->AutoSize = true;
        this->labelFW->Location = System::Drawing::Point(179,

```

```

255);

        this->labelFW->Name = L"labelFW";
        this->labelFW->Size = System::Drawing::Size(27, 13);
        this->labelFW->TabIndex = 29;
        this->labelFW->Text = L"FW:";
        //
        // button1
        //
        this->button1->AutoSize = true;
        this->button1->Font = (gcnew
System::Drawing::Font(L"Microsoft Sans Serif", 7,
System::Drawing::FontStyle::Regular,
System::Drawing::GraphicsUnit::Point,
        static_cast<System::Byte>(0)));
        this->button1->Location = System::Drawing::Point(232,
112);

        this->button1->Name = L"button1";
        this->button1->Size = System::Drawing::Size(40, 23);
        this->button1->TabIndex = 77;
        this->button1->Text = L"reset";
        this->button1->UseVisualStyleBackColor = true;
        this->button1->Click += (gcnew
System::EventHandler(this, &FormMain::button1_Click));
        //
        // groupBoxFile
        //
        this->groupBoxFile->Controls->Add(this->toolStripFile);
        this->groupBoxFile->Location =
System::Drawing::Point(281, 397);
        this->groupBoxFile->Name = L"groupBoxFile";
        this->groupBoxFile->Size = System::Drawing::Size(200,
48);

        this->groupBoxFile->TabIndex = 80;
        this->groupBoxFile->TabStop = false;
        this->groupBoxFile->Text = L"File";
        //
        // toolStripFile
        //
        this->toolStripFile->CanOverflow = false;
        this->toolStripFile->Items->AddRange(gcnew cli::array<
System::Windows::Forms::ToolStripItem^ >(6) {this->toolStripButtonOpen,
        this->toolStripButtonPlay, this->
>toolStripButtonPause, this->toolStripButtonStop, this->
>toolStripButtonRecord, this->toolStripButtonSnapshot});
        this->toolStripFile->LayoutStyle =
System::Windows::Forms::ToolStripLayoutStyle::Flow;
        this->toolStripFile->Location =
System::Drawing::Point(3, 16);
        this->toolStripFile->Name = L"toolStripFile";
        this->toolStripFile->Size = System::Drawing::Size(194,
23);

        this->toolStripFile->TabIndex = 0;
        this->toolStripFile->Text = L"toolStrip1";
        //
        // toolStripButtonOpen
        //
        this->toolStripButtonOpen->DisplayStyle =
System::Windows::Forms::ToolStripItemDisplayStyle::Image;
        this->toolStripButtonOpen->Image =
(cli::safe_cast<System::Drawing::Image^ >(resources->
GetObject(L"toolStripButtonOpen.Image")));
        this->toolStripButtonOpen->ImageTransparentColor =
System::Drawing::Color::Magenta;
        this->toolStripButtonOpen->Name =

```

```

L"toolStripButtonOpen";
    this->toolStripButtonOpen->Size =
System::Drawing::Size(23, 20);
    this->toolStripButtonOpen->Text = L"Open";
    this->toolStripButtonOpen->Click += gcnew
System::EventHandler(this, &FormMain::toolStripButtonOpen_Click);
    //
    // toolStripButtonPlay
    //
    this->toolStripButtonPlay->DisplayStyle =
System::Windows::Forms::ToolStripItemDisplayStyle::Image;
    this->toolStripButtonPlay->Image =
(cli::safe_cast<System::Drawing::Image^>(>(resources-
>GetObject(L"toolStripButtonPlay.Image"))));
    this->toolStripButtonPlay->ImageTransparentColor =
System::Drawing::Color::Magenta;
    this->toolStripButtonPlay->Name =
L"toolStripButtonPlay";
    this->toolStripButtonPlay->Size =
System::Drawing::Size(23, 20);
    this->toolStripButtonPlay->Text = L"Play";
    this->toolStripButtonPlay->Click += gcnew
System::EventHandler(this, &FormMain::toolStripButtonPlay_Click);
    //
    // toolStripButtonPause
    //
    this->toolStripButtonPause->DisplayStyle =
System::Windows::Forms::ToolStripItemDisplayStyle::Image;
    this->toolStripButtonPause->Image =
(cli::safe_cast<System::Drawing::Image^>(>(resources-
>GetObject(L"toolStripButtonPause.Image"))));
    this->toolStripButtonPause->ImageTransparentColor =
System::Drawing::Color::Magenta;
    this->toolStripButtonPause->Name =
L"toolStripButtonPause";
    this->toolStripButtonPause->Size =
System::Drawing::Size(23, 20);
    this->toolStripButtonPause->Text = L"Pause";
    this->toolStripButtonPause->Click += gcnew
System::EventHandler(this, &FormMain::toolStripButtonPause_Click);
    //
    // toolStripButtonStop
    //
    this->toolStripButtonStop->DisplayStyle =
System::Windows::Forms::ToolStripItemDisplayStyle::Image;
    this->toolStripButtonStop->Image =
(cli::safe_cast<System::Drawing::Image^>(>(resources-
>GetObject(L"toolStripButtonStop.Image"))));
    this->toolStripButtonStop->ImageTransparentColor =
System::Drawing::Color::Magenta;
    this->toolStripButtonStop->Name =
L"toolStripButtonStop";
    this->toolStripButtonStop->Size =
System::Drawing::Size(23, 20);
    this->toolStripButtonStop->Text = L"Stop";
    this->toolStripButtonStop->Click += gcnew
System::EventHandler(this, &FormMain::toolStripButtonStop_Click);
    //
    // toolStripButtonRecord
    //
    this->toolStripButtonRecord->DisplayStyle =
System::Windows::Forms::ToolStripItemDisplayStyle::Image;
    this->toolStripButtonRecord->Image =
(cli::safe_cast<System::Drawing::Image^>(>(resources-

```



```

>GetObject(L"toolStripButtonRecord.Image"));
    this->toolStripButtonRecord->ImageTransparentColor =
System::Drawing::Color::Magenta;
    this->toolStripButtonRecord->Name =
L"toolStripButtonRecord";
    this->toolStripButtonRecord->Size =
System::Drawing::Size(23, 20);
    this->toolStripButtonRecord->Text = L"Record";
    this->toolStripButtonRecord->Click += gcnew
System::EventHandler(this, &FormMain::toolStripButtonRecord_Click);
    //
    // toolStripButtonSnapshot
    //
    this->toolStripButtonSnapshot->DisplayStyle =
System::Windows::Forms::ToolStripItemDisplayStyle::Image;
    this->toolStripButtonSnapshot->Image =
(cli::safe_cast<System::Drawing::Image^>(resources-
>GetObject(L"toolStripButtonSnapshot.Image"))));
    this->toolStripButtonSnapshot->ImageTransparentColor =
System::Drawing::Color::Magenta;
    this->toolStripButtonSnapshot->Name =
L"toolStripButtonSnapshot";
    this->toolStripButtonSnapshot->Size =
System::Drawing::Size(23, 20);
    this->toolStripButtonSnapshot->Text = L"Snapshot";
    this->toolStripButtonSnapshot->Click += gcnew
System::EventHandler(this, &FormMain::toolStripButtonSnapshot_Click);
    //
    // labelFrameCounter
    //
    this->labelFrameCounter->AutoSize = true;
    this->labelFrameCounter->Location =
System::Drawing::Point(23, 270);
    this->labelFrameCounter->Name = L"labelFrameCounter";
    this->labelFrameCounter->Size =
System::Drawing::Size(123, 13);
    this->labelFrameCounter->TabIndex = 81;
    this->labelFrameCounter->Text = L"Frame counter
HW/SW:";
    //
    // labelPIF
    //
    this->labelPIF->AutoSize = true;
    this->labelPIF->Location = System::Drawing::Point(23,
285);
    this->labelPIF->Name = L"labelPIF";
    this->labelPIF->Size = System::Drawing::Size(93, 13);
    this->labelPIF->TabIndex = 82;
    this->labelPIF->Text = L"PIF digital/analog:";
    //
    // labelFlag1
    //
    this->labelFlag1->AutoSize = true;
    this->labelFlag1->Location = System::Drawing::Point(23,
302);
    this->labelFlag1->Name = L"labelFlag1";
    this->labelFlag1->Size = System::Drawing::Size(30, 13);
    this->labelFlag1->TabIndex = 82;
    this->labelFlag1->Text = L"Flag:";
    //
    // labelFlag
    //
    this->labelFlag->AutoSize = true;
    this->labelFlag->Location = System::Drawing::Point(59,

```

```

302);

    this->labelFlag->Name = L"labelFlag";
    this->labelFlag->Size = System::Drawing::Size(31, 13);
    this->labelFlag->TabIndex = 82;
    this->labelFlag->Text = L"open";
    //
    // FormMain
    //
    this->AutoScaleDimensions = System::Drawing::SizeF(6,
13);

    this->AutoScaleMode =
System::Windows::Forms::AutoScaleMode::Font;
    this->ClientSize = System::Drawing::Size(859, 484);
    this->Controls->Add(this->labelFlag);
    this->Controls->Add(this->labelFlag1);
    this->Controls->Add(this->labelPIF);
    this->Controls->Add(this->labelFrameCounter);
    this->Controls->Add(this->groupBoxFile);
    this->Controls->Add(this->button1);
    this->Controls->Add(this->groupBoxHostAppl);
    this->Controls->Add(this->checkBoxDock);
    this->Controls->Add(this->progressBarInit);
    this->Controls->Add(this->buttonKill);
    this->Controls->Add(this->textBoxInstanceName);
    this->Controls->Add(this->labelInstanceName);
    this->Controls->Add(this->groupBoxMeasureAreas);
    this->Controls->Add(this->groupBoxVideo);
    this->Controls->Add(this->groupBoxFlag);
    this->Controls->Add(this->groupBoxRangeMode);
    this->Controls->Add(this->labelTempTarget);
    this->Controls->Add(this->labelTempBox);
    this->Controls->Add(this->labelFW);
    this->Controls->Add(this->labelVersionIPC);
    this->Controls->Add(this->labelHW);
    this->Controls->Add(this->labelVersionAppl);
    this->Controls->Add(this->groupBoxOptics);
    this->Controls->Add(this->labelTempFlag);
    this->Controls->Add(this->labelTempChip);
    this->Controls->Add(this->labelFramerate);
    this->Controls->Add(this->label2);
    this->Controls->Add(this->label1);
    this->Icon = (cli::safe_cast<System::Drawing::Icon^
>(resources->GetObject(L"$this.Icon")));
    this->Name = L"FormMain";
    this->Text = L"Imager IPC Sample Application";
    this->Load += gcnew System::EventHandler(this,
&FormMain::FormMain_Load);
    this->Move += gcnew System::EventHandler(this,
&FormMain::FormMain_Move);
    this->FormClosing +=
System::Windows::Forms::FormClosingEventHandler(this,
&FormMain::FormMain_FormClosing);
    this->Resize += gcnew System::EventHandler(this,
&FormMain::FormMain_Resize);

    (cli::safe_cast<System::ComponentModel::ISupportInitialize^
>(this->pictureBox))->EndInit();
    this->groupBoxOptics->ResumeLayout(false);
    this->groupBoxOptics->PerformLayout();

    (cli::safe_cast<System::ComponentModel::ISupportInitialize^
>(this->numericUpDownTempAmbient))->EndInit();

    (cli::safe_cast<System::ComponentModel::ISupportInitialize^

```



```

>(this->numericUpDownEmissivity))->EndInit();
    this->groupBoxRangeMode->ResumeLayout(false);
    this->groupBoxRangeMode->PerformLayout();
    this->groupBoxFlag->ResumeLayout(false);
    this->groupBoxVideo->ResumeLayout(false);
    this->groupBoxFile->ResumeLayout(false);
    this->groupBoxFile->PerformLayout();
    this->toolStripFile->ResumeLayout(false);
    this->toolStripFile->PerformLayout();
    this->ResumeLayout(false);
    this->PerformLayout();
}
#pragma endregion
protected:
    void AppInit(void);
    void AppExit(void);
    void InitIPC(void);
    void ReleaseIPC(void);
    HRESULT MainTimer100ms(void);
    HRESULT MainTimer1000ms(void);
    void GetSoftwareInfo(void);
    void GetDeviceInfo(void);
    void GetDeviceSetup(void);
    void GetOptics(void);
    void GetTempRanges(void);
    void SetOpticsIndex(void);
    void SetTempRangeIndex(void);
    void RenewFlag(void);
    void SetFlag(bool flag);
    void SetEmissivity(void);
    void SetTempAmbient(void);
    void Init(int frameWidth, int frameHeight, int frameDepth);
    void InitMeasureAreas(void);
    void UpdateSize(void);
    void ResizeHostAppl(void);
    HRESULT NewFrame(short *ImgBuf, int frameCounter);
    void FileOpen(void);

    HRESULT OnServerStopped(int reason);
    HRESULT OnFrameInit(int frameWidth, int frameHeight, int
frameDepth);
    HRESULT OnNewFrameEx(void * pBuffer, FrameMetadata *pMetadata);
    HRESULT OnNewFrame(char * pBuffer, int frameCounter);
    HRESULT OnInitCompleted(void);
    HRESULT OnConfigChanged(long reserved);
    HRESULT OnFileCommandReady(wchar_t *path);

private:    System::Void    FormMain_Load(System::Object^    sender,
System::EventArgs^ e) {AppInit(); }
private:    System::Void    timer1_Tick(System::Object^    sender,
System::EventArgs^ e)
    {
        MainTimerDivider++;
        MainTimer100ms();
        if(!(MainTimerDivider%20)) MainTimer1000ms();
    }
private:    System::Void    FormMain_FormClosing(System::Object^    sender,
System::Windows::Forms::FormClosingEventArgs^ e) { AppExit(); }
private:    System::Void    timer2_Tick(System::Object^    sender,
System::EventArgs^ e) {    if (!ipcInitialized) InitIPC(); }
private:    System::Void    pictureBox_Paint(System::Object^    sender,
System::Windows::Forms::PaintEventArgs^ e) {    e->Graphics->DrawImage(
bmp, 0, 0); }

```



```

private: System::Void comboBoxOptics_SelectedIndexChanged(System::Object^
sender, System::EventArgs^ e) { SetOpticsIndex(); }
private: System::Void comboBoxTempRange_SelectedIndexChanged(System::Object^
sender,
System::EventArgs^ e) { SetTempRangeIndex(); }
private: System::Void buttonFlagOpen_Click(System::Object^ sender,
System::EventArgs^ e) { SetFlag(false); }
private: System::Void buttonFlagClose_Click(System::Object^ sender,
System::EventArgs^ e) { SetFlag(true); }
private: System::Void buttonFlagRenew_Click(System::Object^ sender,
System::EventArgs^ e) { RenewFlag(); }
private: System::Void numericUpDownEmissivity_ValueChanged(System::Object^
sender,
System::EventArgs^ e) { SetEmissivity(); }
private: System::Void numericUpDownTempAmbient_ValueChanged(System::Object^
sender,
System::EventArgs^ e) { SetTempAmbient(); }
private: System::Void buttonInit_Click(System::Object^ sender,
System::EventArgs^ e) {};

private: System::Void textBoxInstanceName_TextChanged(System::Object^
sender, System::EventArgs^ e) ;
private: System::Void buttonKill_Click(System::Object^ sender,
System::EventArgs^ e) { if(ipc) ipc->CloseApplication(0); };
private: System::Void FormMain_Resize(System::Object^ sender,
System::EventArgs^ e) { ResizeHostAppl(); }
private: System::Void FormMain_Move(System::Object^ sender,
System::EventArgs^ e) { ResizeHostAppl(); }
private: System::Void checkBoxDock_CheckedChanged(System::Object^
sender, System::EventArgs^ e);
private: System::Void checkBoxBuffered_CheckedChanged(System::Object^
sender, System::EventArgs^ e) { ReleaseIPC(); };
private: System::Void button1_Click(System::Object^ sender,
System::EventArgs^ e) { ResetPending = true; }
private: System::Void buttonSnapshot_Click(System::Object^ sender,
System::EventArgs^ e) { }
private: System::Void buttonRecord_Click(System::Object^ sender,
System::EventArgs^ e) { }
private: System::Void buttonStop_Click(System::Object^ sender,
System::EventArgs^ e) { }
private: System::Void buttonOpen_Click(System::Object^ sender,
System::EventArgs^ e) { }
private: System::Void toolStripButtonOpen_Click(System::Object^ sender,
System::EventArgs^ e) { FileOpen(); }
private: System::Void toolStripButtonPlay_Click(System::Object^ sender,
System::EventArgs^ e) { if(ipc) ipc->FilePlay(0); }
private: System::Void toolStripButtonPause_Click(System::Object^ sender,
System::EventArgs^ e) { if(ipc) ipc->FilePause(0); }
private: System::Void toolStripButtonStop_Click(System::Object^ sender,
System::EventArgs^ e) { if(ipc) ipc->FileStop(0); }
private: System::Void toolStripButtonRecord_Click(System::Object^
sender, System::EventArgs^ e) { if(ipc) ipc->FileRecord(0); }
private: System::Void toolStripButtonSnapshot_Click(System::Object^
sender, System::EventArgs^ e) { if(ipc) ipc->FileSnapshot(0); }
};

}

```

9.5.2. FormMain.cpp Code File

```
#include "stdafx.h"
```

```

#include "time.h"
#include "FormMain.h"

namespace IPCSample {

unsigned char clip(int val) { return (val <= 255) ? ((val > 0) ? val : 0) : 255; };

FormMain::FormMain(HWND hostHandle)
{
    InitializeComponent();
    FrameWidth = 0;
    FrameHeight = 0;
    FrameDepth = 0;
    bmp = gcnew Bitmap(100, 100,
System::Drawing::Imaging::PixelFormat::Format24bppRgb );
    ipc = nullptr;
    ipcInitialized = false;
    Connected = false;
    Painted = false;
    radioButtonRange3Sigma->Checked = true;
    MeasureAreaCount = 0;
    Margin = groupBoxVideo->Size - pictureBox->Size;
    FC0 = FC1 = 0;
    AppendLog = false;
    ResetPending = false;
    List = gcnew System::Collections::ArrayList(100);
}

FormMain::~FormMain()
{
    if (components)
        delete components;
}

void FormMain::AppInit(void)
{
    this->Text = this->Text + " (Rel. " + this->Version->ToString() +
    ")";
    Init(160, 120, 2);
    ipc = gcnew IPC(1);
}

System::Void FormMain::textBoxInstanceName_TextChanged(System::Object^
sender, System::EventArgs^ e)
{
    ReleaseIPC();
}

void FormMain::InitIPC(void)
{
    if(ipc && !ipcInitialized)
    {
        HRESULT hr = ipc->Init(0, textBoxInstanceName->Text);

        if(FAILED(hr))
            ipcInitialized = false;
        else
        {
            ipc->OnServerStopped = gcnew
IPC::delOnServerStopped(this, &FormMain::OnServerStopped );
            ipc->SetCallback_OnServerStopped(0, ipc-
>OnServerStopped);
        }
    }
}

```

```

        ipc->OnFrameIRInit = gcnew IPC::delOnFrameInit(this,
&FormMain::OnFrameInit );
        ipc->SetCallback_OnFrameInit(0, ipc->OnFrameIRInit);

        ipc->OnNewFrameIREx = gcnew IPC::delOnNewFrameEx(this,
&FormMain::OnNewFrameEx );
        ipc->SetCallback_OnNewFrameEx(0, ipc->OnNewFrameIREx);

        //ipc->OnNewFrame = gcnew IPC::delOnNewFrame(this,
&FormMain::OnNewFrame );
        //ipc->SetCallback_OnNewFrame(0, ipc->OnNewFrame);

        ipc->OnConfigChanged = gcnew
IPC::delOnConfigChanged(this, &FormMain::OnConfigChanged );
        ipc->SetCallback_OnConfigChanged(0, ipc-
>OnConfigChanged);

        ipc->OnInitCompleted = gcnew
IPC::delOnInitCompleted(this, &FormMain::OnInitCompleted );
        ipc->SetCallback_OnInitCompleted(0, ipc-
>OnInitCompleted);

        ipc->OnFileCommandReady = gcnew
IPC::delOnFileCommandReady(this, &FormMain::OnFileCommandReady );
        ipc->SetCallback_OnFileCommandReady(0, ipc-
>OnFileCommandReady);

        hr = ipc->Run(0);
        ipcInitialized = SUCCEEDED(hr);
        LastFrameTime = DateTime::Now;
        Tmax = 0;
        ResetPending = true;
        FC0 = FC1 = 0;
    }
    labell->Text = hr ? "NOT CONNECTED" : "OK";
}

}

void FormMain::ReleaseIPC(void)
{
    Connected = false;
    if(ipc && ipcInitialized)
    {
        if(OldApplRect)
        {
            ipc->SetMainWindowEmbedded(0, OldEmbeddedState);
            ipc->SetMainWindowRect(0, OldApplRect);
        }
        ipc->Release(0);
        ipcInitialized = false;
    }
}

void FormMain::AppExit(void)
{
    ReleaseIPC();
    delete ipc;
}

void FormMain::GetBitmap(Bitmap^ Bmp, array<short>^values)
{
    int stride_diff;

```



```

        // Lock the bitmap's bits.
        System::Drawing::Rectangle rect = System::Drawing::Rectangle(0, 0,
Bmp->Width, Bmp->Height);
        Imaging::BitmapData^ bmpData = Bmp->LockBits( rect,
Imaging::ImageLockMode::ReadWrite, Bmp->PixelFormat );
        stride_diff = bmpData->Stride - FrameWidth*3;

        // Get the address of the first line.
        IntPtr ptr = bmpData->Scan0;

        if(checkBoxColors->Checked)
        {
            for ( int dst=0, src=0, y=0; y < FrameHeight; y++, dst +=
stride_diff)
                for ( int x=0; x < FrameWidth; x++, src++, dst+=3 )
                {
                    int C = LOBYTE(values[src          ]) - 16;
                    int D = HIBYTE(values[src - (src%2)  ]) - 128;
                    int E = HIBYTE(values[src - (src%2) + 1]) - 128;
                    rgbValues[ dst      ] = clip(( 298 * C + 516 * D
+ 128) >> 8);
                    rgbValues[ dst+1 ] = clip(( 298 * C - 100 * D -
208 * E + 128) >> 8);
                    rgbValues[ dst+2 ] = clip(( 298 * C
+ 409 * E + 128) >> 8);
                }
        }
        else
        {
            short mn, mx;
            GetBitmap_Limits(values, &mn, &mx);
            double Fact = 255.0 / (mx - mn);

            for ( int dst=0, src=0, y=0; y < FrameHeight; y++, dst +=
stride_diff)
                for ( int x=0; x < FrameWidth; x++, src++, dst+=3 )
                    rgbValues[dst] = rgbValues[dst+1] =
rgbValues[dst+2] = min(max((int)(Fact * (values[src] - mn)), 0), 255);
        }

        // Copy the RGB values back to the bitmap
        System::Runtime::InteropServices::Marshal::Copy( rgbValues, 0, ptr,
rgbValues->Length );

        // Unlock the bits.
        Bmp->UnlockBits( bmpData );
    }

void FormMain::GetBitmap_Limits(array<short>^Values, short *min, short
*max)
{
    int y;
    double Sum, Mean, Variance;
    if(!Values) return;

    if(radioButtonRangeMinMax->Checked)
    {
        *min = SHRT_MAX;
        *max = SHRT_MIN;
        for (y=0; y < FrameSize; y++ )
        {
            *min = min(Values[y], *min);
            *max = max(Values[y], *max);
        }
    }
}

```

```

        }
        return;
    }

    Sum = 0;
    for (y=0; y < FrameSize; y++ )
        Sum += Values[y];
    Mean = (double)Sum / FrameSize;
    Sum = 0;
    for (y=0; y < FrameSize; y++ )
        Sum += (Mean - Values[y]) * (Mean - Values[y]);
    Variance = Sum / FrameSize;
    Variance = Math::Sqrt(Variance);
    Variance *= radioButtonRange1Sigma->Checked ? 1: 3;    // 1 or 3
Sigma
    *min = short(Mean - Variance);
    *max = short(Mean + Variance);
}

```

```

HRESULT FormMain::MainTimer100ms(void)
{
    Painted = false;
    if(Connected && progressBarInit->Visible)
    {
        int i = ipc->GetInitCounter(0);
        progressBarInit->Value = progressBarInit->Maximum - i;
        progressBarInit->Visible = (i != 0);
    }
    if(takeSnap < 300) {
        takeSnap += 1;
    }

    if(takeSnap == 300) {
        ipc->FileSnapshot(0);
    }
    return S_OK;
}

```

```

HRESULT FormMain::MainTimer1000ms(void)
{
    double Mean = 0, Sigma = 0, x, last=0;
    IEnumerator^ Enum = List->GetEnumerator();
    while ( Enum->MoveNext() )
    {
        x = safe_cast<double>(Enum->Current);
        Tmax = max(x - last, Tmax);
        last = x;
        Mean += x;
    }
    Mean /= List->Count;
    Enum->Reset();
    while ( Enum->MoveNext() )
        x = Mean - safe_cast<double>(Enum->Current),
        Sigma += x*x;
    Sigma = Math::Sqrt(Sigma / List->Count);
    List->Clear();

    labelFramerate->Text = String::Format(L"{0:0.0}Hz,
\u0394t={1:0.0}ms, \u0394tmax={2:0}ms, \u03C3={3:0.0}ms",

```

```

        1000.0 / Mean, Mean, Tmax, Sigma);

    if(Connected)
    {
        labelTempTarget->Text    =        String::Format("Target-Temp:
{0:##0.0}°C", ipc->GetTempTarget(0));
        labelTempChip->Text      =        String::Format("Chip-Temp:
{0:##0.0}°C", ipc->GetTempChip(0));
        labelTempFlag->Text      =        String::Format("Flag-Temp:
{0:##0.0}°C", ipc->GetTempFlag(0));
        labelTempBox->Text       =        String::Format("Box-Temp:
{0:##0.0}°C", ipc->GetTempBox(0));

        for(int i=0; i < groupBoxMeasureAreas->Controls->Count; i++)
            ((Label^)groupBoxMeasureAreas->Controls->default[i])->
>Text
                = String::Format("Temp[{0}]: {1:##0.0}°C", i,
ipc->GetTempMeasureArea(0, i));
    }

    return S_OK;
}

void FormMain::GetSoftwareInfo(void)
{
    Dev.SoftInfo.Application      =    gcnew    IPCSample::Version(ipc-
>GetVersionApplication(0));
    Dev.SoftInfo.CD_DLL           =    gcnew    IPCSample::Version(ipc-
>GetVersionCD_DLL(0));
    Dev.SoftInfo.HID_DLL          =    gcnew    IPCSample::Version(ipc-
>GetVersionHID_DLL(0));
    Dev.SoftInfo.IPC_DLL          =    gcnew    IPCSample::Version(ipc-
>GetVersionIPC_DLL(0));
}

void FormMain::GetDeviceInfo(void)
{
    GetOptics();
    Dev.Info.HW_Model              = ipc->GetHardware_Model(0);
    Dev.Info.HW_Spec               = ipc->GetHardware_Spec(0);
    Dev.Info.SerialNumber          = ipc->GetSerialNumber(0);
    Dev.Info.SerialNumberULIS      = ipc->GetSerialNumber(0);
    Dev.Info.FW_MSP                = ipc->GetFirmware_MSP(0);
    Dev.Info.FW_Cypress            = ipc->GetFirmware_Cypress(0);
    Dev.Info.PID                  = ipc->GetPID(0);
    Dev.Info.VID                  = ipc->GetVID(0);
    Dev.Info.OpticsFOV             = ipc->GetOpticsFOV(0, ipc-
>GetOpticsIndex(0));
    Dev.Info.TempMinRange          = ipc->GetTempMinRange(0, ipc-
>GetTempRangeIndex(0));
    Dev.Info.TempMaxRange          = ipc->GetTempMaxRange(0, ipc-
>GetTempRangeIndex(0));
    Dev.Info.TempRangeDecimal_CaliValue = ipc->GetTempRangeDecimal(0,
false);
    Dev.Info.TempRangeDecimal_EffValue = ipc->GetTempRangeDecimal(0,
true);
}

void FormMain::GetDeviceSetup(void)
{
    int cnt = ipc->GetOpticsCount(0);
    if(cnt > 0)
        comboBoxOptics->SelectedIndex = Dev.Setup.OpticsIndex =

```



```

ipc->GetOpticsIndex(0);
    else
        comboBoxOptics->SelectedIndex = -1;
    if(ipc->GetTempRangeCount(0) > 0)
        comboBoxTempRange->SelectedIndex= Dev.Setup.TempRangeIndex =
ipc->GetTempRangeIndex(0);
    else
        comboBoxTempRange->SelectedIndex= -1;
    Dev.Setup.FixedEmissivity = ipc->GetFixedEmissivity(0);
    Dev.Setup.FixedTransmissivity = ipc->GetFixedTransmissivity(0);
    Dev.Setup.FixedTempAmbient = ipc->GetFixedTempAmbient(0);
    numericUpDownEmissivity->Value =
Decimal(Dev.Setup.FixedEmissivity);
    numericUpDownTempAmbient->Value =
Decimal(Dev.Setup.FixedTempAmbient);
    MeasureAreaCount = ipc->GetMeasureAreaCount(0);
}

void FormMain::GetOptics(void)
{
    int i, Cnt = ipc->GetOpticsCount(0);

    comboBoxOptics->Items->Clear();
    comboBoxOptics->Text = nullptr;
    for(i=0; i<Cnt; i++)
        comboBoxOptics->Items->Add(String::Format("{0}°", ipc-
>GetOpticsFOV(0, i)));

    i = ipc->GetOpticsIndex(0);
    if(i < Cnt) comboBoxOptics->SelectedIndex = i;
    GetTempRanges();
}

void FormMain::GetTempRanges(void)
{
    int i, Cnt = ipc->GetTempRangeCount(0);

    comboBoxTempRange->Items->Clear();
    comboBoxTempRange->Text = nullptr;
    for(i=0; i<Cnt; i++)
        comboBoxTempRange->Items->Add(String::Format("{0:##0.0}°C ..
{1:##0.0}°C", ipc->GetTempMinRange(0, i), ipc->GetTempMaxRange(0, i)));
    i = ipc->GetTempRangeIndex(0);
    if(i < Cnt) comboBoxTempRange->SelectedIndex = i;
}

void FormMain::SetOpticsIndex(void)
{
    Dev.Setup.OpticsIndex = ipc->SetOpticsIndex(0,
Decimal::ToUInt16(comboBoxOptics->SelectedIndex));
    GetTempRanges();
}

void FormMain::SetTempRangeIndex(void)
{
    Dev.Setup.TempRangeIndex = ipc->SetTempRangeIndex(0,
Decimal::ToUInt16(comboBoxTempRange->SelectedIndex));
}

void FormMain::SetFlag(bool flag)
{
    ipc->SetFlag(0, flag);
}

```

```

void FormMain::RenewFlag(void)
{
    buttonFlagRenew->Text = String::Format("Renew ({0})", ipc-
>RenewFlag(0) ? "Success" : "Failed");
}

void FormMain::SetEmissivity(void)
{
    Dev.Setup.FixedEmissivity = ipc->SetFixedEmissivity(0,
Decimal::ToSingle(numericUpDownEmissivity->Value));
}

void FormMain::SetTempAmbient(void)
{
    Dev.Setup.FixedTempAmbient = ipc->SetFixedTempAmbient(0,
Decimal::ToSingle(numericUpDownTempAmbient->Value));
}

void FormMain::Init(int frameWidth, int frameHeight, int frameDepth)
{
    FrameWidth = frameWidth;
    FrameHeight = frameHeight;
    FrameSize = FrameWidth * FrameHeight;
    FrameRatio = (double)FrameWidth / (double)FrameHeight;
    FrameDepth = frameDepth;
    FrameCounter1 = LastFrameCounter = FC0 = FC1 = 0;
    timer1->Enabled = true;
    bmp = gcnew Bitmap( FrameWidth , FrameHeight ,
System::Drawing::Imaging::PixelFormat::Format24bppRgb );
    System::Drawing::Rectangle rect = System::Drawing::Rectangle(0, 0,
bmp->Width, bmp->Height);
    Imaging::BitmapData^ bmpData = bmp->LockBits( rect,
Imaging::ImageLockMode::ReadWrite, bmp->PixelFormat );
    int stride = bmpData->Stride;
    bmp->UnlockBits( bmpData );
    rgbValues = gcnew array<Byte>(stride * FrameHeight);
    Values = gcnew array<short>(FrameSize);

    groupBoxVideo->Size = Drawing::Size(FrameWidth, FrameHeight) +
Margin;
    groupBoxRangeMode->Top = groupBoxVideo->Bottom + 5;
    groupBoxFlag->Top = groupBoxRangeMode->Bottom + 5;
    groupBoxOptics->Top = groupBoxFlag->Bottom + 5;
    groupBoxFile->Top = groupBoxOptics->Bottom + 5;
    checkBoxDock->Top = groupBoxFile->Bottom + 5;
    UpdateSize();
}

void FormMain::InitMeasureAreas(void)
{
    if(MeasureAreaCount != groupBoxMeasureAreas->Controls->Count)
    {
        groupBoxMeasureAreas->SuspendLayout();
        groupBoxMeasureAreas->Controls->Clear();

        for(int i=0; i < MeasureAreaCount; i++)
        {
            Label^ lbl = gcnew Label();
            lbl->AutoSize = true;
            lbl->Location = System::Drawing::Point(10, i*15 + 16);
            lbl->Name = L"labelMeasureArea" + i.ToString();
            lbl->Text = "";
            groupBoxMeasureAreas->Controls->Add(lbl);
        }
    }
}

```

```

        groupBoxMeasureAreas->Size
Drawing::Size(groupBoxMeasureAreas->Size.Width, MeasureAreaCount * 15 +
20);
        groupBoxMeasureAreas->ResumeLayout();
        UpdateSize();
    }
}

void FormMain::UpdateSize(void)
{
    int right = max(
        groupBoxVideo->Location.X + groupBoxVideo->Size.Width,
        groupBoxRangeMode->Location.X + groupBoxRangeMode-
>Size.Width);
    int bottom = max(
        groupBoxMeasureAreas->Location.Y + groupBoxMeasureAreas-
>Size.Height,
        checkBoxDock->Location.Y + checkBoxDock->Size.Height);

    groupBoxHostAppl->Visible = checkBoxDock->Checked && Connected;
    if(groupBoxHostAppl->Visible)
    {
        groupBoxHostAppl->Location = Drawing::Point(right + 10,
groupBoxVideo->Location.Y);
        groupBoxHostAppl->Size = Drawing::Size(FrameWidth*2 + 20,
FrameHeight*2 + 20);
        right = groupBoxHostAppl->Right;
        if(!OldApplRect)
        {
            Drawing::Rectangle r = ipc->GetMainWindowRect(0);
            OldApplRect = gnew Drawing::Rectangle(r.Location,
r.Size);

            OldEmbeddedState = ipc->GetMainWindowEmbedded(0);
            ipc->SetMainWindowEmbedded(0, true);
        }
    }
    else
    {
        if(OldApplRect)
        {
            ipc->SetMainWindowEmbedded(0, OldEmbeddedState);
            ipc->SetMainWindowRect(0, OldApplRect);
            OldApplRect = nullptr;
        }
    }

    this->Size = Drawing::Size(right + 20, bottom + 50);
}

void FormMain::ResizeHostAppl(void)
{
    if(groupBoxHostAppl->Visible && Connected)
    {
        double NewWidth = this->ClientSize.Width - groupBoxHostAppl-
>Left - 20;
        double NewHeight = (NewWidth + 20) / FrameRatio;
        if((groupBoxHostAppl->Top + NewHeight + 20) > this-
>ClientSize.Height)
        {
            NewHeight = this->ClientSize.Height - groupBoxHostAppl-
>Top - 20;
            NewWidth = (NewHeight - 20) * FrameRatio;
        }
    }
}

```



```

        groupBoxHostAppl->Size      =      Drawing::Size((int)NewWidth,
(int)NewHeight);
        Drawing::Rectangle          r          =          groupBoxHostAppl-
>RectangleToScreen(groupBoxHostAppl->ClientRectangle);
        r.X += 10;
        r.Y += 20;
        r.Width -= 20;
        r.Height -= 30;
        ipc->SetMainWindowRect(0, r);
    }
}

```

```

HRESULT FormMain::OnServerStopped(int reason)
{
    ReleaseIPC();
    Graphics ^g = Graphics::FromImage bmp);
    g->FillRectangle(gcnew SolidBrush(Color::Black), 0, 0, bmp->Width,
bmp->Height);
    delete g;
    pictureBox->Invalidate();
    return 0;
}

```

```

HRESULT FormMain::OnFrameInit(int frameWidth, int frameHeight, int
frameDepth)
{
    Init(frameWidth, frameHeight, frameDepth);
    return 0;
}

```

```

// will work with Imager.exe release > 2.0 only:
HRESULT FormMain::OnNewFrameEx(void * pBuffer, FrameMetadata *pMetadata)
{
    labelFrameCounter->Text = "Frame counter HW/SW: " + pMetadata-
>CounterHW.ToString() + "/" + pMetadata->Counter.ToString();
    labelPIF->Text = "PIF digital/analog: "
        + ((pMetadata->PIFin >> 15) == 0).ToString() + "/"
        + (pMetadata->PIFin & 0x3FF).ToString();

    switch(pMetadata->FlagState)
    {
        case fsFlagOpen: labelFlag->Text = "open"; labelFlag->ForeColor =
Color::Green; labelFlag->BackColor = labelFlag1->BackColor; break;
        case fsFlagClose: labelFlag->Text = "closed"; labelFlag->ForeColor
= Color::White; labelFlag->BackColor = Color::Red; break;
        case fsFlagOpening: labelFlag->Text = "opening"; labelFlag-
>ForeColor = SystemColors::WindowText; labelFlag->BackColor =
Color::Yellow; break;
        case fsFlagClosing: labelFlag->Text = "closing"; labelFlag-
>ForeColor = SystemColors::WindowText; labelFlag->BackColor =
Color::Yellow; break;
        default: labelFlag->Text = ""; labelFlag->ForeColor = labelFlag1-
>ForeColor; labelFlag->BackColor = labelFlag1->BackColor;
    }
    return NewFrame((short*)pBuffer, pMetadata->Counter);
}

```

```

HRESULT FormMain::OnNewFrame(char * pBuffer, int frameCounter)
{
    return NewFrame((short*)pBuffer, frameCounter);
}

```

```

HRESULT FormMain::NewFrame(short *ImgBuf, int frameCounter)

```

```

{
    DateTime time = DateTime::Now;
    TimeSpan ts = time - LastFrameTime;
    List->Add(ts.TotalMilliseconds);
    LastFrameTime = time;

    FrameCounter0 = frameCounter;
    FrameCounter1++;
    if(ResetPending)
    {
        Tmax = 0;
        FC0 = FrameCounter0;
        FC1 = FrameCounter1;
        ResetPending = false;
    }
    int fc0 = FrameCounter0 - FC0;
    int fc1 = FrameCounter1 - FC1;

    label2->Text = String::Format("Frames from Imager Application:
{0}\nReceived frames: {1}\nNot received frames: {2}",
        fc0, fc1, fc0 - fc1);

    for ( int x = 0; x < FrameSize; x++ ) Values[x] = ImgBuf[x];

    if(!Painted)
    {
        GetBitmap(bmp, Values);
        pictureBox->Invalidate();
        Painted = true;
    }

    return 0;
}

HRESULT FormMain::OnInitCompleted(void)
{
    progressBarInit->Maximum = ipc->GetInitCounter(0);
    progressBarInit->Value = 0;
    progressBarInit->Visible = true;
    GetSoftwareInfo();
    GetDeviceInfo();
    GetDeviceSetup();
    InitMeasureAreas();
    labelVersionAppl->Text = String::Format("Host-Appl.:
{0}.{1}.{2}.{3}",
        Dev.SoftInfo.Application->Major,
        Dev.SoftInfo.Application->Minor,
        Dev.SoftInfo.Application->Build,
        Dev.SoftInfo.Application->Revision);
    labelVersionIPC->Text = String::Format("IPC-DLL: {0}.{1}.{2}.{3}",
        Dev.SoftInfo.IPC_DLL->Major,
        Dev.SoftInfo.IPC_DLL->Minor,
        Dev.SoftInfo.IPC_DLL->Build,
        Dev.SoftInfo.IPC_DLL->Revision);
    labelHW->Text = String::Format("HW: {0}", Dev.Info.HW_Model);
    labelFW->Text = String::Format("FW: {0}", Dev.Info.FW_Cypress);
    label1->Text = "Connected with #" +
Dev.Info.SerialNumber.ToString();
    Connected = true;
    UpdateSize();
    return S_OK;
}

HRESULT FormMain::OnConfigChanged(long reserved)

```

```

{
    GetDeviceInfo();
    GetDeviceSetup();
    InitMeasureAreas();
    return S_OK;
}

HRESULT FormMain::OnFileCommandReady(wchar_t *path)
{
    // System::Windows::Forms::MessageBox::Show( gcnew String(path),
    "File was saved to path:", MessageBoxButtons::OK,
    MessageBoxIcon::Exclamation );
    return S_OK;
}

System::Void FormMain::checkBoxDock_CheckedChanged(System::Object^
sender, System::EventArgs^ e)
{
    UpdateSize();
}

void FormMain::FileOpen(void)
{
    if(ipc)
    {
        System::Windows::Forms::OpenFileDialog^ Dlg = gcnew
System::Windows::Forms::OpenFileDialog;
        String^ s = "All files|*.*|Radiom.
files|*.ravi;*.jpg;*.tiff|Ravi|*.ravi|Avi|*.avi|Jpeg|*.jpg|Tiff|*.tiff|";
        Dlg->Filter = s->Remove(s->Length-1);
        Dlg->FilterIndex = 2;
        Dlg->CheckFileExists = true;
        if (Dlg->ShowDialog() ==
System::Windows::Forms::DialogResult::OK)
        {
            wchar_t Filename[1024];
            pin_ptr<const wchar_t> wch = PtrToStringChars(Dlg-
>FileName);
            wcscpy_s(Filename, 1024, wch);

            USHORT retVal = ipc->FileOpen(0, Filename);
            if(retVal != 0)
                System::Windows::Forms::MessageBox::Show( gcnew
String(Filename), "Could not open file:", MessageBoxButtons::OK,
MessageBoxIcon::Error );
        }
    }
}
}

```


9.6.MATLAB Programming Code

9.6.1. FLIR Image Processing

```
% This script uses infrared images generated by the FLIR Thermacam which
% was on loan from the Civil Engineering Department in Trinity College.
It
% was used to process infrared images of hands in an office environment
at
% a desk. The aim of this script is to identify the area which the
hand(s)
% occupies automatically. This is achieved through processing of the
image
% with a threshold type edge detection method in built into MATLAB.
Objects
% are detected from this. The size and area of the objects are determined
% and object of low size or low perimeter to area ratio are discarded as
% not being hands. Other objects which could be detected in the space
could
% be computer mice, cups of hot beverage, residual heat left by the
% arm/finger/hand in the furniture. As hands have a larger perimeter to
% area ratio than most man made objects, especially when the fingers are
% spread, this can be used to refine the objects in the image.
% The FLIR images evaluated here have the FLIR logo in the top left
corner,
% a temperature bar with min and max temperatures on the bottom row.
Added
% to that in the middle of the image there is a crosshairs. This program
% attempts to detect the min and max temperatures of the images through
an
% OCR (Optical Character Recognition) program. The FLIR logo is blanked
out
% from the images so that it is not detected as an object and the
crosshair
% is removed using a substitution type mechanism of the pixels in the
% area.

clc, close all, clear all
set(0,'DefaultFigureWindowStyle','docked')
%%imshow('InitialMagnification',100)
iptgetpref('ImshowInitialMagnification')
warning off
%WARNING('off',msgID)

%% Load Image and convert to Grayscale
I=imread('images/IR_2566.jpg'); % Load the images to be processed

I2=rgb2gray(I); % The image is grayscale anyway, I2 is converted to
% grayscale.

cropped = Crosshairs(I); % The crosshairs of the images is attempted to
be
% removed by using the Crosshairs function. The
% image is also cropped and FLIR logo removed by
% this function.

%% Find significant data within image
for m=4:4
    foreground=imopen(cropped, strel('disk',m));
    % The image is cleaned up, with JPEG artifacts removed and the image
```

```

    % is smoothed

    figure,imshow(foreground);
    % The resulting image is displayed
end

%% Test to see full contrast image
level = graythresh(foreground); % Threshold values for the altered image
% calculated using the graythresh MATLAB native function.
% GRAYTHRESH(I) computes a global threshold (LEVEL) that can be
% used to convert an intensity image to a binary image with IM2BW. LEVEL
% is a normalized intensity value that lies in the range [0, 1].
% GRAYTHRESH uses Otsu's method, which chooses the threshold to minimize
% the intraclass variance of the thresholded black and white pixels.

fudge2 = 1.3;
% A factor named 'fudge2' is allowed to change the threshold value so
that
% the correct edge can be determined. If the factor is not correct some
of
% the hand/fingers may not be detected properly or furniture could be
% included in the detected area.

bw = im2bw(foreground,level*fudge2);
% The Image is converted to a Black and White image or logical image
based
% on the threshold value times the value set of fudge2. This means that
% pixels with a value lower than the value of "level*fudge2" will be set
to
% the value 0, and those above set to the value 1. This creates a logical
% matrix in which an edge detection program can be performed on the
logical
% matrix.

% The B&W image is displayed for the user to check
figure,imshow(bw)

%% find edges within the image

% The native "edge" detection function in MATLAB is called for the B&W
% image created above "bw", the Sobel method is chosen here but others
% were explored during the research, which had very similar edge detection
% for the purposes of finding the outline of the hand.
%
% EDGE takes an intensity or a binary image I as its input, and returns a
% binary image BW of the same size as I, with 1's where the function
% finds edges in I and 0's elsewhere.
%
% EDGE supports six different edge-finding methods:
%
%     The Sobel method finds edges using the Sobel approximation to the
%     derivative. It returns edges at those points where the gradient of
%     I is maximum.
%
% Here the threshold value is found, however development of the code
above
% and conversion to the B&W image makes the thresholding redundant
[junk threshold] = edge (bw,'sobel');

% fudge_factor is set and used to decrease or increase the value of the

```

```

% threshold for processing in the 'edge' function
fudge_factor = 0.3;

% Edge function is called and returns a b&w image which contains the
edges
% of objects detected.
bw2=edge(bw,'sobel',threshold*fudge_factor);
figure,imshow(bw2)

% In the following script the line created above is not significant enough
% to be processed further so the line is widened using the 'imdilate'
% function
se90 = strel('line',3,90);
se0 = strel('line',3,0);
dilated = imdilate(bw2, [se90 se0]);
%%

% Boundaries are found using the native bwboundaries function which
returns
% a matrix 'L' which contains solid (not outlined) objects detected using
% the edge technique
[B,L] = bwboundaries(bw,'noholes');

% Display the label matrix and draw each boundary
figure,imshow(label2rgb(L, @jet, [.5 .5 .5]))
hold on

% each boundary is represented with a different colour
for k = 1:length(B)
    boundary = B{k};
    plot(boundary(:,2), boundary(:,1), 'w', 'LineWidth', 2)
end

% The properties of each region is gained and assigned to stats.
stats = regionprops(bw, 'area', 'perimeter')

%bw3=edge(I2,'prewitt');
%bw4=edge(I2,'roberts');
%bw3=edge(foreground,'sobel');

%figure,imshow(bw2);
figure,imshow(dilated);
title('Dilated image mask');
filled = imfill(dilated, 'holes');
figure, imshow(filled);
title('Binary image with filled holes');

% The original image imported is overlaid with the border created using
the
% above technique
BWnobord = imclearborder(filled, 4);
BWnobord = filled - BWnobord;
figure, imshow(BWnobord), title('Cleared border image');
bw5 = uint8(bw2);
bw5(bw5>0) = 255;
comb1 = imadd(bw5,cropped);

%% Uninteresting space is set to zero.
% All pixels outside of the area in which objects were detected and
deleted
% are blanked, set to zero.
comb2=cropped;

```



```

comb2(L<1)=0;

%figure,imshow(comb1);
figure,imshow(comb2);

%% size of image and size of ROI calculated
[x,y]=size(comb2);
i = 0;
p = 0;
for k=1:x
    for l=1:y
        if comb2(k,l)>0
            i=i+1;
        end
    end
end

%% Mean is calculated then adjusted to show mean of ROI by
% multiplying by total region then dividing by ROI

% Mean temperature value is calculated here using the Region of interest
% created 'comb2'. Since the area outside of the ROI is set to zero the
sum
% of it can be calculated for only the ROI area. 'i' is the number of
% nonzero values which the sum is divided by to give the average
% temperature.
m1 = sum(sum(comb2))/i

%% Mean is then compared to the calibrated intensity
% This portion of the programming code is for detection of the
temperature
% max and min which the FLIR infracam displays on all images.

%% Scale of intensity is set up
I3 = rgb2gray(I);
%figure, imshow(I3);
I4 = imcrop(I3, [52 227 137 4]);
%figure,imshow(I4);
m3 = mean(I4);

%% Evaluate Temperature Min and Max from Image

% Min temperature pixels are isolated here.
I5 = imcrop(I3, [14 214 25 21]);
% The image is converted to a B&W image for OCR processing
I5(I5<207)=0;
I5(I5>0)=255;
I6 = im2bw(I5);
% Image presented to OCR program must be in a uint8 format
I7 = uint8(I6);
I7(I7==0) = 255;
I7(I7==1) = 0;

% The image is sent to the OCR program and a set of characters are
returned
% set to 'word3'
[word3] = OCR(I7);
% This character set is converted to a number
tempmin = str2double(word3)

% The same process is completed for Max temperature of the FLIR camera
% image

```

```

I51 = imcrop(I3, [204 224 25 11]);
I51(I51<207)=0;
I5(I5>0)=255;
I61 = im2bw(I51);
I71 = uint8(I61);
I71(I71==0) = 255;

[word3] = OCR(I71);
tempmax = str2double(word3)

%% Temperature values given to the calibrated intensity based on
% temperature scale
m4 = double(1:254);
[x1,y1] = size(m4);

% 'dist' is the difference in temperature between units of pixel
intensity
% That is to say, pixel intensity of 100 is 'x Celsius' and a pixel
intensity
% of 101 is 'x + dist Celsius'
dist = ((tempmax-tempmin)/(m4(y1) - m4(1)));

% The values of temperature of each pixel intensity is set up here in a
% matrix called 'tempvalue'

tempvalue = m4;
g=0;
for g=1:y1
    tempvalue(g) = ((m4(g) - m4(1))*dist) + tempmin;
end

%% Find temperature

% Temperature is found by approximating the pixel intensity to the value
of
% temperature calculated for each pixel intensity value. i.e. 1 to 255
% intensity equals a Celsius temperature value given in tempvalue.
tempvalue(round(m1))

```

9.6.2. Crosshairs Function

```

function [ cropped ] = Crosshairs( var1 )
%% Load Image and convert to Grayscale

I2=rgb2gray(var1);

%figure, imshow(I2)

%% Crop image
cropped = imcrop(I2,[0 25 240 195]);
%figure, imshow(cropped);

I2 = cropped;

%% crop to crosshairs

```

```

cropped2 = imcrop(cropped, [105 81 32 32]);

%figure, imshow (cropped2);

level = graythresh(cropped2);
fudge2 = 0.9;
cropped2 = im2bw(cropped2,level*fudge2);

[x y] = size(cropped2);

%% recognise crosshairs
temp = load('crosshairs.mat');
cross2 = temp(1,1).cross2;
cross1 = temp(1,1).cross1;
corr2(cropped2, cross2);
corr2(cropped2, cross1);

if corr2(cropped2, cross2)>0.5
    %figure,imshow(cross2)
    for j=1:x
        for l=1:y
            if cross2(j,l) == 0
                i=j+104;
                k=l+80;
                p=2;
                %cropped(k,i) = mean([cropped(k-p,i-p),cropped(k,i-
p),cropped(k+p,i-p),cropped(k-p,i),cropped(k+p,i),cropped(k-
p,i+p),cropped(k,i+p),cropped(k+p,i+p)]);
                cropped(k,i) = mean([cropped(k-p,i-p),cropped(k+p,i-
p),cropped(k-p,i+p),cropped(k+p,i+p)]);
            end
        end
    end
end
if corr2(cropped2, cross2)<0.5
    %figure,imshow(cross2)
    for j=1:x
        for l=1:y
            if cross2(j,l) == 0
                i=j+104;
                k=l+80;
                p=2;
                cropped(k,i) = mean([cropped(k-p,i-p),cropped(k,i-
p),cropped(k+p,i-p),cropped(k-p,i),cropped(k+p,i),cropped(k-
p,i+p),cropped(k,i+p),cropped(k+p,i+p)]);
                %cropped(k,i) = mean([cropped(k-p,i-p),cropped(k+p,i-
p),cropped(k-p,i+p),cropped(k+p,i+p)]);
            end
        end
    end
end
%figure, imshow (cropped);
if corr2(cropped2, cross1)>0.5
    %figure, imshow(cross1)
    for j=1:x
        for l=1:y
            if cross1(j,l) == 1
                i=j+104;
                k=l+80;
                p=3;
                cropped(k,i) = mean([cropped(k-p,i-p),cropped(k,i-
p),cropped(k+p,i-p),cropped(k-p,i),cropped(k+p,i),cropped(k-
p,i+p),cropped(k,i+p),cropped(k+p,i+p)]);

```



```

        end
    end
end
if corr2(cropped2, cross1)<0.5
    %figure, imshow(cross1)
    for j=1:x
        for l=1:y
            if cross1(j,l) == 1
                i=j+104;
                k=l+80;
                p=3;
                cropped(k,i) = mean([cropped(k-p,i-p),cropped(k,i-
p),cropped(k+p,i-p),cropped(k-p,i),cropped(k+p,i),cropped(k-
p,i+p),cropped(k,i+p),cropped(k+p,i+p)]);
            end
        end
    end
end
end

%figure, imshow (cropped);

cropped(1:12,1:50)=0;

end

```

9.6.3. PMV Calculation Functions

9.6.3.1. *PMV.m*

```

function [ PMVno PPD] = PMV( Me, We, Icle, Ta, Tr,Var,RH )
% Function to Calculate Predicted Mean Vote (PMV) based upon the formulas
% and method described in ISO 7730;2005.
% Predicted mean vote is used to assess the comfort of an average group
of
% people based upon environment variables such as Temperature and
Relative
% Humidity
% This function takes the base variables and returns both PMV and PPD
which
% is Predicted Percentage dissatisfied. PPD is an estimation of what
% percentage of people present in the environment would be dissatisfied
% with the environment
%

% The partial pressure of Humidity is calculated
Pa = RH * 10 * exp(16.6536 - 4030.183/(Ta+235));

% The Metabolic rate is converted from Met to W/m^2
M = Me*58.15;

% Work rate (We in units 'Met' )is converted to W/m^2
% Work rate is generally set to zero in an office environment in which
all

```

```

% the tests in this research was carried out
W = We*58.15;

% The work rate is subtracted from the metabolic rate. See above, W=0
MW = M-W;

% Clothing insulation value input is converted from 'clo' to square
metres
% Kelvin per Watt (m^2.K/W)
Icl = 0.155 * Icle;

% The first calculation is for Fcl which is the clothing surface area
% factor. This must be calculated in different ways based upon the value
of
% Icl. If Icl is less than or equal to 0.078 m^2.K/W then Fcl =
% 1+(1.290*Icl) else Fcl = 1.05+(0.645*Icl), as per ISO 7730
if Icl <= 0.078
    Fcl = 1+(1.290*Icl);
else
    Fcl = 1.05+(0.645*Icl);
end

% Air temperature and Radiant Temperature are converted from Celsius to
% Kelvin
Taa = Ta + 273.15;
Tra = Tr + 273.15;

% Surface temperature of clothing must be solved using iterations, The
% following is the first guess for the surface temperature of the
clothing
Tcla = Taa + (35.5 - Ta) / (3.5 * Icl + 0.1);

% P1 - P5 Are calculation terms
P1 = Icl * Fcl;
P2 = P1*3.96;
P3 = P1*100;
P4 = P1*Taa;
P5 = 308.7 - 0.028*MW + P2*(Tra/100)^4;
% XN and XF are used to find when to stop the iterations
XN = Tcla/100;
XF = Tcla/50;
% N is the number of iterations
N=0;
% When XN-XF is greater than EPS then the iteration is stopped
EPS = 0.00015;

% The Iteration is as follows
while abs(XN-XF) > EPS

    XF = (XF+XN)/2;
    % Hcf is the heat transfer coefficient by forced convection
    Hcf = 12.1*sqrt(Var);
    % Hcn is the heat transfer coefficient by natural convection
    Hcn = 2.38 * abs(100 * XF - Taa)^0.25;

    % The greater of Hcf and Hcn is used for the calculation
    if Hcf > Hcn
        Hc = Hcf;
    else
        Hc = Hcn;
    end

    % XN is calculated here which is the first iteration of the
calculation

```

```

    % of Tc1
    XN = (P5 + P4 * Hc - P2 * (XF^4))/(100+P3*Hc);
    % Number of iterations is increased
    N= N + 1;
    % Gap between XN and XF is reassessed until the gap is smaller than
EPS
    % so that the iteration can be exited
end
% Number of Iterations can be presented here.
N;

% Tc1 is calculated from the above iteration and given a value in degrees
% celsius
Tc1 = 100 * XN -273.15;

% Hc is assigned a value
Hc = 12.1*sqrt(Var);

% Heat loss by evaporation is calculated which is part of the PMV
equation
HL1 = 3.05*10^-3*(5733 - 6.99*MW - Pa); % Heat loss by evaporation

% Heat loss by sweating
if MW > 58.15
    HL2 = 0.42*(MW-58.15);
else
    HL2 = 0;
end

HL3 = 1.7*10^-5*M*(5867-Pa); % Heat loss due to differences in water
vapour breathed

HL4 = 0.0014*M*(34-Ta); % Heat loss through respiration due to
differences in air temp

HL5 = 3.96*10^-8*Fcl*((Tc1+273)^4-Tra^4); % heat exchange by radiation

HL6 = Fcl*Hc*(Tc1-Ta); % Heat loss through convection

TS = (0.303*exp(-0.036*M)+0.028); % Thermal Sensation Transfer
Coefficient

% PMV is calculated below based upon the heat loss components calculated
% above. PMVno is returned to the program which called it
PMVno = TS * (MW - HL1 - HL2 - HL3 - HL4 - HL5 - HL6);

% PPD is also calculated and returned to the program
PPD = 100-95*exp(-0.03353*PMVno^4 - 0.2179*PMVno^2);

end

```

9.6.3.2. *PMVComplete.m*

```

function [ data ] = PMVComplete( M, W, Icl, Var, data )
% PMV Complete Takes a set of data and adds to that data the PMV value
% calculated for each line of the data. Data is input in the form column
3
% = air temperature column 5 = mean radiant temperature, column 4 =
% relative humidity

```



```

%
y = length(data);

for i=1:y
    [data(i,6) PPD] = PMV( M, W, Icl, data(i,3), data(i,5),Var,data(i,4)
);
    % Each line of data is assigned a PMV value according to the
    % calculation made by PMV Function
end

end

```

9.6.3.3. *PMVCompleteALT.m*

```

function [ dataCalc ] = PMVCompleteALT( M, W, Icl, Var, data )
% PMVCompleteALT Takes a set of data and returns The PMV data in a matrix
% calculated for each line of the data. Data is input in the form column
3
% = air temperature column 5 = mean radiant temperature, column 4 =
% relative humidity
y = length(data);

for i=1:y
    % Each line of dataCalc is assigned a PMV value according to the
    % calculation made by PMV Function corresponding to the line in
    'data'.
    [dataCalc(i)      PPD]      =      PMV(      M,      W,      Icl,
data(i,3),data(i,5),Var,data(i,4));
end

end

```

9.6.4. *calcMRT1000.m* Mean Radiant Temperature Function

```

function [ MRT ] = calcMRT1000( globe , air )
% calcMRT1000 takes in globe and air temperatures and returns the mean
% radiant temperature as calculated according to ISO 7726;2001. Diameter
of
% the black globe can be altered here and the other variable is Eg which
is
% the emissivity of the black globe. According to ISO 7726 Matt Black
% Paint has an emissivity of 0.95.

% Diameter of the Black Globe
D = 0.15;

% Emissivity of the surface (matt black paint)
Eg = 0.95;

% Tg is globe temperature (input variable)
Tg = globe;

% Ta is air temperature (input variable)
Ta = air;

% Hcg is the coefficient of heat transfer by convection at the level of

```

```
% the globe, in watts per square metre kelvin. ISO 7726;2001
Hcg = 1.4*((Tg - Ta)/D)^0.25;

% MRT is calculated using the formula in ISO 7726;2001
MRT = ((Tg+273)^4+0.25*10^8/Eg*(abs(Tg-Ta)/D)^0.25*(Tg-Ta))^0.25 - 273;

end
```

9.6.5. HOBOWare Logger Data Processing

9.6.5.1. *getLoggerData.m*

```
% In This script the data from the HOBO logger is processed
% Variables are processed and presented in a format that can be exported
to
% excel for further analysis
%

close all
clear all
clc

load('rory 2013-05-02.mat') % Input the matlab file which is to be
                           % processed. The user will change this for
each
                           % test conducted.

file = 'tempdata.csv'; % File named tempdata.csv has been placed in the
% test folder (dir2). This file contains all the environmental data
% collected by the HOBOWare logger. HOBOWare software was used to extract
% the data and save it in a CSV format for this script to read.

logdata = interpretLogger(dir2, file); % file is loaded into log data
using
                                     % interpretLogger function

% The time of each recording of the logger data is converted to a string
% and held in the matrix 'datestring' for processing later
datestring = datestr(logdata(:,2));

% the length of datestring is assigned to lenLog
[lenLog ~] = size(datestring)

% In this for loop the hour and minute of the logger data is recorded in
% 'timelog' if the data is from the afternoon i.e. 'pm' then 12 is added
to
% the hour
for i = 1 : lenLog
    if datestring(i,7:8) == 'PM' & str2double(datestring(i,1:2))<12
        timelog(i,1) = str2double(datestring(i,1:2))+12;
    else
        timelog(i,1) = str2double(datestring(i,1:2));
    end
    timelog(i,2) = str2double(datestring(i,4:5));
```

end

```
% This for loop finds the time of each infrared recording and finds the  
% corresponding time from the logger.
```

```
for i = 1 : len
```

```
    % The variable 'minmaxhour' finds the rows in the matrix timelog at  
    % which the corresponding hour from the infrared data comes from  
    minmaxhour = find(timelog(:,1)==time(i,1));
```

```
    % The column 3 of the variable 'time' is assigned the exact row from  
    % which the logger data will be used which matches the time that the  
    % infrared data recorded
```

```
    time(i,3) =  
find(timelog(min(minmaxhour):max(minmaxhour),2)==time(i,2))+min(minmaxhou  
r)-1;
```

```
    % the variable 'time' is assigned the data from the logger of  
    % temperature relative humidity and globe temperature  
    time(i,4:7) = logdata(time(i,3),3:6);
```

```
    Me = 1.2; % The assumed metabolic rate
```

```
    We = 0; % The Work rate assumed
```

```
    Icle = 0.8; % The clothing factor calculated on each session
```

```
    Ta = time(i,4); % the air temperature
```

```
    Var = 0.1; % The velocity of the air
```

```
    RH = time(i,5); % The relative humidity from the logger data
```

```
    % The radiant temperature is calculated using the globe temperature  
and
```

```
    % the air temperature using this function
```

```
    Tr = calcMRT1000(time(i,6),time(i,4));
```

```
    % The radiant temperature calculated is assigned to column 7  
    time(i,7) = Tr;
```

```
    % PMV is calculated using the variables assigned above and is  
assigned
```

```
    % to column 8
```

```
    time(i,8) = PMV( Me, We, Icle, Ta, Tr,Var,RH );
```

end

9.6.5.2. *interpretLogger.m*

```
function [ finaldata ] = interpretLogger( dir2 , file )
```

```
% This function takes the logger data in from the raw unprocessed data  
and
```

```
% returns the data in a useable format for MATLAB
```

```
%
```

```
book = textread( [dir2 file], '%s', 'delimiter', ',' );
```

```
% File is read and assigned to variable 'book'
```

```
% Size of book is queried
```

```
[sizeA ~] = size(book);
```



```

% The offset of the start of the data is found using this function in
which
% the start of the data begins with the number '1' which is found. The
% program will use this offset to start putting data into rows and
columns
% from this point onwards in the 'book' variable
offset = find(strcmp(book,'1'));

% The variable fac7 is the number of columns in the data, the program
needs
% to know this as the data is imported in one column of data and will be
% placed into rows and columns according to each minute of the data
% recorded. The variable is calculated by the difference in row numbers
% between the value '1' and '2' which is the recordings of data point '1'
% and '2'
fac7 = find(strcmp(book,'2'))-offset;

% The variable 'E' is assigned the data stream removing the text at the
% beginning of the file
E = book(offset:sizeA);

% The size of 'E' is queried
[sizeA ~] = size(E);

% The start date is found in the following code
dateStart = round(datetime(E{2}))-0.5);

% A data file is set up with the right dimensions to accept the data
% sizeA/fac7 is the length of the data collected
finaldata = zeros(sizeA/fac7,20);

% In this for loop The dates and times of the logger data is converted to
a
% string which is representative of the date and time in MATLAB code in
% this particular instance the date is discarded and the time is taken
% through to the finaldata variable
for i=1:(sizeA/fac7)
    temp = E{(i-1)*fac7+2};
    E{(i-1)*fac7+2} = num2str(datetime(temp(10:20))- 735235);
    finaldata(i,2) = datetime(temp(10:20))- 735235;
end

% count is assigned the value 0
count = 0;

% this for loop converts all data in 'E' to a number rather than current
% status which is string
for i=1:sizeA
    E{i} = str2num(E{i}) ;
end

sizef=sizeA/fac7;

% in the following for loop the data for each line of the logger recorded
% is placed in the corresponding row for time and number of recordings
the
% 'finaldata' variable is returned to the function which has called it
for i=0:sizef-1
    finaldata(i+1,1)=E{(i*fac7)+1};

```

```

% finaldata(i+1,2)=E{(i*fac7)+2};
finaldata(i+1,3)=E{(i*fac7)+3};
finaldata(i+1,4)=E{(i*fac7)+4};
finaldata(i+1,5)=E{(i*fac7)+5};
%finaldata(i+1,6)=E{(i*fac7)+6};
%finaldata(i+1,7)=E{(i*fac7)+7};
%date(i+1,1) = finaldata(i+1,2);

end
end

```

9.6.6. Image Processing Script and Functions

9.6.6.1. *CSVManipulator1000.m Infrared Image Processing Script*

```

% This MATLAB Script takes in the output data files from the Infrared
% camera and returns a black and white image in BMP format
% the temperature of each pixel in the infrared data is converted to a
% brightness in the BMP image returned the BMP is files in the same
% folder as the infrared data file
% This script is called at the very beginning of processing data so the
% operator may see what data has been captured by the infrared camera.
%

clc, close all, clear all
set(0,'DefaultFigureWindowStyle','docked')
%%imshow('InitialMagnification',100)
iptgetpref('ImshowInitialMagnification');
warning off
%WARNING('off',msgID)

if isdeployed
    old=pwd;
    cd(ctfroot);
end

[file dir2] = uigetfile('*.csv'); % The infrared folder and first file is
    % input

if isdeployed
    cd(old);
end

file2 = file(1:5); % the first 5 characters are assigned to file2

dirinfo = dir(fullfile(dir2, [file2 '*.csv'])); % directory information is
    % assigned to dirinfo

[length ~] = size(dirinfo); % the size of dirinfo is assigned to length
filestrings = dirinfo.name; % The first file within dirinfo are assigned
in
    % string format to filestrings

for i = 2:length
    filestrings = [filestrings; dirinfo(i).name]; % All subsequent
strings
    % are assigned to filestrings in rows below the
    % first string

```

```

end

for i = 1:length
    imageCon = CSVConvert1(dir2 , filestrings(i,:),25,35);
    % the image is converted using CSVConvert1 with minimum and maximum
    % temperatures of 25 and 35, respectively
    imwrite(imageCon, [ dir2 'temo' filestrings(i,:) '.bmp'], 'bmp')
    % the image is written to file with the same file name as the
    original
    % data file with .BMP on the end as the file extension
end

```

9.6.6.2. CSVConvert1.m

```

function [ CsvConvert ] = CSVConvert1( dir2 , file ,min, max)
% CSV Convert 1 This function takes an infrared data file and returns a
% matrix of numbers from 0 to 255 dependant on the minimum and maximum
% temperatures input. Each number is representative of the infrared data
% for example if the infrared camera records a temperature of 30 and the
% minimum temperature input is 25 and the maximum is 35 then the returned
% number for that pixel will be (30-25)/(35-25)*255= 127.5. the figure is
% then rounded. The number for each pixel is representative of the
% temperature, whiter is hotter while darker is cooler.
%
%
MatrixImage          =          textread(fullfile(dir2,file),'%f',
'delimiter',';', 'endofline','\r\n' );
% the file is read into the function using the input parameters

CsvImage = zeros(120,160);
% the image file is created which is the width and length of the infrared
% data files
CsvConvert = uint8(zeros(120,160));
% the conversion file is created which will be the returned file at the
end
% of the function

for i=1:120

    for y = 1:160

        CsvImage(i,y) = MatrixImage((i-1)*160+y,1);
        % Each line in the matrix image is read into CSV Image which
        % converts a matrix of cells to a matrix of rnumbers. this double
        % for loop is necessary to remove the formatting which the
        textread
        % function puts on the read data.
    end
end

end

for i=1:120

    for y = 1:160

```



```

        CsvConvert(121-i,y)      =      uint8(round((CsvImage(i,y)-min)/(max-
min)*255));
        % the matrix of temperatures is converted to a matrix of numbers
        % between 0 and 255 which is representative of the brightness of
        % the pixel. The file CsvConvert is returned to the script which
        % called this function

    end

end

end

```

9.6.6.3. *Manual image processing script*

```

%clc, close all, clear all
set(0,'DefaultFigureWindowStyle','docked')
%%imshow('InitialMagnification',100)
iptgetpref('ImshowInitialMagnification');
warning off
%WARNING('off',msgID)

% This script is for processing the data gathered by the infrared camera,
% the script asks the user where the files are what file to start from
and
% presents the data for the user to select the area of the opisthenar,
% proximal phalange, intermediate phalange and distal phalange of the
index
% finger. The average temperature in these areas chosen is calculated and
% the temperature is stored in a data file for further processing.

% Ask the user where to start. If the dataset has already been processed
by
% the script then select 2 for continue
format1 = input('1 for new set, 2 for continue : ');

% If NEW SET i.e. format1 is set above to 1
if format1 ==1
    clc,close all, clear all
    if isdeployed
        old=pwd;
        cd(ctfroot);
    end
    % Get directory and files
    [file dir2] = uigetfile('*.csv');
    filestart = file(1:3);
    if isdeployed
        cd(old);
    end

    % Get all file names to be processed from the directory
    dirinfo = dir(fullfile(dir2, [filestart '*.csv']));
    [len ~] = size(dirinfo);
    filestrings = dirinfo.name;
    for i = 2:len
        filestrings = [filestrings; dirinfo(i).name];
    end

    % The following sets up files which will hold data later
    coords=zeros(len,8);

```

```

format2=1;
AVG = zeros(len,4);

% If CONTINUE
elseif format1==2
    % Select Directory
    dirinfo = dir(fullfile(dir2, [filestart '*.csv'] ));

    [len ~] = size(dirinfo);
    filestrings = dirinfo.name;

    for i = 2:len
        filestrings = [filestrings; dirinfo(i).name];
    end
    % Select start point for the processing
    format2 = input('Number to start from : ');
end

% For loop which runs for the entire data set contained within the
% directory
for i = format2 : len %length
    % Show filename in command window
    filestrings(i,:)
    % Show i (file number currently on, can be used to select start
point)
    % in command window
    i
    % Get CSV of the infrared image
    CSV = CSVReturn(dir2,filestrings(i,:));
    % Convert the CSV to an image
    image = CSVConvert1(dir2 , filestrings(i,:),20,35);
    % Get image height and width
    [ high wid] = size(image);

    % image is retained as the original while image3 is manipulated
    image3 = image;

    % Display image
    imshow(image3);

    % Title of the image is displayed
    title('Opisthenar Measurement')

    % Coordinates are queried with the user while the user selects the
    % above title
    [x1,y1] = ginput(1);

    % coords are saved.
    coords(i,1)=x1;
    coords(i,2)=y1;

    % Size of the opisthenar area is set by x
    x = 30;

    % A grid is setup rr contains column names in each row cc contains
row
    % names in each row.
    [rr cc] = meshgrid(1:x+1);

    % A circle is set up using RR and CC defined above. The circle is a
    % matrix in which the circle is represented by '1's
    C = sqrt((rr-((x/2)+1)).^2+(cc-((x/2)+1)).^2)<=x/2-1;

```

```

% The Co-ordinates need to be rounded to the nearest interger so that
% the program can find the corresponding pixel. Minimum and maximum
% values for a square surrounding the centre pixel are found and
% assigned values ymin, ymax, xmin, xmax.
ymin = round(y1-x/2) ;
ymax = round(y1+x/2) ;
xmin = round(x1-x/2) ;
xmax = round(x1+x/2) ;

% Checks to make sure that the circle is within the matrix of
% temperatures gathered by the infrared camera
if y1-x/2 < 1
    C = C(abs(ymin)+2:x+1,:);
    ymin = 1;
end
if y1+x/2 > high
    C = C(1:high-ymin+1,:);
    ymax=high;
end
if x1-x/2 < 1
    C = C(:,2+abs(xmin):x+1);
    xmin=1;
end
if x1+x/2 > wid
    xmax=wid;
end

CSVOpis = CSV(ymin:ymax,xmin:xmax);
% This line assigns a portion of the matrix surrounding the centre
% pixel given by coords. The temperature data is assigned to CSVOpis

CSVOptic = image3(ymin:ymax,xmin:xmax);
% as above the temperature square is found, the corresponding image
% data is also found which can be used for fault finding assigned to
% CSVOptic

CSVOptic(C==1)=0;
% All values in CSVOptic in which C equals 1 are set to zero. This
% effectively blanks a circle of the optical data rather than a
square.
% The circle has the same dimensions that C.

image3(ymin:ymax,xmin:xmax)=CSVOptic;
% image3 is assigned the value of CSVOptic. image3 now has a circle
of
% black in every point where the opisthenar temperature measurement
% average will take place.

imshow(image3)
% The operator is shown the image with the black pixels

CSVOpis(C==0)=0;
% All values in CSVOpis in which C equals zero are set to zero. All
% values outside of the 'circle' are set to zero. This effectively
% preserves all the data from the circle and can be averaged in the
% code below.

AVG(i,1) = sum(sum(CSVOpis))/sum(sum(CSVOpis~=0,1));
% Opisthenar temperature is averages by finding the sum of all

```



```

% temperature values in the matrix CSVOpis and dividing by the number
% of nonzero values.

% The fingernail measurement follows , the circle diameter is set to 6
% and a circle is generated using meshgrid and D is assigned a
logical
% circle
x = 6;
[rr cc] = meshgrid(1:x+1);
D = sqrt((rr-((x/2)+1)).^2+(cc-((x/2)+1)).^2)<=x/2-1;

% The operator is asked to point to the Distal section of the index
% finger. that is mostly the fingernail. The same process is taken as
% for the opisthenar measurement above except D is used as the circle
% matrix in which the values are calculated.
title('Distal')

[x2,y2] = ginput(1);

CSVFing = CSV(y2-x/2:y2+x/2,x2-x/2:x2+x/2);
CSVFing(D==0)=0;
CSVOptic = image3(y2-x/2:y2+x/2,x2-x/2:x2+x/2);
CSVOptic(D==1)=0;
image3(y2-x/2:y2+x/2,x2-x/2:x2+x/2)=CSVOptic;
imshow(image3)

% Co-ordinates are saved for future reference.
coords(i,7)=x2;
coords(i,8)=y2;

AVG(i,2) = sum(sum(CSVFing))/sum(sum(CSVFing~=0,1));
% Average value for the distal phalange (index fingernail) is found.
end

% The following code presents the data in an excel sheet with one line
for
% each measurmenet period.

% Housekeeping
files2 = filestrings;
[len ~] = size(files2);

time = zeros(len,5);
% Time will collate all the data required. Including PMv data,
% environmental variables, time data, infrared data (opisthenar and
% fingernail temperature)

% Variable set to assigned start time to the data set.
timestart=17;

for i = 1: len
    % The hour and minute of each measurement point is found and assigned
    % to first two columns of 'time'. The matrix 'files2' holds the
    % filenames of all the infrared data. Each filename holds the hour
    % minute and second in which the data was recorded. This code
extracts
    % the hour and minute
    time(i,1) = str2double(files2(i,timestart:timestart+1));
    time(i,2) = str2double(files2(i,timestart+3:timestart+4));

    % This code extract the seconds from the filename data and assigns
to
    % the third column in 'time'
    time(i,3) = str2double(files2(i,timestart+6:timestart+7));

```

```

end

% The following for loop adds formatting to the time data and converts
each
% number to a string so that the data can be exported at a later stage.
The
% string time is assigned to timexs.
for i = 1:len

    if time(i,1) < 10

        if time(i,2) < 10
            timexs(i,:) = ['0' num2str(time(i,1)) ':' num2str(time(i,2))
];
        else
            timexs(i,:) = ['0' num2str(time(i,1)) ':' num2str(time(i,2))
];
        end
    else
        if time(i,2) < 10
            timexs(i,:) = [num2str(time(i,1)) ':' num2str(time(i,2)) ];
        else
            timexs(i,:) = [num2str(time(i,1)) ':' num2str(time(i,2)) ];
        end
    end
end

end

% The data is saved so it can be accessed later and by other scripts and
% functions

save('NEWDATARUN.mat')

```