Temperature and comfort monitoring systems for humans

Garcia-Souto, M d Pilar

Temperature and comfort monitoring systems for humans

by

M d Pilar Garcia-Souto

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I certify that this thesis, and the research to which it refers, are the product of my own work, and that any ideas or quotations from the work of other people, published or otherwise, are fully acknowledged in accordance with the standard referencing practices of the discipline.

Signed : ____________________________

M d Pilar Garcia-Souto

A mis padres

Abstract

Thermoregulation system and human body responses, both physiological (i.e. skin and core temperature) and psychological (thermal sensation and thermal comfort), have been of considerable interest to researchers. However, while reactions to extreme conditions are well understood and explained, there is a considerable knowledge gap for mild temperature range adaptation. Previous research focused on the whole body response, while local analysis is more appropriate for a new generation of intelligent thermal control systems such as needed in planes. Furthermore majority of previous studies were carried out predominantly on mannequins or with subjects placed in highly controlled lab chambers, hence adaptations in normal shared spaces is not investigated in sufficient depth. In addition, no study investigated infants' temperature adaptation.

This thesis describes the comprehensive study of the human temperature distribution in selected areas, both for adults and infants under the age of 2. Furthermore, variation of core and local skin temperature, thermal sensation and level of comfort due to long periods of inactivity were also investigated in adults. These studies have set the basis for the development of temperature monitoring systems.

The first monitoring system specific to children under 2 provides fever detection based on skin temperature measurement. It was developed for a Spanish textile company (AITEX), and it is a patent under consideration. The second system monitors level of comfort and thermal sensation of adults in indoor environments. The system is based on pre-existing statistical studies and Fanger's steady-state model. It adapts to the individual while analysing real time skin temperature distribution, and identifies behavioural responses. The system was developed within the international project SEAT, to provide greater comfort to passengers in long-haul flights but is being considered for use in shared environments such as open space offices. Additionally, concepts for contact-less systems for core temperature estimation are proposed, addressing practical problems for large-scale fever screen.

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Table of contents

ABSTRACT **4**

ACKNOWLEDGEMENTS **6**

TABLE OF CONTENTS **8**

LIST OF FIGURES **11**

LIST OF TABLES **13**

1 INTRODUCTION AND AIMS **15**

2 LITERATURE REVIEW **21**

2.1 THERMOREGULATION 21
  2.1.1 Balance equation of heat exchange *22*
  2.1.2 Heat exchange process *27*
  2.1.3 Acclimatization *29*
  2.1.4 Health issues *30*
2.2 CORE TEMPERATURE: DEFINITION AND MEASUREMENT METHODS 30
  2.2.1 Fever *33*
2.3 SKIN TEMPERATURE 34
  2.3.1 Derivation of mean skin temperature *34*
  2.3.2 Measurement methods *37*
2.4 BODY TEMPERATURE 38
2.5 FACTORS OF BODY TEMPERATURE AND THERMOREGULATION 39
  2.5.1 Environmental conditions *39*
  2.5.2 Anthropometric characteristics *41*
  2.5.3 Variable individual characteristics *43*
  2.5.4 Others factors *45*
2.6 RELATION OF CORE AND SURFACE TEMPERATURE IN A HUMAN BODY 47
2.7 MODELS 48
  2.7.1 Thermoregulatory system *48*
  2.7.2 Prediction of core temperature *50*
  2.7.3 Prediction of mean skin temperature *51*
2.8 RANGES OF TEMPERATURE 51
2.9 CLOTHING CHARACTERIZATION 52
  2.9.1 Clothing thermal insulation factors *52*
  2.9.2 Estimation methods *53*
  2.9.3 Predicting methods *54*
  2.9.4 Typical thermal insulation values *55*
2.10 COMFORT IN ENCLOSED SPACES: RELEVANT ASPECTS 55
  2.10.1 General indoor environments *56*
  2.10.2 Flight environment *59*
  2.10.3 Ranking *60*
2.11 THERMAL COMFORT 61
  2.11.1 Rating scales *62*
  2.11.2 Factors *62*
  2.11.3 Environmental indices for comfort measurement *66*
  2.11.4 Models *67*
  2.11.5 Thermal comfort level estimation *70*
  2.11.6 Comfort zone *76*
  2.11.7 Towards an comfort level assessment system *80*
  2.11.8 Thermal comfort studies into vehicle cabins *81*

3 EXPERIMENTAL SETUP **84**

3.1 SUBJECT GROUPS 84
3.2 MEASUREMENT ROOMS 85
3.3 SELECTION OF SKIN LOCATIONS 85
3.4 EQUIPMENT 86
3.5 PROCEDURE 88

4 INFANTS TEMPERATURE MONITORING: FEVER RECOGNITION IN CHILDREN UNDER 2 90

4.1 Study design 91
4.1.1 Group stratification 92
4.2 Data analysis 93
4.2.1 Body and local skin temperature characterization 93
4.2.2 Body and skin temperature relation 94
4.2.3 Identification of suitable locations 94
4.2.4 Identification of febrile babies using local skin temperatures 94
4.3 Results 95
4.3.1 Core temperature characterization 95
4.3.2 Skin temperature characterization 98
4.3.3 Relation between core and skin temperature 103
4.3.4 Non suitable locations 105
4.3.5 Suitable locations to non-invasive core temperature monitoring 106
4.4 Discussion 112
4.4.1 Classification of the suitable locations 112
4.4.2 Error of a single fever sensor 113
4.4.3 Evaluation of possible systems for fever identification 115
4.4.4 Implications of the use of single or multiple thresholds 117
4.5 Conclusions 118

5 TEMPERATURE IN ADULTS AT DIFFERENT TEMPERATURE LEVELS 120

5.1 Study design 121
5.1.1 Group stratification 122
5.2 Data analysis 122
5.2.1 Skin temperature mapping at different room temperatures 122
5.2.2 Statistical model generation: assumptions and procedure 123
5.2.3 Temperature prediction: simple multi-linear regression 125
5.2.4 Temperature prediction: multiple multi-linear regression 125
5.2.5 Comparison with accuracy for mean skin temperature 127
5.3 Results 128
5.3.1 Skin temperature mapping at different room temperatures 128
5.3.2 Identification of multicollinearity 130
5.3.3 Prediction of local skin temperatures: single multilinear regression 130
5.3.4 Observed core and skin temperature behaviour 131
5.3.5 Prediction of local skin temperatures: multiple multilinear regression 132
5.3.6 Comparison with accuracy for mean skin temperature 132
5.4 Discussion 132
5.4.1 Relevant factors 132
5.4.2 Thermoregulatory system 135
5.4.3 Temperature mapping: comparison with previous studies 136
5.4.4 Single versus multiple multilinear regressions 139
5.5 Conclusions 140

6 ALTERNATIVE NON-INTRUSIVE METHODS FOR CORE TEMPERATURE ESTIMATION IN ADULTS 142

6.1 Core temperature estimation using local skin temperature measurements 143
6.1.1 Study design 143
6.1.2 Data analysis 143
6.1.3 Results 147
6.2 Core temperature estimation using IR images of ears 157
6.2.1 Study design 157
6.2.2 Data analysis 158
6.2.3 Results 158
6.2.4 Discussion 161
6.3 Conclusion 162

7 EFFECT OF LONG PERIODS OF INACTIVITY ON TEMPERATURE, THERMAL SENSATION AND COMFORT LEVEL IN ADULTS 164

7.1 Study design 164
7.1.1 Scope 164

7.2 Data analysis 165

7.2.1 Evolution of temperature in time 165

7.2.2 Temperature change in time: effect of room temperature 165

7.2.3 Evolution of thermal sensation and comfort level in time 166

7.2.4 Time correction factor 166

7.3 Results 167

7.3.1 Evolution of temperature in time 167

7.3.2 Temperature change in time: effect of room temperature 167

7.3.3 Evolution of thermal sensation and comfort level in time 171

7.3.4 Time correction factor 174

7.4 Discussion 176

7.4.1 Temperature evolution in time 176

7.4.2 Thermal sensation and comfort level evolution in time. 184

7.5 Conclusions 185

8 THERMAL COMFORT MODEL 187

8.1 Proposed thermal comfort model 188

8.1.1 Basic thermal comfort model 190

8.1.2 Personal temperature module 192

8.1.3 Behavioural adaptation module 193

8.1.4 Decision module 194

8.1.5 Application of the system to a group of people 195

8.2 Physical monitoring system 197

8.3 Underlying studies 197

8.3.1 Personal estimation of thermal sensation and comfort level 198

8.4 Assessment of the model 202

8.5 Conclusions 204

9 CONCLUSIONS 206

9.1 Achievements 206

9.2 Future work 212

REFERENCES 214

APPENDICES 239

Appendix A: WHO Child Growth Standards 239

Appendix B: Thermal insulation of individual garments 241

Appendix C: Ethical approval QMREC2008/31 242

C-1) Information sheet 242

C-2) Consent form 244

Appendix D: Ethical approval QMREC2008/72 245

D-1) Information sheet 245

D-2) Consent form 247

Appendix E: Features of the measuring devices 248

Appendix F: Thermal sensation and comfort questionnaire 249

Appendix G: Identification of alpha and beta errors 250

G-1) Z-test 250

G-2) Overlap between two distributions: alpha and beta errors 251

G-3) Selecting threshold in alpha-beta graphs 252

Appendix H: Tabulation of normal curve areas 256

Appendix I: Characterization of body and local skin temperature distributions 257

I-1) Core temperature 257

I-1) Local skin temperature 258

Appendix J: Identification of relevant factors of local skin temperature in babies 263

Appendix K: Relation between core and local skin temperature in babies 265

Appendix L: Characterization of skin temperature distribution at several cohorts of healthy and febrile babies. 267

Appendix M: Core and skin temperature mapping in adults at different environments 270

Appendix N: Core and local skin temperature prediction models 275

Appendix O: Insides of non-intrusive methods for core temperature estimation 277

Appendix P: Core temperature estimation based on IR images 286

Appendix Q: Effect of long periods of inactivity 287

Appendix R: Thermal comfort model 297

List of figures

Figure 1: Body temperature evolution in cold conditions (Aschoff and Wever 1958)..............23
Figure 2: Relation between heat production, evaporative and no evaporative heat loss, and deep body temperature in a homeothermic animal. Adapted from [Mount, 1974] 28
Figure 3: Location of measuring sites listed in Table 5. Figure taken from ISO 9886:2004......37
Figure 4: Clothing insulation parameters..52
Figure 5: Relation between PMV and PPD 73
Figure 6: Local discomfort caused by vertical air temperature difference (ISO 7730) 74
Figure 7: Local discomfort caused by warm and cold floors (ISO 7730)..................................74
Figure 8: Local thermal discomfort caused by radiant temperature asymmetry (ISO 7730)......75
Figure 9: Air speed required to offset increased temperature (from ASHRAE Standard 55) 78
Figure 10: Dissatisfaction at different ventilation rates (reproduced from [Olesen, 1973] 79
Figure 11: Location of measuring for baby's cohort (figure adapted from ISO 9886:2004)......86
Figure 12: Measuring sites for adults..86
Figure 13: Ear thermometer..87
Figure 14: Skin thermometer 87
Figure 15: Thermal imager Fluke TiR1 88
Figure 16: Skin temperature sensor applied over the skin..91
Figure 17: Possible location and states of the fever sensor on the garment................................92
Figure 18: Group stratification 92
Figure 19: Core temperature distribution..96
Figure 20: Representation of the expected local skin temperatures...99
Figure 21: Summary of relevant parameters for each of the local skin temperatures................99
Figure 22: Mean temperature deviation of categories 1 and 3 with respect to mean for category 2. Limit values identify differences on the temperature of ±0.3ºC. 101
Figure 23: Mean skin temperature at locations *T5*, *T6* and *T14* versus number of layers covering the location. For *T14*, two cases of only one layer were considered, socks and shoes. 103
Figure 24: Forehead temperature versus core temperature..103
Figure 25: Normalized temperature distribution on the right arm in upper location for two cohorts. a) $Tc< 37.3°C$. b) $Tc\geq 37.3°C$. 105
Figure 26: Alpha (detected false positives) and beta (missed true positives) errors for different skin temperature thresholds at the forehead for 3 given cohorts. 106
Figure 27: Alpha (detected false positives) and beta (missed true positives) errors for different skin temperature thresholds at the right scapula. 107
Figure 28: Alpha (detected false positives) and beta (missed true positives) errors for different skin temperature thresholds at the right arm in upper location. (*A* or *SWB*) awake or sleeping with a blanket; (*SWOB*) sleeping without a blanket...108
Figure 29: Alpha (detected false positives) and beta (missed true positives) errors for different skin temperature thresholds at the left arm in lower location. (*A* or *SWOB*) awake or sleeping without blanket; (*SWB*) sleeping with a blanket 108
Figure 30: Alpha (detected false positives) and beta (missed true positives) errors for different skin temperature thresholds at the left hand. (A) awake; (SWB) sleeping with a blanket.........109
Figure 31: Alpha (detected false positives) and beta (missed true positives) errors for different skin temperature thresholds at the right abdomen. (*A* or *SWOB*) awake or sleeping without a blanket; (*SWB*) sleeping with a blanket 110
Figure 32: Alpha (detected false positives) and beta (missed true positives) errors for different skin temperature thresholds at the left paravertebral. (*A* or *SWOB*) awake or sleeping without a blanket (*SWB*) sleeping with a blanket. 110
Figure 33: Alpha (detected false positives) and beta (missed true positives) errors for different skin temperature thresholds at the left posterior thigh. (*A* or *SWOB*) awake or sleeping without blanket (*SWB*) sleeping with a blanket 111
Figure 34: Alpha (detected false positives) and beta (missed true positives) errors for different skin temperature thresholds at the left wrist. (*A*) awake; (*SWB*) sleeping with a blanket..........112
Figure 35: Possible readings 117
Figure 36: Local skin temperature at forehead for different environmental temperatures. 128

Figure 37: Skin temperature distribution in adults for different room temperature conditions 129
Figure 38: Comparison of present and previous studies of local skin temperature. (Full lines) observed values in the present study. (Broken lines) observations of other authors: (1) Burton 1955, (2) Werner 1980, (3) Houdas 1982, (4) Webb 1992, (5) Huizenga 2004 and (6) Munir 2009. 137
Figure 39: Core temperature distributions at different local skin temperatures ranges 147
Figure 40: Core temperature versus skin temperature at several locations....149
Figure 41: Assessment of core temperature models regarding their effectiveness, number of parameters involved and level of relaxation of the constraints. *Effectiveness* = $R^2 * N_{cases}$....152
Figure 42: Assessment of core temperature models regarding the number of parameters involved, the R-value they achieve and the level of relaxation of the constraints. 153
Figure 43: Thermal image taken with a camera Fluke TiR1 157
Figure 44: Examples of thermal images of ears....157
Figure 45: Frequencies of deviation between T_c and $T_{average}$....159
Figure 46: Frequencies of deviation between T_c and T_{max}....159
Figure 47: Relation between core temperature and ear channel temperature for adults (maximum temperature detected by the IR imager). 160
Figure 48: Relation between core temperature and ear channel temperature for adults (average temperature detected by the IR imager in a circular area around the ear). 160
Figure 49: Core and local skin temperatures versus time in prolonged periods of inactivity for different T_{room} categories, defined according to **Table Q2**. 167
Figure 50: Variation of core temperature and local skin temperatures in prolonged periods of inactivity. Same graphs but presented by location are given in **appendix Q3**. Indices for skin temperature in the legend stand for forehead (0), upper chest (1), upper arm (3), abdomen (5), hand (7), knee (9) and shin (11). 168
Figure 51: Change in time of core and local skin temperatures versus room temperature during prolonged periods of inactivity. Skin temperature indices stand for forehead (0), upper chest (1), upper arm (3), abdomen (5), hand (7), knee (9) and shin (11). 171
Figure 52: Thermal sensation and comfort level versus time during prolonged periods of inactivity at different T_{room} categories, defined according to **Table Q2** 172
Figure 53: Thermal sensation and comfort level vs. time during prolonged periods of inactivity 172
Figure 54: Thermal sensation and comfort level curves at the beginning and end of a prolonged period of inactivity; and average....173
Figure 55: Change in time of thermal sensation and comfort level versus room temperature during prolonged periods of inactivity....174
Figure 56: Logo of the international SEAT project. 189
Figure 57: Sketch of thermal comfort model....189
Figure 58: PMV values versus room temperature for different values of clothing insulation..191
Figure 59: PMV values versus room temperature for different values of metabolic rate....191
Figure 60: Example of bad use of the air conditioning system by the passenger where the passenger falls asleep with the air supply on and eventually feels very cold. 193
Figure 61: Flow chart of the thermal comfort model....196
Figure 62: Prototype of the physical system for comfort monitoring....197
Figure 63: Aircraft cabin mock-up at Thales (Toulouse) 197
Figure 64: Thermal sensation and comfort level relation 198
Figure 65: Comfort level versus thermal sensation 199
Figure 66: Thermal sensation and comfort level versus room temperature....199
Figure 67: Comparison between voted *TS* and *CL** values and those predicted by the full models. 200
Figure 68: Comparison between voted *TS* and *CL** values and those predicted by one of the simplified models. 201
Figure 69: Accuracy of *basic thermal comfort model* 203
Figure 70: Accuracy of *personal temperature model* 204
Figure 71: Accuracy of *TS* prediction when combining *basic thermal comfort model* and *personal temperature model* (combination 3)....204

List of tables

Table 1: Metabolic rate during different activities [ISO 7730, 1994]..24
Table 2: Heat production of an adult person during different activities [ISO 7730, 1994]. 24
Table 3: Factors influencing each of the heat transfer modes. Adapted from [Ingram, 1975] ...27
Table 4: Studies of alternative methods to the golden standards for core body temperature......32
Table 5: Scheme of skin temperature measuring sites proposed by ISO 9886:2004..................37
Table 6: BMI categories defined by the World Health Organization [WHO, BMI]..................43
Table 7: Ranges of clothing insulation estimated by Araźny [Araźny, 2006] for different thermal environments..55
Table 8: Dimensions for the assessment of office environmental quality as classified by Vischer [Vischer, 1989][Vischer, 1996]. In italic indications of assessment scales, which rate 1 to 5. ...56
Table 9: Ranges of air velocity and subjects reactions [PLEA, 2007].......................................57
Table 10: Seat characteristics for different travel options. More popular values are presented in brackets 60
Table 11: Thermal comfort scales: ASHRAE, Bedford and Preference scale. Points are given in the symmetrical (op1) and asymmetrical (op2) scale. 62
Table 12: Three categories of thermal environment. Percentage of dissatisfied due to general comfort and local discomfort [ISO 7730, 2005][CEN, 1998] 77
Table 13: Recommended categories for local thermal discomfort parameters...........................77
Table 14: Recommended criteria for thermal comfort and ventilation rates according to ISO 7730 and CR 1752 [ISO 7730, 2005][CEN, 1998]...78
Table 15: Required ventilation per person with and without smoking 79
Table 16: Local air velocities on a body in seated position inside a vehicle cabin.....................82
Table 17: Characterization of suitable locations for core temperature monitoring attending to temperature distribution and error curves 113
Table 18: Possible cases of fever assessment by a single sensor 114
Table 19: Error estimation for single fever sensors 115
Table 20: Error estimation for systems of several fever sensors..116
Table 21: Characterization of proposed sensors 117
Table 22: Summary of previous studies where local skin temperature was observed for different environmental conditions...121
Table 23: Description of the experimental data based on 1612 samples, 48% of them taken in male volunteers and 52% taken from female volunteers 122
Table 24: Room...122
Table 25: Computed R-values of the linear regression between the obtained and predicted skin temperatures at each location and for each method – control and modifications-.....................132
Table 26: Comparison on the efficiency of core and skin temperatures prediction. Cases under consideration are: (Single factor) Equations where only T_{room} is used as independent parameter. (Control) equations used as control –equation **35**-, where up to 7 independent variables are taken into account. (Mod 4) Equations obtained with modification 4 –equation **39** -..............139
Table 27: 80% confidence intervals of the predicted core and skin temperatures in three different cases, described in**Table 26**. 139
Table 28: Constrains to the model: local skin temperatures for which the new model applies. Values have been chosen to provide higher correlation...150
Table 29: Optimal models under assessment method 1 for the prediction of core temperature of an adult based on environmental and skin temperature measurements. No skin temperature constraints apply. 152
Table 30: Optimal models under assessment method 2 for the prediction of core temperature of an adult based on environmental measurements and skin temperature measurements. Strict skin temperature constraints apply (0 relax factor) 153
Table 31: Coefficients for the core temperature predictive model based on IR images of ears. 161
Table 32: Coefficients for the multi-linear regressions computing the time-factors (m_i) of core and local skin temperatures, which is $\Delta Tskin/\Delta t$ and $\Delta Tc/\Delta t$...175

Table 33: Coefficients for the multi-linear regressions computing the time-factors (m_i) of thermal sensation and comfort level. 176
Table 34: Characterization of the core and skin temperature vs. time curves....176
Table 35: Characterization of the thermal sensation and comfort level vs. time curves....184
Table 36: Basic scheme of decisions for the estimation of the reliability of the thermal sensation obtained by the *Behavioural adaptation model*. Furthermore the history for the particular person is taken into account as a correction factor. 194
Table 37: Example of decision process done in the *decision module*. The outputs of the *basic thermal model* are tagged with 1, the outputs of the *behavioural-adaptation module* with a 2 and finally with a 3 the outputs of *personal temperature module*. 194
Table 38: Decision in the *personal temperature module* 202
Table 39: Decision in the *personal temperature module* 203

1 Introduction and aims

The ability to maintain a constant body temperature is one of the main characteristics in mammals, and which makes us different from cold blooded animals. Mammals have developed the means of adaptation to different environments. Particularly interesting is the case of humans and their behavioural adaptation such as the use of clothing and indoor climate control systems. Hence, thermoregulation system and reaction of human body to different environments, both physiological (i.e. skin and core temperature) and psychological (thermal sensation and thermal comfort) are of great interest to biologists and indoor climate engineers. First of all, thermoregulation maintains people alive by keeping their core body temperature within limits by means of physiological, morphological, and behavioural responses to the environmental conditions. Understanding its purpose, causes, effectors and limitations leads to a better human adaptation to the environment, adaptation to a wider range of environmental conditions, the identification of unhealthy environments and the maximum exposure to them without undertaking health risks. Secondly, the establishment of normal physiological and psychological response to given environmental (i.e. air temperature, radiant temperature, air velocity, humidity) and individual (i.e. clothing, activity) conditions allows the identification of thermoregulatory system malfunction due to health problems and also the level of comfort (e.g. too hot, hot, neutral, cold or too cold) one might experience within that particular environment. Hence, thermoregulation and physiological and psychological responses have been widely studied and modelled in the literature, both theoretically and experimentally.

Thermoregulation is the mechanism by which the core body temperature of a person is maintained within fairly narrow limits. This system balances the heat produced (the metabolic rate), energy spent in doing work and the heat exchange with the surroundings, which occurs as a combination of radiant, convective and conductive channels. Heat balance is achieved by physiological changes (e.g. peripheral vasoconstriction reduces the heat exchanged with the environment while vasodilatation induces an increase; evaporative heat loss is increased by panting and sweating), morphological changes (e.g. hormonally based changes in the metabolic rate, modification of the sub-dermal insulation), and behavioural changes (e.g. perform exercise for greater production of heat, reduction/increase of the surface area in order to reduce/increase the heat exchange with the environment). Both healthy conditions and comfortable conditions are defined by which environments the thermoregulatory system can cope with, for how long it can sustain the balance and when it reaches its limits.

Directly related to the thermoregulation are core body temperature and skin temperature. Core body temperature refers to the tissues of the body located at a sufficient depth such that they are not affected by the external temperature. However, this is just a concept and can not be practically measurable. Several methods are proposed for its estimation, e.g. rectal temperature, tympanic temperature and pulmonary artery temperature among others. These methods were compared in the literature, with the conclusion that for non-clinical purposes the tympanic temperature measured by infrared thermometer is a good option as it is accurate, fast, clean and friendlier than the others. Measurement of the core body temperature aims, in most cases, to detect fever, i.e. an abnormally high body core temperature. The exact value for fever onset is still under discussion. Fever might be caused by health problems such as infections, hence its early identification can be used to save lives or avoid epidemics. Fever can also be seen in people while exercising or working under extreme hot conditions; in these cases its monitoring could alert when high risk conditions are reached. Skin temperature refers to the temperature at the surface of the skin. It is generally measured and reported as a weighted average for the whole body. Several formulas were proposed to obtain the mean skin temperature. These formulas take into consideration different number of locations and different weighting coefficients, which can be obtained according to the area extension or best fit in multilinear regressions among other approaches. Skin temperature changes with the thermal environment, clothing, and type of activity. Hence, it is of great interest to evaluate the thermal balance of the body in cold stress and the level of thermal comfort of a person in a given environment. It also rules the amount of heat exchanged with the environment as this is in part related with the gradient of temperature between body surface and air. Skin temperature can be measured with thermistors, although contact-less radiation thermometers are preferred as they are easy to use, friendlier and they do not cover the areas of interest, hence do not affect the temperature. Finally, mean body temperature can be obtained as a combination of core body temperature and skin temperature.

The thermoregulatory system is very complex, and so is the prediction of core body temperature and skin temperature. Identified relevant factors are environmental conditions (e.g. temperature, humidity, air velocity, characteristics of the transient conditions), individual anthropometric characteristics (e.g. age, gender, physical fitness level), and variable individual characteristics (e.g. activity level, clothing, emotions, level of acclimatization, food intake, circadian rhythm) among others. Understanding the relative effect of each of these factors leads to more accurate prediction models, whose complexity and scope are increasing.

The comfort a person experiences within an enclosed space can be divided into several aspects, mainly:

- air quality
- thermal comfort
- aural comfort
- spatial comfort.

These aspects influence the productivity, morale/satisfaction, and health or well-being of the occupants. Although there is not a defined method of combining the level of comfort due to each of these factors, temperature was found to be the most important aspect for comfort. The study of comfort is necessary from an engineering point of view to establish design criteria both of space and environmental control systems, evaluate the performance of HVAC systems, or for the optimization of energy.

Thermal comfort investigates the level of comfort a person experiences when subjected to certain environmental conditions. Thermal comfort can be defined in several ways; it is a neutral state at which a person would not wish to feel any cooler or any hotter. A person can specify his/her thermal comfort by means of rating scales which quantify both thermal sensation and comfort level. The ASHRAE scale is perhaps the most widely used. It lists 7 different thermal sensations (i.e. hot, warm, slightly warm, neutral, slightly cool, cool, cold) and assign a number to each of them (+3, +2, +1, 0, -1, -2 and -3). Similarly, environmental indices were created in order to describe with a unique parameter the different aspects of the environment such that they can be related to the thermal comfort of a person. These indices can be empirical (e.g. scales of warmth, equivalent temperature or operative temperature) or analytical (e.g. predicted 4-hour sweat rate, predicted mean vote or PMV or heat stress index). Among these indices the Predicted Mean Vote (PMV) is the most used to determine the level of comfort of a person with the environment. Created in 1970 by Fanger and valid in steady-state conditions, this index has been adopted by international standards such as ISO and ASHRAE. It is a complicated formula that combines metabolic rate, clothing insulation, environmental conditions, heat transfer coefficients and clothing surface temperature. PMV is a statistical value as it represents the average vote of a large group of people when subjected to a given environment. Although an average person might be comfortable, there are always people who would feel uncomfortable. The PPD index, which relates with PMV, indicates the Percentage of People Dissatisfied. Both PMV and PPD are global parameters which indicate the level of comfort of the body as a whole. There are also local factors which can cause discomfort (e.g. draughts, vertical air temperature difference, warm or cold floors, warm or cold walls, and warm or cold ceilings), which can be also quantified. The monitoring of thermal comfort is of great interest, especially now with the increase of time spent indoors and with the increase of the comfort expectations. Standards related to the indoor environments are established by international organizations such as ISO, CEN and ASHRAE based on thermal comfort data. Spaces at which it applies are offices, cafeterias, cinemas, theatres, airports, train stations, plane cabins, and so on.

Despite of the great interest in thermoregulation and thermal comfort, there are still areas which have not been fully addressed as data field studies of the skin temperature are limited. Most of the studies were performed in manikins or naked adults within environmental chambers. This does not reflect every day situations such as someone working in an office, travelling or going to the cinema, theatre, and so on. Female representation in these studies is very limited, and no data is available for young children. Furthermore, most of the data field studies focused on global parameters such as mean skin temperature, and did not report local skin temperatures. As a consequence, most of the current models for skin temperature only predict the mean skin temperature values, and have as a result limited applicability. The prediction of thermal sensation and comfort level is based on statistical models which only give the average response to given conditions, hence do not cover a significant percentage of the population. Furthermore these models are not able to adapt in real time to particular individuals, something which would allow a better understanding of the comfort situation of a given person and a better adaptation to his/her requirements. Besides the great potential of core temperature for the identification of health problems, there are not non-invasive methods which allow its measurement and monitoring at a mass screen and no clinical scale. The listed weaknesses in the field have been addressed in the present work representing our contribution to the state of art. A summary is presented below mapping the contributions within the chapters.

A comprehensive skin temperature mapping was collected for 2 different cohorts: (1) clothed children under 2 years old; and (2) clothed adults at a variety of environmental conditions while sitting. The study of the first cohort addresses the lack of data for young children while the second one focuses in the everyday conditions of a great part of the population. In both cases, female and male were equally represented, something that was missing in previous field studies. The factors affecting core temperature and skin temperature at different locations were identified. Among others, gender, age, body mass index, level of activity, and clothing were studied. In the particular case of the adults, prediction local skin temperature models were developed. These studies are presented in ***chapter 4*** and ***chapter 5***.

Two different core temperature monitoring systems were developed. They are non-intrusive, hence addressed to long-term and every-day use, something long time missing because or current options are not practical. These kinds of systems are not thought for clinical purposes but mass screening which, as stated previously, could be very beneficial. The first system was developed for the identification of fever in children under 2 years old. It is based on embedded sensors in the clothing, does not require cables and alerts carers if children are likely to have a fever. The second system focuses on groups of adults. Different options were proposed, based on skin temperatures and infrared images of ears. This latter option is completely novel. Details and results of these systems are presented in ***chapter 4*** and ***chapter 6***.

Physiological (core temperature and skin temperature) and psychological (thermal sensation and comfort level) responses to long periods of inactivity in steady-state environments were studied. Even when subjected to the same conditions, people feel the environment differently depending on how long they have spent in it. Consequently skin temperature and core temperature response varies. Simulating long periods of low activity while sitting, thermoregulatory response was studied for adults sitting up to 195 minutes while resting or performing typical office activities. This is applicable to most of the daily activities, e.g. working in offices, relaxing while watching a movie or travelling. This knowledge would lead to more accurate human response prediction models. This study is reported in ***chapter 7***.

Finally a predictive thermal comfort model indicating level of comfort and thermal sensation of adults in indoor environments has been developed. The model utilises statistical studies existing in the literature and Fanger's steady-state model, hence it considers the average response of a person as an initial approximation. However, it monitors continuously and also adapts to the individual by analyzing real time skin temperature distribution and adjusts to the occupant's feedback such as the use of personal air conditioning devices. This system could be used in those cases were a person sits for long periods of time. It has been developed within the international project SEAT, in an attempt of providing greater comfort to passengers in long haul flights. This system is presented in ***chapter 8***.

2 Literature review

Physiological signals provide information about the physical and psychological state of the person, such as heart rate (HR), encephalogram (EEG), electrocardiogram (ECG), galvanic skin response (GSR). One of the most important parameters is the body temperature. Apart from being one of the most common indicators for illness, it is also one of the main parameters in the evaluation of the thermal sensation and thermal comfort of a person within a given environment.

2.1 Thermoregulation

Thermoregulation is the mechanism by which the core body temperature of homoeothermic animals is maintained within fairly narrow limits. Thermoregulation occurs as a result of physiological, morphological, and behavioural responses to the environmental conditions. The most important aspects of the environmental conditions are air temperature, radiant temperatures (infrared and solar radiation), air velocity, humidity, wetting by precipitation or otherwise, and the nature of the floor if insulation is poor [Ingram, 1975]. Thermoregulation is achieved by having control over both heat production and insulation.

Some of the most important works in the field are by Burton AC, Hardy JD, Stolwijk JAJ, Ingram DL, Gagge AP, Edholm OG, Fanger PO and de Dear R, to mention a few. They studied the thermoregulation process, its factors and attributes, in animals and humans. Fundamentals about thermoregulation are withdrawn from the books published by Burton [Burton, 1955] and Ingram [Ingram, 1975].

2.1.1 Balance equation of heat exchange

Burton defined a person's body as a "thermodynamic engine" that continuously transforms chemical energy of food into mechanical work and heat. The heat produced by the metabolic activity or metabolic rate (M) balances with the rate of heat lost (H), the work being performed (W) and rate of change of stored heat (S) (equation **1**).

$$M = H + W + S \tag{1}$$

M is always positive as well as W, when not negligible. S is positive when heat is being stored and mean body temperature is rising. H accounts for the heat exchange between body and environment, which is positive in general, when the generated heat is being dissipated to the environment. H becomes negative when the environment acts as a heat source, e.g. during rewarming following hyperthermia or when environmental temperature is greater than body temperature. Heat exchange is measured by calorimetry, either by direct or indirect process.

The heat exchange through the skin (H) is given by the combination of radiant (H_R), convective (H_C), conductive (H_K) and evaporative heat loss (H_E) (equation **2**). H_R, H_C, and H_K could be positive or negative, depending on the gradient of temperature between body and environment, for which they are denoted as "sensible" terms of heat dissipation. H_E is caused by the heat taken out by evaporating water. It is nearly always positive, although under extreme conditions there may be net condensation of water vapour on the body. In addition, a small amount of heat exchange by respiration in the form of evaporation and convection ($E_{res} + C_{res}$) also takes place [ISO 9920, 1995].

The general heat balance equation of the body can be written as equation **3** [ISO 7933, 2004][ISO 11079, 1993][ISO 9920, 1995].

$$H = H_R + H_C + H_K + H_E \tag{2}$$

$$M - W = S + H_R + H_C + H_K + H_E + E_{res} + C_{res} \tag{3}$$

Heat loss also occurs by expulsion of urine and faeces (about 1% of the total resting heat loss) or by the warming of inhaled air (<1%). A small quantity of heat is also transferred to ingested food and water, consumption of the later being larger at high environmental temperatures. Heat exchange due to these factors is usually neglected.

Thermoregulation maintains body temperature stable despite the fluctuations in the environmental conditions, although the peripheral tissue temperatures vary considerably as shown in **Figure 1**, which was adapted from Aschoff and Wever [Aschoff, 1958] .

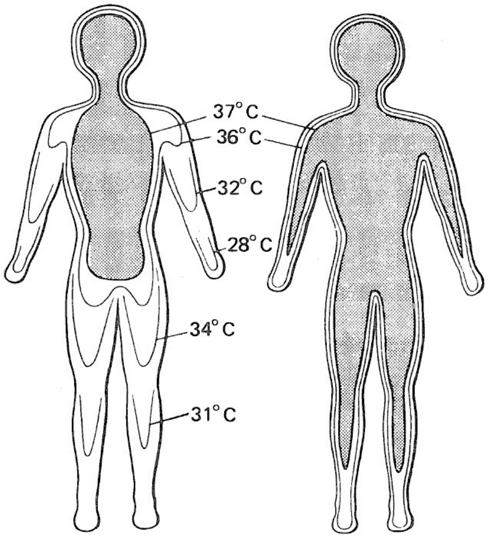


Figure 1: Body temperature evolution in cold conditions (Aschoff and Wever 1958)

2.1.1.1 Metabolic rate

Metabolic rate is the overall sum of all exothermic chemical reactions in the body. M depends on the anthropometric characteristics of the person and activity (**table 1)** – essentially muscular activity – [Edholm, 1978]. The resting metabolic rate is approximately 10% lower in women than men and declines gradually with age, being highest for babies. Heat production per different activities is shown in **table 2**. The maximum rate a person can achieve depends on their fitness. Most people can increase the heat production between rest and the hardest physical work of which they are capable by at least ten times, while athletes can reach a factor of 20.

Metabolism is commonly estimated by the rate of oxygen consumption, subjected to external work being negligible, as the heat liberated per unit quantity of oxygen consumed that can be measured. If external work is performed, the metabolic rate appears as the heat produced plus the external work.

Activity	M (W/m^2)
Reclining	46
Seated, relaxed	58
Sedentary activity (e.g. office, school, laboratory)	70
Standing, light activity (e.g. shopping, light industry)	93
Standing, medium activity (e.g. shop assistant, domestic work, machine work)	116

Table 1: Metabolic rate during different activities [ISO 7730, 1994].

Activity	Heat (kcal/hour)
Resting or sleeping	65
Awake, sitting quietly	100
Light exercise	170
Moderate exercise	290
Strenuous exercise	450
Very strenuous exercise	600

Table 2: Heat production of an adult person during different activities [ISO 7730, 1994].

2.1.1.1.1 Shivering

Shivering is an autonomic modification of heat production due to uncoordinated activity of muscle fibres [Edholm, 1978]. Shivering increases the heat production, up to 5 times the resting metabolic rate for the first few minutes and 2-3 times when prolonged for 1 hour [Edholm, 1978][Rosenzweig, 1989]. Muscles start to shiver soon after the subjection to cold with amplitude that it is not visible to casual observation. It spreads from facial muscles to trunk and to arms and legs; higher intensity is observed in muscles at the trunk region than those of the limbs [Tikuisis, 1991]. Shivering onset and increase of M are greater for lean people than for normal people [Tikuisis, 1991].

2.1.1.2 Radiant, convective and conductive heat loss

The radiation and convective heat exchange (H_R and H_C) refers to the exchange between the surface of the body (including clothing and uncovered skin) and the environment [ISO 11079, 1993].

Heat exchange due to radiation was first accounted based on the Stefan-Boltzmann law for total radiation of the perfect black body [Hardy, 1949], and further adjusted as the emissivities of both body and surroundings are below 1 [Jakob, 1957] (see equation **4**):

$$H_R = F.\ \sigma . A_1(T_1^4 - T_2^4) \quad \textbf{(4)}$$

where F, radiative interchange factor, is a function of the emissivities (e) and effective radiating areas (A) of both body (1) and surroundings (2).

The conductive heat exchange (H_K) is the rate of heat being transferred between the body's surface and environment or external surfaces –e.g. floor- due to direct contact. It is related to the area of contact, the degree of insulation and, in most of the cases, to the temperature difference. In can be accounted for by the expressions for convective and radiation heat exchange [ISO 11079, 1993], or in most cases, by using Fourlier's law, based on empirical Newton's law of cooling (equation **5**). Here A is the surface area, T_1-T_2 is the temperature difference across the medium, and C is the thermal conductance also called 'cooling constant' and whose inverse is the "thermal insulation" or "thermal resistance". The environmental temperature (T_2) accounting for radiant, convective and conductive heat loss (H_R, H_C, H_K) are radiant, air and floor temperature respectively.

$$H=A.C.(T_1-T_2) \tag{5}$$

Heat lost due to radiation, convection, and conduction can be modified by changes in the rate at which blood flows through the skin, as this changes the skin temperature and the tissue insulation between the core and the skin surface. E.g. on exposure to heat, an increased peripheral blood flow allows an increase in the rate of heat loss. The capacity for a surface to lose heat depends also on its position.

2.1.1.3 Evaporative heat loss

Heat is lost by evaporation of moisture, both from skin and respiratory tract, accounting for at least a 20% of the total heat loss (one-third from the respiratory tract and two-thirds from the skin surface). Evaporative heat loss is of great importance as it is the only means of dissipation when the environmental temperature is greater than the body temperature. This occurs due to the ability to sweat and allows thermoregulation under a relatively large range of environmental conditions. The evaporative heat loss appears to be controlled by a combination of skin and tympanic temperature [Hardy, 1966].

2.1.1.3.1 Cutaneous evaporative loss

The evaporation from the skin occurs as a consequence of the difference of vapour pressure at the skin and the environment, as reflected in the Gagge's formula [Gagge, 1937], hence it is more significant under dry heat. It depends on the percentage of wetted area of the body. Heat transfer comes from the latent heat of vaporization of water, which is temperature dependent – i.e. 2501 J/g at 0ºC and 2406 J/g at 40ºC -.

Man has the capacity to sweat copiously which permits him to survive in dry heat at 50ºC or more with a normal deep body temperature. The amount of whole-body sweat one produces depends on the severity of the heat load [Ingram, 1975][Mount, 1968] [ISO 7933, 2004], the cumulative changes in the body heat storage rate [Flouris, 2010], and increases with the intensity of the activity [Flouris, 2010][Smith CJ, 2010]. It also depends on individual characteristics such as sex, with men producing more sweat than women [Fox, 1969][Wyndham, 1965], or the person's heat balance status, being quantified as the ratio of evaporation required for heat balance relative to the maximum evaporation possible [Bain, 2010b]. However they are not associated with rectal, tympanic, mean skin, or mean body temperatures [Flouris, 2010]. The sweat rates are highly dependent on the location, being highest on the back and lowest at fingers, thumbs, and palms [Smith CJ, 2010]. Sweat only occurs after 5-40 minutes of initial exposure to heat, starting at the lower legs and gradually moving to abdomen, chest, and finally forehead and forearm [Hertzman, 1952][Randall, 1953]. This order prevails even when the heat load is local. Continuous prolonged exposure to severe heat can tire the glands out which cease to function. When subjected to transient exposures to heat – neutral to heat – sweat onset occurred when average skin temperature was above 33.5ºC and tympanic temperature was above 36.6ºC at the same time [Hardy, 1966]. The relationship between sweat secretion and evaporation was theoretically described by Tam et al. [Tam, 1976] and experimentally characterized by Werner et al. [Werner, 1980a] and Stolwijk and Hardy [Stolwijk, 1966][Hardy, 1966] among others. Measuring at different room temperatures, they obtained the curves of evaporative rate versus sweat rate for the whole body. Local evaporation rate curves differ considerable from the curve of the mean evaporation rate [Werner, 1980a].

2.1.1.3.2 Respiration

Respiration causes evaporative heat transfer in the upper respiratory tract and it is due to the continuous movement of air over this area. The heat loss per unit of air volume respired is a function of the environmental temperature and humidity [ISO 11079, 1993] such that the warmer and more humid the air, the smaller the net heat loss. ISO [ISO 7933, 2004] provided empirical equations for the calculation of C_{res} and E_{res}. Heat lost is calculated to be 62J/litre for normal breathing, when the air enters and leaves via the nostril; under heat stress, when exhalation takes place via mouth, the heat lost is about 116J/litre. In fact, an increase in the respiratory frequency or "panting" is a specialized mechanism for increasing the evaporation.

In summary **Table 3** presents the main factors of each of the 4 modes of heat transfer.

Mode of transfer	Individual characteristics	Environmental characteristics
Radiant	Mean radiant temperature of surface; effective radiating area; reflectivity and emissivity	Mean radiant temperature solar radiation and reflectivity of surroundings
Convective	Surface temperature; effective convective area; radius of curvature and surface type	Air temperature; air velocity and direction
Conductive	Surface temperature; effective contact area	Floor temperature; thermal conductivity and thermal capacity of solid material
Evaporative	Surface temperature; percentage wetted area; site of evaporation relative to skin surface	Humidity; air velocity and direction

Table 3: Factors influencing each of the heat transfer modes. Adapted from [Ingram, 1975]

2.1.1.4 Heat storage

The heat that a person stores (*S*), known as thermal capacity, is commonly assumed to be 3.47kJ/(kg.ºC), which lies between the extremes values of 1.88 for fat and 4.18 for water, and is adjusted to the fat content of the subject. An average 70kg man with a mean rise in body temperature of 1ºC absorbs 70x3.47 = 242.9kJ, which represents approximately 35 minutes of resting heat production.

2.1.1.5 Mechanical power

The effective mechanical power (*W*) is small and can be neglected in most common situations, like when resting or working in a computer [ISO 7933, 2004].

2.1.2 Heat exchange process

There are three main categories for room temperature to which the body reacts differently: cold, neutral and hot, denoted as *BC*, *CD* and *DE* in the **figure 2**. The transition point C is denoted as "critical temperature".

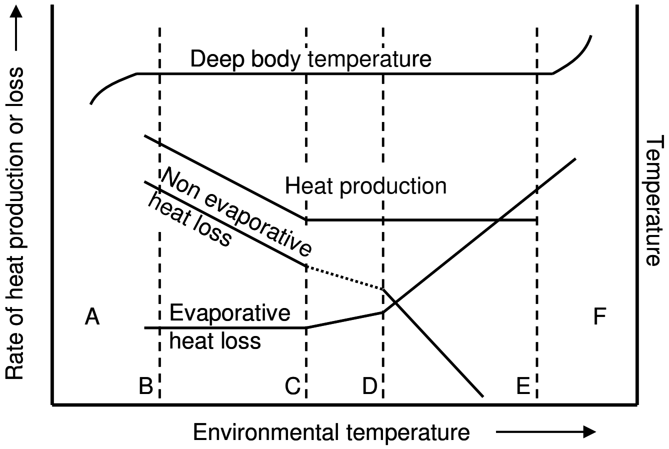


Figure 2: Relation between heat production, evaporative and no evaporative heat loss, and deep body temperature in a homeothermic animal. Adapted from [Mount, 1974]

The zone of thermal neutrality was originally defined as the range of environmental temperatures where the metabolic rate is constant and minimum. Alternative definitions were given [Mount, 1974] regarding different aspects, such as minimal metabolism (region *CE*), least thermoregulatory effort hence minimal material intake demand (region *CD*), or comfort (region not necessarily coinciding with any of the earlier cases). Here, neutral region (*CD*) is when body temperature is easily kept constant, with a constant and minimal heat production, a “sensible” (or non-evaporative) heat loss nearly constant, and little evaporative heat loss. The neutral zone varies with the age and adaptation level to the environment [Edholm, 1978] and the time of the day [Rosenzweig, 1989].

At environmental temperatures below “critical temperature” (cold region), metabolic rate increases by means of oxygen consumption in an attempt to maintain thermal equilibrium. The heat is lost through radiation, convection, and conduction as they depend on the gradient of temperature. Loss is reduced by means of insulative and behavioural adaptations, and by vasoconstriction as it lowers the gradient of temperatures occurs, with the peripheral tissues.

Under hot conditions where sensible heat is gained, evaporation (from body surface or by panting) becomes the main heat loss channel. Behavioural adaptation are common such as decreasing clothing or increasing the area subjected to evaporation. The starting point of the hot region (point *D*) corresponds to the onset of peripheral vasodilatation, which results in an increase of the thermal conductance and so an increase on the sensible heat loss. Beyond the hot region, when heat production starts to increase again, the deep body temperature will follow unless increased evaporative cooling takes place.

2.1.3 Acclimatization

Men can adapt to short and long periods of cold and heat stress exposure. Adaptation to individual cold or hot stress exposures takes place by behavioural or autonomic changes in heat production and heat exchange with the environment as detailed by Bligh et al. [Bligh 1976]:

- Modification of heat production:
  - Behavioural: co-ordinated movements of the whole body, i.e. exercise.
  - Autonomic, such as shivering.
- Modification of heat exchange with the environment
  - Behavioural: changing the ratio of surface area to mass [Edholm, 1978] [Fraise, 1973][Grivel, 1973].
  - Autonomic: immediate variations on body-environment thermal gradient by means of blood flow change; or variation of the evaporative heat loss by inducing panting or sweating.

Acclimatization to long-term climate changes requires other behavioural, morphological and physiological processes [Bligh 1976]. The adaptation overcomes the physical and physiological symptoms of cold or heat strain, i.e. discomfort, restless sleep, finding mental of physical work hard to do, unreasonable irritability typical in a person under heat stress [Edholm, 1978]. Adaptive correction effectors generate hormonally based changes on the metabolic rate; and modify the sub-dermal insulation [Bligh 1976], from 0.15clo at full vasodilatation to about 0.8-0.9 clo at full vasoconstriction [Burton, 1955].

Effective acclimatization to heat can be developed by everybody, whatever their origin [Edholm, 1978]. It involves an increase in the capacity for work, decrease of heart rate and core temperature [Griefahn, 1997], greater volume of sweat (double after 20 days [Edholm, 1978]) and less concentrated [Ingram, 1975]. Acclimatization begins in the first exposure to heat and progresses rapidly, even with short exposures [Ingram, 1975], with no extra benefits when exposed for longer than 100 uninterrupted minutes, or several exposures a day [Leithead, 1964]. Level of acclimatization and time required depend both on the subjects' characteristics and the exposure conditions. Acclimatization is more rapid in subjects who are in good physical condition, taking 4-7 days for full development and enduring for about 2 [Ingram, 1975] to 1 week [Garrett, 2009] before it is progressively lost. Acclimatization to different hot environmental conditions (warm-humid, hot-dry and radiant heat) is similarly and interchangeable [Griefahn, 1997]. Population at humid continental climates do not adapt to heat during summer due to the frequent air-conditioning use and avoidance of outdoor activity [Bain, 2010a].

Acclimatization, tolerance and response to cold has been broadly studied [Edholm, 1978][Mount 1979]. Thermal adaptation to cold is much slower compared to heat as the peripheral blood flow is lower [Höppe, 2002], and might be dependent on factors such as ethnicity [Edholm, 1978], clothing [Li, 2009], or exercise while exposed to cold [Launay, 2002]. It is believed that man's success in spreading into colder climates has largely been dependent on technology rather than on biology [Edholm, 1978].

2.1.4 Health issues

Exposure to cold and hot conditions can lead to heath problems as discussed by Edholm et al. [Edholm, 1978]. Body temperature falling below about 35ºC results in difficulties to walk and reduction of mental capacity and understanding ability. When body temperature rises above 39-40ºC, 41ºC in some cases, sudden collapse or *syncope* with loss of consciousness occurs [Wyndham, 1973b]. This is commonest form of *heat illness*. Other effects of exposure to heat although no life-threatening are *muscular cramps*, likely to be developed if sweating is heavy and salt is not replaced, and *sunburn* due to the absorption of solar radiation by the skin [Edholm, 1978]. Body temperatures below 28 or above 42ºC are life-threatening. The establishment of safety and risk range of environmental conditions is of high interest; they were identified for general population [Ellis, 1973] and workers at extreme heat conditions [Wyndham, 1973b].

2.2 Core temperature: definition and measurement methods

The core body temperature refers to the temperature of all tissues located at a sufficient depth so they are not affected by a temperature gradient through surface tissues [ISO 9886, 2004]. It is considered an important index of health status [Dollberg, 1993], being also used to detect and prevent heat-related illnesses [Höppe, 2002] like heat exhaustion or heat stoke in athletes during long exercise [Newsham, 2002]. Core body temperature remains within a narrow physiological range, mainly thanks to the thermoregulation [Stolwijk, 1966].

Core temperature is a concept and not practically measurable as such. Several approximation methods are proposed [Togawa, 1985][ISO 9886, 2004] such as oesophageal temperature, intra-abdominal temperature, oral temperature, auditory canal temperature, urine temperature, rectal temperature, or tympanic temperature. They observe mean temperature of the body mass or temperature of the blood supplied to the brain and therefore influencing the thermoregulation centres in the hypothalamus. **Rectal temperature** indicates the mean temperature of body core mass, as being surrounded by a large mass of abdominal tissues. It does not fully represent the blood temperature as the production of heat from local muscles might affect the reading. It is considered to be the most accurate approximation by ISO among the methods outlined. **Tympanic temperature** is measured by a thermal transducer placed as close as possible to the tympanic membrane, without causing damage, reflecting arterial blood temperature variations. Pre otoscopic examination and removal of wax deposits are recommended. This temperature is only applicable when environmental temperature around the head ranges 18-58 ˚C, air velocity is less than 1 m/s and mean radiant temperature is close to air temperature.

The two golden standard for core temperature used in the literature are rectal [Paes, 2010][Rubia-Rubia, 2010] and pulmonary artery [Maxton, 2004] [Robinson, 1998] [Lefrant, 2003] [Bridges, 2009] [Lawson, 2007] [Milewski, 1991] temperatures. Still, significant difference between them was found [Maxton, 2004][Robinson, 1998]. Alternatively other authors use bladder temperature [Langham, 2009][Maxton, 2004], temperature measured at nasopharyngeal [Maxton, 2004] or oesophageal temperature [Robinson, 1998]. When accuracy level is not so critical, more practical methods are sought and compared with the golden standards (**Table 4**); for example axilla and temporal artery temperature which are the less invasive methods, not very accurate but still useful for fever screen [Siberry, 2002], or a variant to temporal artery method combining forehead and behind-the-ear temperatures which appears to be more reliable than the forehead in its own [Carroll, 2004] [Lawson, 2007]. Alternative methods ought to have ±0.3°C accurate and 0.3-0.5°C standard deviation for precise [Bridges, 2009]. 0.5ºC is considered as a clinically important temperature deviation [Langham, 2009].

Ear temperature measured with infrared devices is the most popular alternative method. It is easy to apply, fast, safe and highly tolerable by the patient [Kocoglu, 2002][Talo, 1991][Milewski, 1991]. It was found accurate by many authors (see **Table 4**), both during febrile and non-febrile periods [Nimah, 2006], and validly assesses the presence of fever [van Staaija, 2003]. Mean tympanic temperature was found to be just about 0.1-0.2°C off from rectal temperatures [Kocoglu, 2002] [Rubia-Rubia, 2010], which is acceptable in non medical purposes [Rubia-Rubia, 2010]. NICE organization [NICE, 2007] establishes that healthcare professionals should it with children aged 4 weeks to 5 years besides a electronic or chemical dot thermometer in the axilla, although it should not be used as a replacement for golden standard [Paes, 2010]. Tympanic temperature readings appear to be moderately dependent on the environmental temperature (slightly underestimates in cold and slightly overestimates in warm conditions) [Werner, 1980a], the use of an ear tug which increases the measurement [Shenep, 1991], or the patient's age [Terndrup, 1991]. However the presence of acute otitis media was proved to have little direct effect [Kelly, 1991][Brennan, 1994].

Assessed method			References
Axilla	FA	RE	[NICE, 2007] under 5yr old
	UN	RE	[Anagnostakis, 1993][Kocoglu, 2002][Edwards, 2002]
	UN	PA	[Bridges, 2009][Lawson, 2007][Maxton, 2004][Robinson, 1998]
	UN	BL	[Langham, 2009]
Temporal artery	FA	PA	[Bridges, 2009] [Lawson, 2007]
	UN	RE	[Siberry, 2002] but good as fever screen [Della-Giustina, 2003]
	UN	BL	[Langham, 2009]
Tympanic	FA	RE	[Kocoglu, 2002][van Staaija, 2003][Nimah, 2006] and also indwelling bladder[Rubia-Rubia, 2010] in non medical purposes[Talo, 1991] and oral[NICE, 2007] under 5 yrs old [Shenep, 1991][Terndrup, 1991][Newsham, 2002] [Kelly, 1991]
	FA	PA	[Bridges, 2009][Milewski, 1991]
	UN	RE	[Langham, 2009] vs bladder
	UN	PA	[Lawson, 2007][Maxton, 2004][Robinson, 1998]
	UN	BL	[Langham, 2009]
Oral	FA	RE	[Kelly, 1991]
	FA	PA	[Bridges, 2009]?[Lawson, 2007]
Ear-forehead	FA	PA	(Carroll, 2004)[Lawson, 2007]
Forehead chemical thermometers	FA	PA	[NICE, 2007] under 5yrs old
	UN	BL	[Langham, 2009]
Rectal	FA	PA	[Milewski, 1991]
	UN	PA	[Maxton, 2004][Robinson, 1998]
Bladder	FA	PA	[Maxton, 2004][Lefrant, 2003]
	UN	PA	[Robinson, 1998]
Nasopharyngeal	FA	PA	[Maxton, 2004]
Oesophageal	FA	PA	[Robinson, 1998][Lefrant, 2003]
Guts temperature	FA	RE	[Edwards, 2002][Byrne, 2007] good during exercise

Table 4: Studies of alternative methods to the golden standards for core body temperature. Studies are classified by method studied, conclusion achieved - Fair Approximation (FA) or Unreliable (UN) -, and standard used for assessment – Rectal (RE), Pulmonary Artery (PA) or Bladder (BL)-.

The use of one or other method depends on the field of work. For critical medical purposes non-invasive measurements are not advisable [Langham, 2009]. When fast response is required, such as in abrupt changes of environmental temperature, supine exercise or recovery, oesophageal and intestinal temperatures [Lee, 2000][Byrne, 2007] or an ingestible telemetric temperature sensor [Byrne, 2007] are recommended. Rectal and tympanic temperatures correlate strongly during exercise but poorly in the recovery phase [Newsham, 2002], presenting significant lag respect to pulmonary artery [Maxton, 2004]. Rectal temperature shows the same changes as oesophageal or auditory canal temperature under thermal and metabolic steady state [Webb, 1993b]. For long-term monitoring like in circadian rhythm studies, gut temperature (from an ingested pill) appears to be a viable alternative [Edwards, 2002] [Waterhouse, 2005].

2.2.1 Fever

Fever is the occurrence of abnormally high core body temperature. Fever can typically be divided into three stages [Ng 2, 2005]. First the fever onset, where the body tries to increase its temperature while vasoconstriction occurs to prevents heat loss through the skin. Second the plateau of fever with the highest core temperature value. Finally, fever breaks with a reduction in the temperature. IR scanner might overlook individuals within first or third stage of fever. Fever can occur due to health problems such as infections, or during intensive exercise. Its monitoring is of great importance and it is recommended for those who may be at risk, i.e. it could identify an infection or prevent most of the heat-related illnesses in athletes [Briner, 1996][Newsham, 2002]. Furthermore, methods for outdoor fever screening are useful like during the SARS (*severe acute respiratory syndrome)* epidemic of 2003 [Liu, 2004].

The range of body temperature in nonfebrile healthy adults varies depending on the location, i.e. 34.4–37.8ºC rectal temperature, 35.4–37.8ºC tympanic temperature or 35.5 –37.0ºC axillary temperature [Sund-Levander, 2002]. There are also variations depending on gender, decline with age [Sund-Levander, 2002] or change in local metabolism, concentration of vascular networks and local variations in blood flow [ISO 9886, 2004]. The threshold at which fever starts is subjective. Some take it as body temperature over 38.0°C [Anagnostakis, 1993][van Staaija, 2003][Ng, 2005]. It can also be defined as the 95th percentile of normal ear temperature, which is 37.9°C for infants aged between 2 and 47 months [Powell, 2001].

In conclusion, fast, continuous and reliable methods for fever detection are of great interest for a broad range of scenarios, from people at airports or cinemas to children at their nursery. The current work addresses this need and presents some methods for continuous core temperature monitoring systems, both for children and adults.

2.3 Skin temperature

Skin temperature distribution is a physiological response to the combined effect of thermal environment, clothing, and type of activity, hence a parameter of interest for the evaluation of thermal balance and cold stress [Nielsen, 1984] [Mitchell, 1969] and the thermal comfort [Höppe, 2002]. Skin temperature provides fast information to central circuits, which promptly initiate corrective action even before the hypothalamus temperature is affected, such as shivering or sweating [Rosenzweig, 1989], and rules the amount of heat exchanged between a person and the environment [Mitchell, 1969].

Local skin temperature has been measured under various environmental conditions (temperature and humidity), personal circumstances (clothing and activity) and personal characteristics (gender and constitution) [Werner, 1980a][Houdas, 1982][Webb, 1992] [Huizenga, 2004][Munir, 2009][Burton, 1955][Olesen, 1973]. However, local skin temperature map on self-clothed adults undertaking low level activities while sitting in “mild” environmental temperatures has not been investigated sufficiently when it represents a great percentage of population’s every day life, working in offices, travelling, or while in theatres or cinemas. This gap is addressed in the chapter 4 of the current work. Furthermore, skin temperature mapping in children of infant age has not been reported. Chapter 3 addresses the cohort of children under 2 years old.

2.3.1 Derivation of mean skin temperature

The “true” mean skin temperature ($\overline{T_{skin}}$) is the average of an infinite number of skin surface temperatures [Nielsen, 1984]. This is not practically measurable and so approximations ought to be used, where few locations are selected, ideally representing sub-areas of the body with a homogeneous temperature. Approximations can be of different nature (using different number of points, locations and weighting factors), although they all follow the general form of $\sum c_i.T_i$, where c_i is the fraction of total body area having temperature T_i [Mitchell, 1969]. These formulas can be classified in 4 main groups according to the way they were obtained [Nielsen, 1984]:

- Area weighted formulae, based on the measurement of human surface areas done by DuBois and DuBois [DuBois, 1915]: Mitchell and Wyndham [Mitchell, 1969], Hardy and DuBois [Hardy, 1938], and Nielsen [Nielsen, 1984]. Webb et al. [Webb, 1992] used an unweighted average, although they tried to put temperature probes on the volunteer's body according with the percentage of the body surface areas given by Hardy and DuBois [Hardy, 1938].
- Weighted formulas obtained by multilinear regressions and based in the optimal agreement with the reference values (few measuring points used): Teichner [Teichner, 1958] and Ramanathan [Ramanathan, 1964].
- Physiological formulae, with weighing coefficients selected according to the relative influence of the particular skin areas on the temperature centre rather than from their significance in heat exchange: Nadel [Nadel, 1973] and Crawshaw [Crawshaw, 1975]. These formulae are reported to show poor agreement with the reference values [Nielsen, 1984].
- Formulae made by modification or failure in citation of existing formulae: Mitchell and Wyndham [Mitchell, 1969] and Nadel [Nadel, 1973].
- Others: Munir's weighted average based on the mass of the skin layers [Munir, 2009].

Many different formulas have been proposed and assessed by Teichner [Teichner, 1958], Ramanathan [Ramanathan, 1964], Mitchell and Wyndham [Mitchell, 1969] and Nielsen et al. [Nielsen, 1984] to mention a few. Conclusions about which formula is the most accurate are contradictory, perhaps because the assessment conditions are different. The temperatures of reference (T_{ref}) used for comparison are different, e.g. QREC formula [Teichner, 1958], area-weighted formula of 7, 13 and 15 local skin temperatures [Ramanathan, 1964][Nielsen, 1984] [Mitchell, 1969] respectively. The environmental conditions differ, it can be addressed to cold influenced people [Teichner, 1958][Ramanathan, 1964][Veghte, 1965][Mitchell, 1969], or comfortable and warm people [Veghte, 1965][Mitchell, 1969][Nielsen, 1984]. Also, the characteristics of the subjects differ, being some of them nude [Ramanathan, 1964][Mitchell, 1969] and some clothed [Teichner, 1958][Nielsen, 1984], some resting [Ramanathan, 1964][Mitchell, 1969][Teichner, 1958][Nielsen, 1984], some working

[Nielsen, 1984], some exercising [Lund, 1974], and so on. Also the results depend on the way estimated and reference values are compared. Some choose as best formula that whose linear regression fits closely to the slope of 1 and intercept value of zero [Lenhardt, 2006]. Others decide according to the percentage of data within a given range, e.g. ±0.2ºC or ±0.5ºC from the reference values, being 1ºC the largest tolerable difference between measured and model values [Mitchell, 1969].

According to Mitchell, the ideal way of determining the $\overline{T_{skin}}$ is by 4π (sees the target from every angle) radiometer thermometers or thermographic cameras. When no possible, he suggests a 15 area-weighted average of temperatures. This is generally regarded as too complex and time consuming for everyday use, and so simpler alternatives are sought. The minimum number of locations that need to be used is more controversial. Nielsen suggests a limit of seven points in cool environment, or a 4-sites formula for its use in field investigations in milder conditions when $\overline{T_{skin}}$ is between 29.2 and 32.7ºC. With this formula less than 10% of the results would deviate more than ±0.5ºC from the reference temperature. Teichner proposed a 6-points formula, while Ramanathan and Mitchell proposed a 4-points formula. Finally, Teichner and Ramanathan propose the use of a single site temperature (medial thigh) as a fair approximation of $\overline{T_{skin}}$ against the believe of Nielsen and Mitchell, although the latter acknowledges its high correlation with the optimal mean, hence could provide easily useful information about the behaviour of $\overline{T_{skin}}$. Furthermore, the number of sites required for the estimation of $\overline{T_{skin}}$ depends on the individual and environmental conditions [Nielsen, 1984], and so does its accuracy [Mitchell, 1969]. For subjects wearing none or light clothing in warm comfortable conditions the use of few measuring points is acceptable since the local temperature deviation is small; for heavier clothing and in cold, more measuring points are needed due to the nonuniformity of the temperature [Nielsen, 1984], being the agreement poor [Mitchell, 1969]. This was systematically studied by Veghte et al. [Veghte, 1965]. In that case, it should be specified at which thermal environment, clothing, and type of activity each formula applies [Nielsen, 1984].

The International Standard 9886 [ISO 9886, 2004] proposes three weighting schemes for the calculation of the skin temperature, with 4, 8 and 14 points respectively. The set of 14 points should be selected in order to be more accurate (see **Table 5** and **Figure 3**).

Name	Sites
1	Forehead
2	Neck (back)
3	Right scapula
4	Left upper chest
5	Right arm in upper location
6	Left arm in lower location
7	Left hand
8	Right abdomen
9	Left paravertebral
10	Right anterior thigh
11	Left posterior thigh
12	Right shin
13	Left calf
14	Right instep

Table 5: Scheme of skin temperature measuring sites proposed by ISO 9886:2004

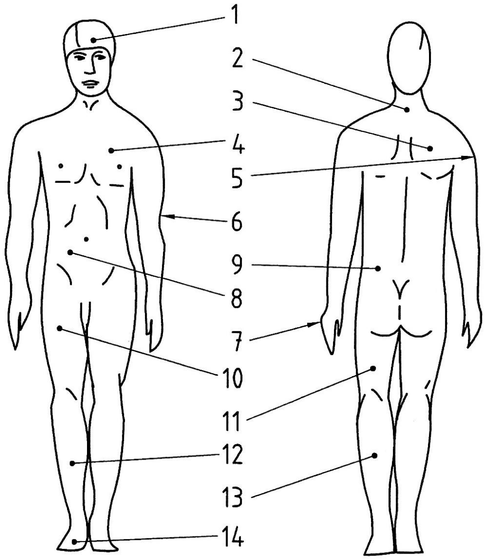


Figure 3: Location of measuring sites listed in Table 5. Figure taken from ISO 9886:2004

2.3.2 Measurement methods

Skin temperatures measurements can be compared when they are taken in the same conditions, i.e. same type of sensors and environment. Furthermore skin temperature must be in a steady state [Houdas, 1972], which takes about 20 minutes [Nagano, 2005]. Skin temperature can be measured both with contact probes or contact-less radiation thermometers as discussed by Togawa [Togawa, 1985].

Contact probes, such as thermocouples and thermistors are commonly used, can be placed at the skin surface under the clothing and so they are convenient for long temperature monitoring. The main disadvantage is that contact with the skin is required, hence temperature gets affected with thermal contact goodness and contact pressure. Also its time response is slower and they are generally hard-wired, which is not practical in most situations, exercise and clinical settings. To overcome this latter problem Smith *et al.* [Smith ADH, 2010] proposed the use of wireless iButtons. Alternatively, radiation thermometers do not require contact, hence they do not disturb the thermal conditions on the surface [Togawa, 1985], and have a fast response. Both methods were assessed by Burnham et al. [Burnham, 2006] who proved them to be valid and reliable compared with the inner skin temperature, although the infrared skin device is slightly more responsive. They concluded that the performance of the infrared thermometers is equal to or superior to that of the traditionally used thermistor. IR techniques are used in thermoregulation and comfort studies [Huizenga, 2004], and for detection of metastatic breast cancer, cysts, assessment of skin burns and frostbite, and differentiation between benign and malignant lesions [Barnes, 1963].

Infrared sensors work in the basis that every object emits infrared radiation in relation to its temperature accordingly with the Stefan-Boltzmann law (equation **6**). ε represents the emissivity, ranging from 0 for a transparent object or a perfect mirror to 1 for perfect absorber and emitter, or *black bodies*. The emissivity of human skin is 0.99 for infrared wavelengths greater than 4 microns [Barnes, 1963]. Infrared cameras capture thermograms, where quantitative information regarding the temperature of the object's surface is stored. When measuring the human skin, short wavelength filters are used so that camera is sensible only to waves of 1.8-15 microns, where the skin is opaque or black. Otherwise, readings might be wrongly affected by visible light or from transmissions or reflections of short-wavelength.

$$E = \varepsilon.T^4 \tag{6}$$

2.4 Body temperature

Mean body temperature (MBT) is the mass-weighted average temperature of body tissues, and can be used as fundamental characterization of a person's thermal status [Lenhardt, 2006]. Strictly it would be the integral of body temperature over the volume of the person. There are two methods for which MBT can be obtained, both based in the differentiation of core and peripheral tissues, as explained by Lenhardt. MBT can be measured by means of direct measurement of core temperature and peripheral tissue temperature, the latter being painful and risky. Otherwise MBT can be estimated from core and mean skin temperatures following the widely-used formula proposed by Burton [Burton, 1935] (equation **7**), based on the logic that peripheral tissue temperature decreases parabolically from core to skin temperature. Burton proposed the value **0.64** for the coefficient **a**. Lenhardt et al. [Lenhardt, 2006] compared the two methods and found Burton's formula to be very accurate over a range of core temperatures from 18.5ºC to 37.1ºC and especially accurate for core temperatures between 31 and 36.5ºC, with a difference of only -0.09º ± 0.42ºC. Hence, Burton's formula is highly accurate in near-steady state neutral conditions [Burton, 1935] and less accurate at the coldest temperatures, during the rapid cooling phase and for some cases of feverish people. Alternative a-values have been proposed by other authors, including e.g. a=0.7 for neutral environments [Hardy, 1938]; a=0.7 for hot environments [Stolwijk, 1966]; a=0.8 during muscular work in a hot environment [Vallerand, 1992]; or a=0.75 in cases of forced body cooling and rewarming [Webb, 1993a].

$$MBT = a.T_{core} + (1-a).T_{skin} \qquad a=0.64 \tag{7}$$

2.5 Factors of body temperature and thermoregulation

2.5.1 Environmental conditions

2.5.1.1 Environmental temperature

The dependency of the heat exchange between body and environment with the ambient temperature is widely acknowledged (see section 2.1), with its corresponding effect on skin temperature [Nielsen, 1984] [Nagano, 2005][Yanagisawa, 2007][Kaynakli, 2004]. This can be easily observed by exposing the subjects to a step change in temperature, that is, a sudden change in the room temperature which can be either positive (from lower to higher temperature) or negative (from higher to lower temperature). For a positive (negative) step the surface temperatures increase (reduce) both at naked skin and clothed areas, until it reaches the optimal temperature for the environment. Once optimal temperature is reached, it is kept reasonably constant with just few fluctuations due to the human regulatory system [Tortora, 2002]. The relation between the mean skin temperature and the environmental conditions is given by Houdas et al. [Houdas, 1972]. Thermal conductivity and blood flow of the skin also changes with the environmental temperature. Thermal conductivity at different room temperatures was given by Burton [Burton, 1955] and Werner [Werner, 1980a]. Basal and maximum skin blood flow was measured for different room temperatures by Werner among others.

2.5.1.2 Humidity or vapour pressure

The influence of ambient humidity on the heat exchange, especially evaporative heat, already discussed in section 2.1, has an immediate effect in the mean skin temperature, as observed by Mairiaux [Mairiaux, 1987] and Nielsen [Nielsen, 1984].

2.5.1.3 Air velocity

Variations in air velocity affect skin temperature as a consequence of a variation in the convective exchange and evaporative heat losses [Mairiaux, 1987], as discussed in section 2.1. An increase in air velocity can either decrease or increase the skin temperature, depending on the difference between skin and air temperatures, being the first the most common case.

2.5.1.4 History of environmental conditions

Physiological parameter such as tympanic, rectal and mean skin temperature, metabolic rate and evaporative heat loss do not only depend on the current environmental temperature but also on previous conditions. This is due to the different time response of the physiological parameters to environmental changes, skin temperature and evaporative heat loss being the fastest [Hardy, 1966]. Also small, rapid ambient temperature swings about the ideal temperature seem to increase skin temperature without increasing the variance of skin temperature with time, showing that the time constant of skin temperature response to heat and cold is different [Wyon, 1973a]. In the opposite case, Wyon observed that larger, slower temperature swings about the ideal temperature increase the variance with time of skin temperature, without altering the average skin temperature.

2.5.2 Anthropometric characteristics

2.5.2.1 Age

The effect of age in the thermoregulatory response of subjects when exposed to cold or heat is controversial, partially for the difficulty of separating chronological age from other factors which change in concert with the biological aging process [Inoue, 1992] [Havenith, 1995b]. Inoue et al. and Havenith et al. studied relative influence of age by fixing other anthropometric parameters such as on body fatness and surface area:mass ratio. Inoue observed that heart rate, blood flow, rectal and mean skin temperature were not significantly different during equilibrium (T_{air} =28ºC). However, when exposed to cold, the decrease in T_{re} and $\overline{T_{skin}}$ and the increase of blood flow were significantly greater for the older men. There was not difference in the heart rate. With respect to exposures to warm humid environment, Havenith observed that chronological age affects the cardiovascular effector's responses such as heart rate, arterial blood pressure, forearm blood flow and vascular conductance. However, the effect on body temperature, sweating, heat storage and heat loss was negligible. Park et al. [Park, 1997] observed that the blood flow statistically decreases with the age of the subjects, being a 32% lower for elders compared to teenagers. Hodges et al. [Hodges, 2010] observed that cutaneous and forearm peak vasodilator capacity decrease non-linearly with the age, and so does the resting value at forearm, being males more severely affected than females. Inoue et al. concluded that old age has a limiting factor for the development of both cold and heat tolerances, perhaps suggesting a reduced adaptive temperature range.

2.5.2.2 Gender

The thermoregulatory control in women has been experimentally proved to be different due to the reproductive hormones [Charkoudian, 1999] and vary with the phase of the menstrual cycle [Webb, 1993b]. Also the decay of cutaneous and forearm peak vasodilator capacity is greater for males than females [Hodges, 2010]. Gender losses its relevance in variance in heat storage, body core and skin temperature, heart rate, blood pressure and skin blood flow when the maximal O_2 intake or other anthropometric data are included in the prediction equation [Havenith, 1990].

2.5.2.3 Physical fitness or fat

The constitution of a person can be partially characterized by his/her percentage of body fat, assessed in different ways [Durnin, 1974][Webb, 1992], the surface-area-to-mass ratio or the Body Mass Index (BMI).

BMI is the most widely used tool to identify obesity problems as it can be easily calculated based on the weight and height of a person (equation **8**). This index is used by the World Health Organization (WHO) since the early 1980s to characterize adults according with **Table 6**, assessing how much the weight departs from what is normal or desirable for a person a specific height. However, BMI do not take into account factors such as frame size and muscularity, hence the defined categories should not be used in special cases such as athletes, children, and elderly. In case of children and teenagers (2 to 18 years old) the thresholds are dynamic and defined in relation to the distribution of BMI-values of the same age population. Characterization for children under two years is more challenging as they grow up quickly. BMI category limits depend on the gender and highly on the age. Few studies present data for this population [WHO, BMI] (**appendix A)** [British 1990][Cole, 2000], but they do not reach a consensus as the BMI distribution observed depends on the population.

$$BMI = \frac{weight}{height^2} \quad \textbf{(8)}$$

Physical characteristics appear to be related to one's ability to thermoregulate during cold exposures as slender men present a greater increase in metabolic rate [Inoue, 1992], and contribute to the variance of rectal temperature, heat storage [Havenith, 1990] and heat strain, which is lower in bigger subjects [Havenith, 1995a]. Fat is a poor thermal conductor compared with muscle or skin as reported by [Hardy, 1954], which has an immediate effect on the skin temperature, this being colder above fatty concentrations and bony structures and higher above blood concentrations such as veins, haematomas, bruises, and infections. Also the person's fitness ought to be considered as aerobically trained individuals experience a larger increase in rectal temperature (>39.5ºC) than untrained ones when exercising in the heat [Mora-Rodriguez, 2010], without suffering fatigue or heat illness [Lee, 2010].

WHO-BMI categories

Category	BMI range (Kg/m^2)
Severely underweight/Anorexic	BMI < 16.5
Underweight	16.5 ≤ BMI < 18.5
Normal	18.5 ≤ BMI < 25
Overweight	25 ≤ BMI < 30
Obese Class I	30 ≤ BMI < 35
Obese Class II	35 ≤ BMI < 40
Severely Obese	40 ≤ BMI < 45
Morbidly Obese	45 ≤ BMI < 50
Super Obese	50 ≤ BMI < 60
Hyper Obese	BMI ≥ 60

Table 6: BMI categories defined by the World Health Organization [WHO, BMI]

2.5.3 Variable individual characteristics

2.5.3.1 Activity/metabolic rate

Metabolic rate is a major component on the thermoregulation, it rules the total heat loss and thus of heat stored in the body in a given ambient conditions [Mairiaux, 1987]. There is a significant time lag between metabolic rate and heat loss and core temperature, but still, the rectal temperature is related to activity level from sleep (50W) to hard sustained exercise (600 W), increasing with the activity level from 36 to 39ºC for the extreme cases [Webb, 1993b]. Relation between core temperature and metabolic rate also exists in cooled subjects as observed by Hayward et al. [Hayward, 1977].

Mean skin temperature and skin temperature distribution partly responds to the type of activity and its intensity [Nielsen, 1984], as observed by several authors [Havenith, 1995a][Mairiaux, 1987]. In cold or neutral conditions a change on the activity from rest to exercise causes an initial drop on the skin temperature, followed by a subsequent and progressive increase as exercise continues [Saltin, 1968]. Discrepancies appear at warm environments, where some believe the skin temperature increase with the metabolic rate [Givoni, 1967], and others believe them to be independent [Missenard, 1973].

These apparent discrepancies reflect the complex interactions between core and skin temperature [Mairiaux, 1987]. Movements of limbs or body, typical of sports or working conditions, produce convective cooling [Nielsen, 1984]. Hence, different activities of equivalent metabolic rate might induce different skin temperatures [Mairiaux, 1987][Adams, 1977]. In the case of inability of moving the extremities, a lower mean skin temperature is observed [Svedberg, 2005]. Svedberg et al. detected temperature on the hand palm and on the foot dorsal in non-walking children to be around 1.1°C and 0.85°C lower than healthy children respectively, and almost double standard deviation of the temperature distributions. In cold environments (around 16 and 19 ºC), muscular movement of the extremities promotes blood circulation, increasing skin temperature [Huizenga, 2004].

Kondo et al. [Kondo, 2010] reviews and reports the effects of exercise and its intensity. Exercise increases the threshold for cutaneous vasodilatation, although does not seem to affect the threshold for the onset of sweating. Higher exercise intensities decrease the sensitivity of the skin-blood-flow and increase the sensitivity to body temperature of the sweating response.

2.5.3.2 Clothing

Clothing affects the distribution of skin temperature by increasing the thermal insulation of the covered parts of the body, and thus decreasing the heat exchange between the body surfaces and environment [Nielsen, 1984]. It also affects the level of acclimation of men to cold [Li, 2009]. Hence, it ought to be taken into account in predictive models [Mairiaux, 1987]. The level of thermal insulation and evaporative resistance a garment or an ensemble provides depend on the type of clothing (material, thickness, number of layers), as tabulated by Standard 9920 [ISO 9920, 1995].

The difference on the clothing has little importance on the effect over the skin temperature at normal room temperature while it becomes significant at higher stress levels (increased activity and/or air temperature) [Holmer, 1992]. In cool environments, clothing may be associated with an increase on skin temperature [Vogt, 1983] while it has a marked cooling effect in warm environments as the unevaporated sweat may accumulate and wet the clothing, creating a microclimate[Craig, 1972][Mairiaux, 1987]. Hair and the ‘dead air’ (air enclosed in a very narrow space like between skin and clothing) can be treated as clothing. Long hair decreases the heat transfer coefficients for the head and neck due its insulative properties [de Dear, 1997] while ‘dead air’ provides a great thermal insulation, estimated to be 1.85 clo units [Burton, 1955], which is comparable to the best-insulating fur of animals [ISO 9920, 1995]. Furthermore, if wearable systems are employed to measure the skin temperature, the use of a band for its fixation might induce error as the heat transfer at that location changes [Deng, 2008].

2.5.3.3 Emotions

Emotions such as fear, sadness, anger, frustration, amusement or boredom are known to affect some of the physiological signal of the body, like skin temperature, galvanic skin response and heart rate [Kreibig, 2007] [Lisetti, 2004] [Nasoz, 2010]. Also mental arithmetic, mental testing, pain, noise and emotional stimuli affect sweating at palm and forearm [Ogawa, 1975]. Finding unique physiological patterns for the recognition of emotions would lead to a more friendly and sympathetic human-machine interaction.

2.5.3.4 Acclimatization

Long-term exposures to heat stress causes behavioural, morphological and physiological changes on the individuals, i.e. decrease the metabolic rate [Bligh 1976] or increase the volume of sweat –double after 20 days [Edholm, 1978]- and lower its concentration [Ingram, 1975]. This affects the mean skin temperature, which lower for acclimatized subjects [Candas, 1980]. Hence, acclimatization factor should be included in mean skin temperature prediction formulas [Mairiaux, 1987].

2.5.3.5 Food intake

The level of food intake (fasting, under eating, maintenance or overeating) affects the heat loss and rectal changes, being significantly higher for greater food intake [Webb, 1993b]. Also the temperature of ingested food and beverages affects the rectal temperature, thermal sensation and physiological strain index [Stanley, 2010]. Inoue et al. acknowledge the dietary-induced thermogenesis effect and asked their volunteers not to ingest food or water within the 2 hours prior to the experiments [Inoue, 1992].

2.5.4 Others factors

2.5.4.1 Location

The dependency of skin temperature on the region or segment under consideration is long been recognized for a given environment conditions, and especially in cold [Werner, 1980a][Houdas, 1972]. Other physiological parameters also vary with the location such as sweating rates and evaporating powers [Houdas, 1972], thermal conductivity and its increase with environmental temperature due to the different vasoconstriction and vasodilatation levels [Burton, 1955], cutaneous blood flow [Park, 1997] or convective and radiative heat transfer coefficients [de Dear, 1997].

2.5.4.2 Circadian rhythm

A circadian rhythm is a roughly 24-hour cycle of biochemical, physiological, and behavioural processes. The period is 24-hours due to the length of the day, although studies proved that it could be modified to 27-hours if required [Minors, 1996]. A well known parameter following a circadian rhythm is the metabolism, which changes throughout the day and night to fuel the processes of sleeping, walking, eating, and other states [Webb, 1993b]. Core temperature also varies during the day [Van Someren, 2000][Fanger, 1973a] with mechanisms similar to those during exercise [Waterhouse, 2005], and with amplitudes of about 1ºC, the lowest at night [Webb, 1993b], as a great variety of mammals [Mortola, 2004]. The circadian rhythm of body temperature varies with age; in comparison with adults, it is poorly developed in the neonate and deteriorates in the aged subject [Weinert, 2007]. There is also circadian variation of skin temperature [Marotte, 1982], following approximately parallel curves to the core temperature during the day [Fanger, 1973a]. Mairiaux et al. [Mairiaux, 1987] acknowledged the circadian rhythm as a possible source of error for the prediction of mean skin temperature.

2.5.4.3 Exposure to RF

Prolonged exposure to Radiofrequency (RF) radiation, such as during magnetic resonance or subjection to RF radiation by a surface coil, significantly increase the local skin temperature although does not seem to affect the mean body temperature [van den Bergh, 2000][Morvan, 1992]. The relative increase on skin temperature for a given specific absorption rate depends on the type of tissue and blood flow, especially in patients with a limited thermoregulatory function as in obesity, diabetes, or cardiovascular disease [van den Bergh, 2000]. Safety levels of RF radiation are controlled and specified by organizations such Food and Drug Administration or International Electrotechnical Commission [FDA, 1998][IEC, 1995].

2.5.4.4 Vaccination

First vaccination in children at about 10 weeks of age led to a significant increase in minimum overnight temperature compared to the control night [Jackson, 2001].

2.5.4.5 Position

The difference in the heat transfer area involved in convective heat exchange at different positions such as standing or sitting on a chair is significant. They were measured by Kurazumi et al. [Kurazumi, 2004]. Maximum occurs when standing.

2.6 Relation of core and surface temperature in a human body

Mean skin temperature was observed to be related with the rectal temperature [Mairiaux, 1987][Houdas, 1972], but others differ [Saltin, 1968]. Core and skin temperature were also proved to relate linearly at the onset of vasoconstriction and shivering [Cheng, 1995]. If interested in the relation of core and local skin temperatures, forehead is the most obvious choice. Forehead is typically exposed, hence thermal clothing insulation do not need to be considered and its temperature is easily measured. The use of forehead temperature for the estimation of core temperature is controversial although it does perform quite well for the detection of fever [Togawa, 1985]. Ng DK et al. [Ng, 2005] studied the agreement of non-contact infrared forehead temperature (NIFT) measurements and tympanic temperatures for children aged between 1 month and 18 years. They observed a reasonable accuracy beside a difference of 2.34°C between both temperatures, and could establish cut-off point of forehead temperature for fever detection at 35.1°C. However, the false-positive rate of fever screening is high. In the same line, Ng EYK et al. [Ng 2, 2005] studied the feasibility and effectiveness of IR systems measuring frontal and side profiles of face temperature for fever detection in mass blind screening. They believe this system is noninvasive, speedy, cost effective and fairly accurate, hence a useful tool at situations where public health is under concern due to a widespread infection. A different approach of estimation core temperature throughout skin temperature measurements would be the use of liquid crystal tape at abdomen, like done with infants by Togawa et al. [Togawa, 1985].

2.7 Models

2.7.1 Thermoregulatory system

Several thermal models of the thermoregulation system of the human body have been developed and reviewed [Hwang, 1977][Munir, 2009]. These models combine heat and mass transfer equations in order to predict skin and core temperature, skin blood flow, and sweat rate among physiological parameters in response to air temperature, velocity and humidity, mean radiant temperature, person's activity and clothing [Gagge, 1973] [Nevins, 1973a].

One of the earliest body temperature models is the core-shell model [Aschoff, 1958], based on the concept that core remains at a nearly constant temperature while the shell temperature varies accordingly to the environmental conditions. Webb et al. [Webb, 1992] believe that this enduring concept of body temperature distribution has suffered from the lack of sufficient data with which to evaluate it beside some studies where surface and "core" temperature have been measured, but it is supported by their experimental data. Webb observed the least temperature change from comfort to hot or cold at the core, with progressively larger variations at muscle, subcutaneous and skin. Core and shell correspond to a functional, not an anatomical, division [Webb, 1992].

Stolwijk and Hardy [Stolwijk, 1966b] proposed an early mathematical model where the human body was represented by three cylinders - head, trunk, and extremities-, each of them divided into two or more concentric layers to represent the different anatomical and functional differences. This evolved in the Stolwijk's 25-node model of thermoregulation [Stolwijk, 1971], one of the most influential multi-node models, being used as the basis for many other human thermal-modelling studies [Munir, 2009]. The Stolwijk model solves simultaneously the heat balance equations at 25 nodes. Those represent six locations - head, trunk, arms, hand, legs and feet- at four different layers – core, muscle, fat and skin layer- plus the central blood compartment, thermally connected to all the other nodes.

Munir et al. [Munir, 2009] among others assessed the performance of the Stolwijk's 25-node model against experimental data. The prediction of mean skin temperature by this model is accurate in a sedentary person in a thermal-transient state, both in the value and the trend; however discrepancies occur at local level, as it overestimates temperatures of the legs and feet and underestimate temperature at arms, abdomen and forehead [Munir, 2009]. Munir believes those discrepancies might be due to the non-account for sweat accumulation and its evaporation.

Many are the modifications made to Stolwijk's model, which include improving modelling of the thermoregulatory systems and body segmentation [Fiala, 1999][Fiala, 2001][Sakoi, 2005a][Xu, 1997][Yokoyama, 2007]; including an active system which accounts for the sweating, shivering and peripheral vasomotion of unacclimatised subjects [Fiala, 2001]; considering individual body characteristics such as effects of counter-current heat exchange in the blood flow and blood flow characteristics in local tissue [Zhang, 2001] or sweat accumulation and its evaporation [Takada, 2009][Munir, 2009]; increasing the number of body segments to increase the skin temperature resolution [Tanabe, 2002][Huizenga, 2001]; adjustment of basal skin blood flow distribution and coefficients under transient conditions [Munir, 2009]; inclusion of a very accurate representation of the arteries in the body and pulsatile blood flow in the large arteries [Salloum, 2007]; and applications for specific purposes, such as cold-water immersion[Castellani, 2007]. Furthermore, the model has also been simplified as a two node model [Gagge, 1971].

Well known is the so called Berkeley Comfort Model developed by Huizenga et al. [Huizenga, 2001] based on the Stolwijk model. They increased the number of body segments, adjusted convection and radiation coefficients, improved blood flow model at limbs, and included a node accounting for the clothing. Alternative models have been developed by other authors. Werner et al. [Werner, 1980a] develops a model for the description of the thermoregulatory system based in experimental studies and focused in the topographical differences. Nelson et al. [Nelson, 2009] developed a thermoregulation model of a high degree of spatial resolution and anatomical realism compared with previous compartment models. They used 130 millions of cubic elements to represent the body. This allows the prediction of temperature responses at an organ or tissue level and account for the differences due to the body position such as standing, sitting, or reclining.

Besides the complexity of these thermoregulation models, they are limited and usually only applicable under controlled conditions. Even the sophisticated physiological model of human thermoregulatory response proposed by Huizenga et al. [Huizenga, 2001] is self-criticized by the author as not capable of predicting subjective response to complex environments [Huizenga, 2004]. Even in highly anatomical models like the one developed by Nelson, a difference of 0.5°C between measured and predicted core temperature values or a difference of 1ºC between measured and predicted skin temperature represent a "good agreement" [Nelson, 2009].

At a more neurological level, the evolution of the body temperature regulatory system and how the brain responds to thermoregulatory changes has been broadly discussed [McAllen, 2010]. In the review made by McAllen et al. they concluded that multiple control loops exist in the brain, each of them with an effector system and a central temperature sensor of its own. Werner describes the human temperature regulation process as the combination of a distributed multi-sensor, multi-processor and a multi-effector proportional feedback control system following a distributed parameter control strategy [Werner, 1980b][Werner, 2010].

Kanosue et al. [Kanosue, 2010] developed a discrete characterization of the thermoregulatory system in an attempt of facilitating the comparisons. They outline inputs, conditions and thermoregulatory effectors to consider in different circumstances, and also non-thermoregulatory system orders of altering the core temperature such as when fever occurs as a demand from the immune system.

2.7.2 Prediction of core temperature

Gehring et al. [Gehring, 2001] developed a model to predict the nonlinear increase on time of core temperature when subjects are exposed to warm and hot environments. They used data from 6 European research institutes which were combined in a single database for the Heat Stress Project within the scope of the BIOMED 2 programme of the European Union. The model reflects dependencies on air temperature, mean radiant temperature, partial vapour pressure, air velocity, metabolic rate, gender, clothing insulation, level of acclimatization and body surface area. Wyndham et al. [Wyndham, 1953] established a form of relationship between rectal temperature and wet bulb (or effective) temperature for different rates of metabolism (equation **9**) and their conclusions were supported by [Lind, 1963]. Y is the 4th hour rectal temperature in ºC, x is effective temperature in ºC and a_m and b_m are constants which are dependent upon metabolic rate in Kcal/m_2/h.

$$Y= a_m + b_m \cdot e^{0.4615x} \quad \textbf{(9)}$$

2.7.3 Prediction of mean skin temperature

Several are the equations for the prediction of mean skin temperature. The most simplistic ones take room temperature as the only parameter and assume linear regression [Mairiaux, 1987][Saltin, 1968] [Missenard, 1973], although they might be applicable only for a given condition, such as volunteers were at work, volunteers were resting, air velocity and/or room temperature within a given range, and so on. However, the relationship between mean skin and room temperature is no linear, with a changing point round 30-35 °C [Mairiaux, 1987]. Mairiaux also derived an equation for mean skin temperature prediction using room humidity as only factor, and conclude that ambient water vapour pressure is only significant when body cooling requires the evaporation of sweat at the skin surface, in agreement with [Candas, 1980].

Mehnert et al. [Mehnert, 2000] observes that mean skin temperature depends on many factors and derived a multiple linear regression based on air and radiant temperature, humidity, air velocity and core temperature. They also included metabolic rate when volunteers were clothed. As improvement to other models, this can be used in conditions with high radiation and high humidity. They observed that 83.3% and 81.8%, respectively, of the predicted skin temperatures were within the range of 1 °C of the observed skin temperatures for the nude and clothed subjects.

2.8 Ranges of temperature

One of the purposes of the study of different environmental conditions is the identification of the optimal conditions for man's highest performance. Wyndham et al. [Wyndham, 1973a] studied the performance of men during mine work at room temperatures between 27.2 and 35.6ºC and air movements between 0.5 and 4m/s. The mean productivities at temperatures of 30ºC onwards fell off and decreased faster at low air movements than at higher air movement. Wyon et al. [Wyon, 1973b] observed significantly higher type-writing performance at air temperatures of 20 than at 24ºC. Langkilde et al. [Langkilde, 1973] investigated the mental performance of 12 university students at 3 room temperatures: preferred air temperature, 4ºC lower and 4ºC higher.

The performance of mental work was found to be the same under the 3 conditions. However, at 4ºC above the preferred temperature, subjects tended initially to overestimate their own performance. They also considered that they became sleepier and more fatigued, and that the air was less fresh at the high temperature level.

The maximum time that a person could be exposed to hot working environments have been revised [Malchaire, 2000][Malchaire, 2002] and standardized [ISO 7933, 2004]. They use the *Predicted Heat Strain (PHS)*, a modification of the *Required Sweat Rate*. They suggest a maximum rectal temperature of 38ºC corresponding to a probability of 10^{-3} of a worker being at risk; and a maximum water loss of 5% of the body mass to protect 95% of the working population from dehydration.

2.9 Clothing characterization

Thermal insulation is defined as the resistance to dry heat loss from a body. It can be expressed both in clo-unit or SI, that is square metre degrees Celsius per watt (m^2.°C/W) with 1 *clo* = 0.155 m^2.°C/W. For clothed people the loss occurs in two steps. First, the dry heat is lost from the skin surface to the clothing surface by convection, radiation and conduction processes. Then the dry heat loss is transferred from the clothing/skin surface to the environment. The resistance to heat flow is expressed by *insulation of the clothing ensemble* (I_{cl}) and *surface resistance between clothing/skin and environment* (I_a). The *total insulation* (I_T) is the insulation from the skin surface to the environment.

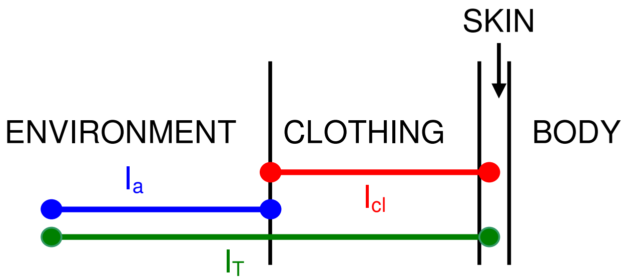


Figure 4: Clothing insulation parameters

2.9.1 Clothing thermal insulation factors

The insulation due to a garment is mainly influenced by its thickness, the body area that it covers and the thickness of dead air that it encloses, while the type of material has limited influence. Other factors are the number of layers, kind of texture of the fabric, fashion of clothing, colour and the way the clothing is worn [Araźny, 2006]. Also the openings of the ensembles such as collars or cuffs have an important effect on the insulation value, as they allow a certain air exchange with the environment. This air exchange may increase when the subject is moving, known as *pumping effect*, which may reduce the thermal insulation between 5% and 50%, depending on number of openings and the type of textile (i.e. permeability, stiffness). Hence, readjustment of the thermal insulation for great metabolic rates is required, with a 20% reduction if $M>100W/m^2$ and 10% if M is in the range of 60-100 W/m^2 [ISO 9920, 1995][ISO 11079, 1993]. Also the environment conditions affect thermal resistance. Rain or high humidity damp the clothing, decreasing its insulating properties [Burton, 1955]. Air velocity (v_a), either by an increase of air velocity or locomotion and limb movements, decreases I_a and causes some air to penetrate through the fabrics. The combination of these factors is quantified by the relative air velocity (v_{ar}) as seen in equation **10**, with its second term limited to 0.7m/s [ISO 11079, 1993]. In indoor environment and sedentary activities, the air velocity does not present an issue.

$$v_{ar} = v_a + 0.0052 * (M - 58) \qquad \textbf{(10)}$$

2.9.2 Estimation methods

The International Standard Organization [ISO 9920, 1995] proposes several methods for the estimation of thermal characteristics (resistance to dry heat loss and evaporative heat loss) in steady-state conditions for clothing ensembles. One of these methods uses the total heat balance equation and indirect calorimetry. Other estimates the thermal insulation of a garment as a function of the body surface area it covers, quantified by the *clothing area factor* (f_{cl}) [ISO 9920, 1995][ISO 7730, 1994]. This is the rate between the surface area of a clothed person (A_{cl}) and the surface area of the nude body (A_{Du}). Other methods are explained more in detail below as they have been used in some way in this study.

2.9.2.1 Method 1

The most common tool to measure the thermal insulation of a garment or an ensemble is the use of a full-size thermal manikin equipped with facilities for heating and dry-heat loss simulation. The manikin is dressed in the ensemble or garment to be tested and placed in an environmental chamber with steady conditions. Mean skin temperature, heat loss and operative temperature are observed towards the estimation of total thermal insulation (I_T), resistance between the ensemble and the environment (I_a) and thermal insulation of the ensemble (I_{cl}) following the equations indicated by the International Standard Organization [ISO 9920, 1995]. Different standards use this technique, however manikin size and test conditions are not the same [Huang, 2007], with two possible variants (serial or parallel methods) [Huang, 2008]. The insulating properties of a great variety of garments and ensembles have been evaluated using this technique and are tabulated in the ISO 9920 [ISO 9920, 1995]. A sample of values for typical garments is enclosed in **Appendix B**.

2.9.2.2 Method 2

Thermal insulation of a specific ensemble can be obtained by means of the tabulated values given in ISO 9920. One option would be to find a similar or comparable clothing ensemble and identify its thermal insulation (interpolation between two ensembles may be used). Otherwise, the insulation for each garment is identified and their contributions combined by using the empirical equation **11** or its simplified form equation **12** [ASHRAE, 2001].

$$I_{cl} = 0.835 \sum I_{clu} + 0.161 \qquad \textbf{(11)}$$

$$I_{cl} = \sum I_{clu} \qquad \textbf{(12)}$$

2.9.3 Predicting methods

Although there are several methods for the estimation of the clothing thermal insulation, it is of high interest the prediction of the clothing thermal insulation based only on personal and environmental parameters that are easy to measure or easy to identify. Araźny [Araźny, 2006] studied the thermal insulation of the clothing in different stations in the Norwegian Arctic. The researcher estimated the I_{cl} by using only the metabolic rate of a given person and the mean daily values of air temperature and wind velocity. The predicted total insulation of the clothing and the surrounding air layer was obtained by Burton and Edholm's formula [Burton, 1955] (equation **13**), while the insulation of the surrounding air layer was obtained by Fourt and Hollies' formula [Fourt, 1970] (equation **14**); all parameters in SI-units. Finally, the predicted insulation of clothing is calculated by equation **15**.

$$I_T = \frac{0.082 * [91.4 - (1.8 * T + 32)]}{0.01724 * M} \tag{13}$$

$$I_a = \frac{1}{(0.61 + 1.9 * \sqrt{v_a})} \tag{14}$$

$$I_{clu} = I_T - I_a \tag{15}$$

2.9.4 Typical thermal insulation values

The clo-units for clothing insulation were defined such that one unit ensures sense of thermal comfort for a sitting person ($M=58W/m^2$), at environmental conditions of $T_a=21°C$, $H_a=50\%$ and $v_a=0.1m/s$ of air movement [Araźny, 2006] [Burton, 1955]. Clothing insulation values for different thermal environments are presented in **Table 7** [Araźny, 2006]. In general, most of the people in cities wear 1 clo unit of thermal insulation most of the time. Geographical differences occur, mainly because of the difference in the usual indoor temperatures. Europeans set room temperature around 18.3°C and wear usually more than 1 clo, perhaps up to 1.3 clo units. Instead set room temperature at around 24°C and wear less than 1 clo unit, perhaps down to 0.7 clo units.

I_{clp} (clo)	Thermal environment
<0.30	Very warm
0.31-0.80	Warm
0.81-1.20	Neutral
1.21-2.00	Cool
2.01-3.00	Cold
3.01-4.00	Very cold
>4.00	Artic

Table 7: Ranges of clothing insulation estimated by Araźny [Araźny, 2006] for different thermal environments.

2.10 Comfort in enclosed spaces: relevant aspects

There are several factors which affect the general comfort in enclosed spaces, each of different significance but with a minimum required for acceptable level of general comfort. These factors can be classified into 7 categories (see **table 8**) by Vischer [Vischer, 1989][Vischer, 1996], some of which are discussed by Schwede [Schwede, 2006] and Williams [Williams, 1997] as summarized in this section. Those dimensions have a 40% influence on productivity, 25% on morale or satisfaction, and a 21% in health or well-being of the occupant.

Air Quality	Thermal Comfort	Noise Control	Building Noise
Air Movement *stuffy…circulating* Air Freshness *stale air…fresh air* Ventilation *bad…good* Odours *unpleasant…not noticeable* Humidity *too dry…comfortable* Warmth *too warm…comfortable*	Cold temperature *too cold…comfortable* Temperature Shift *too frequent...generally constant* Temperature *uncomfortable..comfortable* Drafts *drafty…no drafts*	Office Noise Levels *too noisy… comfortable* Specific Noises of Voices and Equipment *disturbing…not a problem* Noise Distraction *bad…good*	Noise from the Lights *buzz/noisy…not noticeable* Noise from the Air System *disturbing…not noticeable* Noise from Outside the Building *disturbing…not noticeable*

Privacy	Lighting Comfort	Spatial Comfort
Voice Privacy *bad…good* Telephone Privacy *bad…good* Visual Privacy *bad…good*	Electric Lighting *bad…good* Glare from Lights *high glare…no glare* Brightness of the Electric Lights *too much light...does not get too bright* Colours *unpleasant…pleasant* Daylight *bad…good*	Amount of Space in your Work Space *bad…good* Work Storage *adequate…insufficient* Furniture Arrangement in your Work Space *bad…good* Personal Storage *adequate…insufficient* Furniture Comfort *bad…good*

Table 8: Dimensions for the assessment of office environmental quality as classified by Vischer [Vischer, 1989][Vischer, 1996]. In italic indications of assessment scales, which rate 1 to 5.

The study of comfort data is needed from an engineering point of view to establish design criteria and guidelines, evaluate the performance of a given environmental control system, and conservation or optimization of energy [Nevins, 1973b].

2.10.1 General indoor environments

2.10.1.1 Air quality

One of the dimensions for the environment comfort is the quality of the air, which in itself covers air movement, air freshness, ventilation, existence of odours, humidity and warmth as listed by Vischer. As judgments about air movement, air freshness and ventilation contain the other subcategories, we focus only on these three.

2.10.1.1.1 Air movement

Air movement lowers the thermal sensation of a person in a given environment. The cooling effect largely depends on the velocity of that air movement [Fountain, 1996] and the environmental temperature [PLEA, 2007]. In everyday conditions, reactions to air movement are given in **Table 9**. However, under hot conditions 1m/s is pleasant and indoor velocities up to 1.5m/s are acceptable. Greater velocities might blow about light objects, which indirectly causes nuisance. Under cold conditions, velocities of 0.25m/s should not be exceeded, and velocities <0.1m/s would be judged as "stuffy".

v_a (m/s)	Subject reactions
<0.25	unnoticed
0.25-0.50	pleasant
0.50, 1.00	awareness of air movement
1.00, 1.50	draughty
>1.50	annoyingly draughty

Table 9: Ranges of air velocity and subjects reactions [PLEA, 2007]

2.10.1.1.2 Ventilation

The effect of ventilation in offices and residential buildings is discussed by Seppänen [Seppänen, 2004]. Ventilation is necessary to remove or reduce concentration of indoor-generated pollutants to acceptable levels. Bad ventilation affects the air quality and thermal sensation of occupants in a very short time. Good ventilation (at least 10-20 litters per person) reduces the sick building syndrome symptoms and the probabilities of communicable respiratory illnesses as well as respiratory allergies and asthma; also it improves task performance, productivity, and the perceived air quality (PAQ) among occupants. However, ventilation could have harmful effects on indoor climate and air quality if not properly designed, installed, maintained and operated.

Ventilation in aircrafts is necessary to provide sufficient fresh air to dilute human body odour to an acceptable level for 80% of the population. Empirical guidelines [Brundrett, 2001] establish that a minimum ventilation rate of 2200 ppm and fresh air rate of 2.5 litres/second/person are required, 9 being adequate for the comfort of most passengers.

2.10.1.1.3 Air freshness

The air freshness perception is highly subjective, depending on the perception of odours or contaminants. There is a wide variety of contaminant sources such as the occupants themselves, who generate CO_2 and sweat; facilities such as copying machines or laser printers; building materials and outdoor pollutants; mould growth; radon gas or micro organisms. The acceptance of odours decreases with air temperature and humidity, depends on previous exposures to the same smell, type of occupant (visitors vs. regulars) [Böck, 2000], gender, or if the person is smoker [Maroni, 1995]. Air freshness can be obtained by good ventilation.

The empirical guidelines for CO_2 concentrations and humidity are given [Brundrett, 2001]. In everyday spaces a CO_2 concentration greater than 1000ppm is observed as unsatisfactory air quality. Within airplanes concentrations are particularly high during take-off and landing, limit established by Civil Aviation Authority (CAA) at 30000 ppm, although this value is under revision. In terms of humidity, 40-50% is believed to be a comfortable humidity at sea level. Discomfort commences in some wearers of contact lenses below 50%. Within aircrafts, the optimal humidity values for human beings conflict with ideal values for aircraft devices. As a compromise, the Air Transport Medicine Association accepts a cabin humidity of 12-21%.

2.10.1.2 Thermal comfort

Temperature was found to be the most important aspect for comfort [Williams, 1997] as human body is particularly sensitive to environment temperature and senses temperature changes in a short time. Thermal comfort is one of the factors for satisfaction and well-being within an environment as stated by Vischer. Aspects of the thermal comfort are experience of cold, heat, drafts or temperature shifts. When accounting for temperature fluctuations, several descriptors ought to be considered, those are: basal temperature about which fluctuation occurs, rate (degree per hour) at which temperature increases and decreases, and the peak-to-peak amplitude of the fluctuation [ASHRAE, 2004].

The temperature control by occupants of a space leads to satisfaction [Williams, 1997]. Air temperature can be controlled by use of basic room and/or supply temperature thermostats. There are however other factors that affect the thermal comfort as indicated by Fanger [Fanger, 1970], both environmental (radiant temperature, humidity, air velocity) and personal (clothing and metabolic rate). Those play an important role in the heat exchange between body and environment, and so control ought to be considered in more complete thermal comfort systems.

Thermal comfort (rating scales, factors, models and indices) is discussed in section 2.11.

2.10.1.3 Aural comfort: Noise control and Privacy

The aural aspects of the comfort include the noise control, both from environmental space and their occupants, and the feeling of privacy. Those are 3 of the 7 dimensions for environment quality considered by Vischer [Vischer, 1989][Vischer, 1996]. The impact of a noise on the occupants of a space depends on many relative and absolute factors, which are the sound pressure level, the source of the noise, the changeability of the noise and environmental situation [Ayr, 2003]. In terms of privacy, people feel uncomfortable if they can overhear conversations from other rooms, as they understand their own lack of privacy. The acoustic environment can be modified by introducing baffles, noise attenuators or white noise (music or constant background). White noise would improve the feeling of privacy, but it might be a distraction and/or nuisance factor in under-occupied buildings or after hours [Sharland, 1988].

2.10.1.4 Lighting comfort

The lighting comfort is associated with the kind of light source (natural or electric), the brightness and colour, and furthermore the existence of glares. Light relates with the ability to see, task performance, mood, health, communication and social interaction, and aesthetic judgment as observed by Veitch et al. [Veitch, 2001]. Visibility is the minimum criterion for lighting quality. Natural light and artificial light cause different levels of stress and mood [Schwede, 2006]. Veitch observed that the type of fluorescent light affects the visual performance and visual fatigue; colour influences mood, emotional response to the environment and performance. Reflections or excessive brightness, known as glares, produce different levels of annoyance, depending on their size and position on the field of view.

2.10.1.5 Spatial comfort

Furniture type and layout play an important role in the feeling of comfort or discomfort. Poorly designed working spaces might lead to health problems, e.g. back pain; hence this is regarded in health and safety risk assessments. Furthermore, density of people working within a space might affect their comfort level perception [Schwede, 2006].

2.10.2 Flight environment

Other factors are to be considered when studying the comfort level of passengers in long haul flights; those are cabin pressure, seat features and health risks. Those factors were revised and discussed by Brundrett [Brundrett, 2001] as summarized in this section.

Seat characteristics, such as poor seat comfort and insufficient leg room, are the main reasons for passenger dissatisfaction. CAA regulates the safety guidelines for aircraft seat spacing, i.e. seat pitch, degree of tilt and seat width (**table 10**). Narrow seats may impede normal blood circulation, increasing the risk of oedema and deep venous thrombosis when sitting for long periods of time. Furthermore passengers seated in isolated seats (between window and aisle) feel ‘surrounded’ and trapped, leading to physical and psychological passenger discomfort.

Parameter	Charter planes	Economy	Business
Seat pitch (cm)	71-74	76-86	97-152
Degree of tilt	21 °	50º	90º
Seat width	38-49 (42)	38-49 (42)	-

Table 10: Seat characteristics for different travel options. More popular values are presented in brackets

Low environmental pressure has an important physiological effect on oxygen saturation in the blood, particularly for very young people, elderly and those who are less fit. Cabin pressure is significantly lower than what people normally experience. It is set by airlines, although the official maximum is the equivalent to 2440 m of altitude. This factor is not very relevant in short flights due to limited exposure to low pressure.

In terms of health, low rate of ventilation increases cross-infection risk as in any other public area. As a consequence of remaining seated for long periods of time, passengers might develop oedema (presence of excessive fluid in tissue spaces), deep vein thrombosis (formation of a blood clot within a blood vessel) or swelling of lower limbs (proportional to the duration of sitting, greater at lower cabin pressures and noticeable after 3 hours). Intake of plenty of fluids and gentle exercise is recommended.

Other less important comfort level factors are health problems associated with high altitude flying (ear drums, oxygen shortage, ozone irritation and health, radiation exposure), jet lag i.e. fatigue and sleep disturbance resulting from disruption of the body's normal circadian rhythm as a result of jet travel; and thermal sensation resulting from sudden ambient temperature changes, when passenger enters/exits the aeroplane.

2.10.3 Ranking

The general comfort attending to all (or part) of the reviewed parameters is assessed and quantified with global parameters such as the *functional comfort*, introduced by Vischer, which weight the annoyance produce by each of the individual parameters. Temperature was found to be the most important aspect for comfort [Williams, 1997], with 49% of the occupants of office buildings claiming to feel uncomfortable on a daily basis because of it [Melikov, 2005]. The second most relevant aspect might vary depending on the study. Williams found it to be lighting, noise, freshness, layout, appearance, smell and humidity in that order, while Melikov et al. observed that the second factor to be air quality. Even although the vertical air temperature between head and feet was up to 3ºC, only 24% of the occupants complained that they were daily bothered by draught, especially at the lower leg. In simulations of 7-h transatlantic flights with different rates of fresh outside air supply while maintaining a constant rate of total air supply, generating relative humidity between 7 and 28%, volunteers preferred to have greater rates of fresh outside air supply besides the humidity being lower [Strøm-Tejsen, 2007]. At the lowest rate, they complained of headache, dizziness, and claustrophobia due to the increased level of contaminants. When investigating comfort within means of transport, other factors such as vibration, ergonomics and acceleration became of high relevance [Silva, 2002]. Silva reviewed the impact of those factors and their weights of the individual influences for their combination in general indices for comfort level such as the *ride comfort index* or *new ride quality meter*.

2.11 Thermal comfort

The thermal comfort is a subject widely studied in the literature. It investigates the level of comfort that a person might experience when subjected to some given environmental conditions or the ranges of temperature that someone can be subjected to without facing a health risk. Thermal comfort is defined as “that condition of mind which expresses satisfaction with the thermal environment” by the American Society of Heating Refrigeration and Air-conditioning Engineers (ASHRAE). This psychological definition is generally accepted by the researchers in the field, and used in thermal comfort standards [ASHRAE, 2004][ISO 7730, 1994]. Alternatively, thermal comfort can be thermophysiological defined based on the activation of thermal receptors at skin and hypothalamus; or based on the heat balance of the human body stating as comfortable those situations where skin temperature and sweat rate are within a comfort range [Höppe, 2002]. Thermal comfort does not necessarily mean an optimum in terms of health [Höppe, 2002].

2.11.1 Rating scales

Rating scales of thermal comfort are used to enquire people about how they feel about a given thermal environment, such that their perception can be quantified. Most popular scales are ASHRAE 7-point thermal sensation (TS), Bedford scale (TB_B) or preferred thermal sensation (TP), defined on **Table 11**. TS is the more accepted one, being used in American and European standards [ASHRAE, 2004][ISO 7730, 1994]. When using a symmetrical scale, the neutral temperature is that voted in average as zero by the occupants of the room. Those temperatures which produce mean votes between -0.5 and +0.5 would be in the comfort zone. This corresponds with a maximum 10% of people dissatisfied, limit recommended both by ASHRAE 55 and ISO 7730 standards.

Although closely related, thermal sensation and comfort level do not represent the same concept. Thermal sensation quantifies the sensation of cold or warmth while thermal comfort indicates the feeling a person experiences (pleasant or unpleasant). Thermal comfort is largely dependent on the subject's thermoregulatory situation and it is responsible for behavioural responses [Hensel, 1973]. Physiological neutrality (thermal equilibrium) does not necessarily mean *comfort* [PLEA, 2007].

Points		ASHRAE (TS)	Bedford (TS_B)	Preferred TS (TP)
Op1	Op2			
+ 3	7	Hot	Much too warm	Much cooler
+ 2	6	Warm	Too warm	Cooler
+ 1	5	Slightly warm	Comfortably warm	Slightly cooler
0	4	Neutral	Comfortable	No change
- 1	3	Slightly cool	Comfortably cool	Slightly warmer
- 2	2	Cool	Too cool	Warmer
- 3	1	Cold	Much too cool	Much warmer

Table 11: Thermal comfort scales: ASHRAE, Bedford and Preference scale.
Points are given in the symmetrical (op1) and asymmetrical (op2) scale.

2.11.2 Factors

Air temperature, mean radiant temperature, humidity, air velocity, and personal parameters of metabolic rate and clothing insulation are primary factors for the heat exchange between body and environment, hence primary factors of the thermal comfort [ASHRAE, 2001][Fanger, 1973a]. The effect of these parameters on thermoregulation has been previously discussed in section 2.5. There are also other secondary factors which affect the comfort level, such as personal characteristics, past experience, socio-cultural factors, habits and expectations, which are also discussed here.

2.11.2.1 Air velocity

The comfort region of a person varies with the air velocity. A sedentary person (1.2 met) wearing light clothing (0.5 clo) would accept an extension of the upper comfort limits by 1 K for every 0.275 m/s air velocity (above 0.2 m/s and up to 0.8 m/s, thus by a maximum of only 2 K) [ASHRAE, 2001], although most sources take the limit as 1.5 m/s for non-thermal reasons [PLEA, 2007], that is more than 5 K. There are several numerical approximations for the cooling effect (thus extension of temperature comfort limits) as reported in PLEA, e.g. equation **16**:

$$\Delta T = 6 \bullet (v_a - 0.2) - 1.6 \bullet (v_a - 0.2)^2 \qquad (up\ to\ v_a = 2\ m/s) \tag{16}$$

2.11.2.2 Radiant temperature

Sakoi et al. [Sakoi, 2005b] studied local and whole body comfort when subjected to different thermal asymmetries (anterior-posterior, right-left, and up-down) created by radiation panels. Local skin temperature and sensible heat loss changed depending on the non-uniformity, although mean values remained almost the same. The relation among those two variables was found to be dependent on the thermal non-uniformity. Also solar radiation affects the thermal comfort as proved for vehicle occupants [Hodder, 2002][Hodder, 2007]. Intensities of 200W.m^{-2} increase on average the thermal sensation by one point. For high intensities (1000W.m^{-2}) the type of glazing is also relevant, with smaller shift in the thermal sensation when using glazing of low transmission of visible radiation. Spectrum of the radiation was not relevant.

2.11.2.3 Humidity

The effect of humidity in the sensation of warmth is only important at high air temperatures [Griffiths, 1973] or under very cold conditions [Fermanel, 1999]. At the lower temperature, humidity related with the feeling of oppressiveness and discomfort, with a minimum at 50% [Griffiths, 1973].

2.11.2.4 Swings of ambient temperature

Wyon et al. [Wyon, 1973a] studied the psychological effect of different temperature swing conditions on people while performing sedentary mental work through 7.5 hours. The temperature swings were of sinusoidal-type, with 0-8ºC amplitude and 8-32 min period. With small rapid swings of ambient temperature subjects felt more sleepy and fatigued, the air was less fresh than at constant ambient temperature and the working rate and accuracy decreased. However they did not feel less thermally comfortable. With larger, slower temperature swings subjects worked slightly faster, felt more alert and the air to be fresher and so it is preferred to small rapid swings of temperature. However they felt too hot and too cold more often. Overall, constant, optimally comfortable temperature, where this can be achieved, is preferable.

2.11.2.5 Posture

Posture influences the thermal comfort as metabolic rate per unit body surface area changes [Raja, 1997]. Raja et al. developed a systematised method for coding normal office work postures, which reflects the changes in effective body surface area available for heat exchange.

2.11.2.6 Gender

The effect of gender on thermal comfort is controversial. Some authors did not find difference between the preferred ambient temperature of males and females [Fanger, 1973a][Olesen, 1973], although the non-uniformity of skin temperature is larger for females than for males, with SD of 1.43 and 1.04ºC respectively [Olesen, 1973]. Others found gender to affect the thermal comfort, temperature preference, and use of thermostats when considering everyday thermal environments such as homes, offices and universities [Karjalainen, 2007]; this is in conjunction with cultural and psychological factors [Humphreys, 1998][Fountain, 1996][Brager, 1998][de Dear, 2004]. Females are more sensitive to thermal aspects than males [Pellerin, 2003]. Karjalainen's studies indicate that females are more critical of their thermal environments, especially in the office environment, feeling less satisfied with room temperatures, prefer higher temperatures, and feel both uncomfortably cold and uncomfortably hot more often. Still males use thermostats in households more often than females. The reasons for the gender differences probably lie in the 'complex process of human adaptation' [Humphreys, 1998]. Furthermore sweating response is different; males begin sweating at a lower core temperature and have a greater sweat rate in humid conditions than similarly trained females [Sharon, 2007]. When the combined effect of temperature and noise was studied in the comfort level [Pellerin, 2003], it was found that females accepted noisier environments than males.

2.11.2.7 Geographical dependence

The dependency of thermal sensation on the country or region of residency is not clear. Most tropical thermal comfort experiments conducted in climate chambers find no significant differences between the comfort temperatures (neutral and preferred temperatures) of long-term residents of tropical climates and those residing in temperate or cold climate zones [Fanger, 1970][de Dear, 1991a][de Dear, 1991c]. However, field studies of the same populations repeatedly and consistently find significant differences of several degrees Celsius [de Dear, 1991b]. It seems that adaptation has little influence on preferred ambient temperature, but it is relevant under uncomfortable warm or cold conditions [ASHRAE, 2001].

2.11.2.8 Circadian rhythm

Fanger et al. [Fanger, 1973a] investigated the possible change on preferred ambient temperature during the day as it seems conceivable due to the internal body temperature circadian rhythm. However they did not observed any change in an 8-hour experiment, simulating a normal sedentary working day in an office 9 am to 5pm.

2.11.2.9 Day to day

When having the same clothing (0.6 clo), activity (seating), air velocity and humidity, only a slight change on the ambient temperature preferred by people in different days (SD of 0.6ºC) was found [Fanger, 1973b], hence it is not a significant factor.

2.11.2.10 Psychological aspects

Comfort feeling is influenced by psychological aspects both indoors and outdoors [Höppe, 2002]. People have different reactions to same environments depending on whether they are working in an air-conditioned or a natural-ventilated building [Brager, 1998]. Some observed that people working in an air-conditioned building, over which they have zero control, are less critical as they expect that their thermal comfort will be automatically [de Dear, 2004]. Others believe people feels more comfortable when they have control over their environments, e.g. in a naturally ventilated building [Zhang, 2010c]. Rohles observed that prejudgment is also important [Rohles, 1980]: (a) people feel warmer without any changes of thermal parameters in the chamber when they are told the temperature is higher than it really is or when adding wood-panels, carpets and comfortable furniture to the room; (b) people are likely to prefer warmer temperatures in wintertime and colder in summertime as it can be seen as a kind of luxury. Outdoors the psychological expectancy and even the thermal history are certainly the major aspects for the subjective assessment and satisfaction [Höppe, 2002]. People votes a hot day as pleasant when they are in the beach or after previous unseasonably cold days, unlike in every-day circumstances. Hence, thermal history of a subject should be regarded in predicting thermal comfort models, but is hardly standardized. The preferred temperature after step-type change would be dependent on the previous conditions and varying for at least 50 minutes until it reaches a steady state [Nagano, 2005]. Finally, although the cold and warm receptors on the skin are continuously active, consciousness of the temperature sensation is not always present (e.g. at skin temperatures near 34ºC) [Hensel, 1973].

2.11.3 Environmental indices for comfort measurement

Many physiological temperature scales have been proposed in an attempt to quantify the thermal characteristics of a given environment in a single value, and consequently the thermal comfort of a person within that environment [Ingram, 1975]. These indices can be classified into two categories, empirical and analytical indices [PLEA, 2007], from which some of the existent indices are reported.

2.11.3.1 Empirical indices

Scales of warmth were empirically developed in an attempt to combine air temperature, humidity and velocity. The ***effective temperature (ET) scale*** is the earliest scale of warmth, developed by Yagloglou [Houghten, 1923]. The scales that depend on the effective temperature have become the best-known measures of heat stress [Mount 1979]. This scale was later modified by Bedford, who introduced the ***corrected effective temperature (CET) scale*** [Bedford, 1940] with the extra accounts for the radiant. The ***equivalent temperature (EqT)*** was introduced by Dufton [Dufton, 1932] and later used and modified by Tanabe et al. with their *manikin-based equivalent temperature* [Tanabe, 1994]. The ***wet-bulb globe thermometer index (WBGT)*** is a simplification of the ***effective temperature***, developed by Yaglou [Yaglou, 1957]. The ***equivalent warmth (EqW)*** is a modification of the ***EqT***, developed by Bedford [Bedford, 1936]. Others are the ***skin wettedness***, the ***effective radiant flux***, the ***standardized***

environmental temperature, or the ***Wind Chill Scale***, introduced by Siple and Passel [Siple, 1945]. Other popular index is the ***operative temperature*** (T_0), which is a calorimetrically derived temperature scale [Gagge, 1940] that combines in one the temperature equivalents of the radiant and the convective environments. This is made by using combining the mean radiant (T_r) and air (T_a) temperature by means of the coefficients of heat transfer by radiation (K_R) and by convection for a given air movement rate (K_C)**.** This scale only looks at the transfer of sensible heat.

2.11.3.2 Analytical indices

Predicted mean vote (PMV) is an index developed by Fanger based on his heat balance equation [Fanger, 1970]. This index has been adopted by international organizations such ASHRAE and ISO. It is further discussed in section 2.11.5.1. Variants to this index are proposed by Hanqing et al. [Hanqing, 2006] for large eddy simulation (LES) of the environment. ***IREQ*** is defined as the resultant clothing insulation required for given environmental conditions to maintain the body in a state of thermal equilibrium with acceptable levels of body and skin temperatures [ISO 11079, 1993]. Other analytical indices are: the ***predicted 4-hour sweat rate (P4SR)*** i.e. a warmth scale created from observations [McArdle, 1947], the ***heat stress index (HIS)*** [Belding, 1955], the ***index of thermal stress (ITS)*** [Givoni, 1963], or the ***new effective temperature (ET*)*** [Gagge, 1971] based on the two-node-model.

2.11.4 Models

The models for the assessment of thermal comfort can be classified into three categories, those are *steady-state models*, *dynamic models*, and *adaptive models*, as discussed by ASHRAE [ASHRAE, 2001].

Steady-state models apply only to steady-state conditions. They can be used mainly in indoor environments, common weather reports or health watch/warning systems (decreasing excess mortality), especially in the heat [Höppe, 2002]. Well known is the model developed by Fanger et al. relating comfort data to physiological variables based on the heat balance of the body with the environment [Fanger, 1967]. Fanger introduced the *predicted mean vote (PMV)* and *predicted percentage dissatisfied (PPD) indices* [Fanger, 1970], applicable in typical indoor environments. These indices take into account that thermal sensation and thermal comfort of a person depend partly on his activity and clothing and on the four environmental variables: air temperature, mean radiant temperature, air velocity and humidity. The equation developed in 1967 predicts the comfort for the combined six parameters. Finally he introduced additional factors to complement his model, i.e. unilateral heating or cooling of the body, asymmetric radiant fields, draughts, and cold/warm floors. His equations and indices, widely in use, have been adopted by the American and European standards, ASHRAE and ISO. They are further discussed in section 2.11.5.

Dynamic models are applicable to transient situations, like relative short times spent outdoors (mostly less than one hour) as the thermal steady state is hardly reached [Höppe, 2002]. If steady-state models were to be used, discomfort, skin and core temperature are likely to be overestimated, especially in cold conditions as it might take hours to reach the steady state compare with the 30 minutes needed in hot conditions. In that sense, the thermal history of a subject is important for dynamic models; for most applications some standardization will be necessary. Compared with the steady-state models, dynamic models provide temporal courses of thermophysiological parameters. An example of dynamic model is the *Two-Node Model* developed by Gagge [Gagge, 1971] for the prediction of physiological responses to transient situations with low and moderate activity levels. This model is a simplification of more complex thermoregulatory models developed by Stolwijk and Hardy [Stolwijk, 1966b] already described in 2.7.1. After calculating skin and core temperatures among other parameters, Gagge's model uses empirical expressions to predict thermal sensation (TSENS) and thermal discomfort (DISC). These indices are based on 11-point numerical scales where positive stands for warm and negative for cold, very similar to the TS. The extra terms are ±4 (very hot/cold) and ±5 (intolerably hot/cold). DISC rates from zero to five, meaning comfortable, slightly uncomfortable but acceptable, uncomfortable and unpleasant, very uncomfortable, limited tolerance and intolerable.

The Berkeley Comfort Model, developed by Huizenga, Zhang, Arens et al. [Huizenga, 2004][Zhang, 2004], predicts human physiological and subjective response, both locally and for the whole body, in non uniform and transient environments typically encountered in buildings and automobiles. The model is based on existing physiological model of human thermoregulatory response [Huizenga, 2001] and includes the relation of thermal sensation with skin and core temperatures. Temperature of hand and fingers is of particular interest because of their importance in regulating the body's heat dissipation, outside neutral conditions when its temperatures fluctuate considerably (1 and 2ºC respectively). The model is later updated so that it predicts, based on skin and core temperature the thermal sensation [Zhang, 2010a] and local comfort [Zhang, 2010b] at 19 different parts of the human body, and also the whole-body thermal sensation and comfort level [Zhang, 2010c]. Local thermal sensation for each body part is obtained as a function of the local and mean skin temperature and the time derivatives of skin and core temperatures representing the response to transients. Local thermal comfort is obtained from local and whole-body thermal sensations. Zhang observed that the whole-body thermal sensation and comfort level is about the average of the individual locations when each of them is near to neutral. However, the overall sensation and comfort would be defined by the 2 locations at higher stress (cold or hot), independently of how neutral and comfortable the other body locations are.

Other dynamic models were developed by Nevins et al. [Nevins, 1973a], Rugh et al. [Rugh, 2004] and Kaynakli et al. [Kaynakli, 2005b]. Nevins' model combines the two-node model of Gagge, slightly modified, with a model of the "effort" required for thermoregulatory control. This is applicable over a useful range of environmental conditions and for activity levels of 0.8 to 1.6 mets. Rugh addressed the assessment of thermal comfort in transient, non-uniform thermal conditions such as within automobiles, as they believe a more efficient climate control system would lead to a significant fuel-saving. They developed a physiological thermal regulatory system model, a physical model (manikin) which includes heating and sweating, and an empirical model to predict local and global thermal sensation and comfort. Kaynakli addresses the transient conditions people might experience when working indoors in warm and hot climate countries, as corridors and lobbies among other spaces which get direct sun light would have higher temperatures than the air controlled offices. Kaynakli's model accounts for the body response (changes in the sensible and latent heat losses, skin temperature and wettedness) to warm-up period, taking into account local discomforts and obtaining thermal comfort indices.

Adaptive models are those which predict the conditions under which people are likely to feel comfortable in buildings, rather that predicting the comfort responses. Examples of adaptive models obtain the prediction of core temperature in comfort [Humphreys, 1998] or the operative temperature for comfort within climates and buildings where neither cooling nor central heating is required [de Dear, 1998b]; both models take into account the outdoor temperature. Adaptive models acknowledge the ability of people to adjust to their environment by behavioural changes and adaptation. They are useful for the setting of temperature within a building throughout the year, helping to reduce the expenditure of energy.

PMV and PPD indexes make useful predictions of the optimal comfort temperatures for building occupants in settings where centrally controlled air-conditioning is in operation -where the occupants are removed from the thermal comfort control loop-. However, in situations where the building occupants are required to interact with the building in order to make themselves more comfortable, as in a naturally ventilated building, the adaptive comfort standard seem more useful [de Dear, 2004]. Van Hoof et al. [Van Hoof, 2007] discuss the use of adaptive comfort models in moderate maritime climate zones, both in terms of usability and energy. These models were found to be very limited in such climates, being applicable only during summer months. Furthermore, the authors suggest the use of a more gradual parameter to account for the outdoor air temperature rather than the monthly average.

Thermoregulation models have been used in thermal comfort studies for various purposes [Munir, 2009], such as precise analysis of asymmetrical thermal radiation between the human body and its surroundings [Zhang, 2005][Tanabe, 2002]; the coupling of simulations of human thermal models with computational fluid dynamics [Xue, 1999][Gao, 2006] or prediction of indoor thermal comfort [Atmaca, 2007][Kaynakli, 2004]. Ghali et al. developed a space heat model to account for the thermal response of people subjected to the radiant asymmetry of a stove [Ghali, 2008] and included in previous transient bio-heat model by the same authors. Malchaire et al. developed a model to assess risks of heat disorders while working in hot conditions [Malchaire, 2001]. Eight European laboratories participated in this project. They developed a parameter called *Predicted Heat Strain* which they believe to be better than the *Required Sweat Rate*.

2.11.5 Thermal comfort level estimation

PMV (Predicted Mean Vote) and the PPD (Predicted Percentage of Dissatisfied) are two statistical indexes that quantify the thermal comfort level in steady-state, hence in most indoor environments [Fanger, 1970]. However, they are inaccurate or inapplicable for the evaluation of non-uniform conditions [Tanabe, 1994]. PMV predicts the mean value of the votes of a large group of people on the 7-points *thermal sensation* scale when they are subjected to the environmental conditions under study. The PPD expresses the percentage of subjects on a large group of people that feels uncomfortable when they are subjected to the environmental conditions under study. The relation between the thermal sensation and the PMV values is given on **Table 11** [ISO 7730, 1994].

PMV and PPD refer to the whole body thermal comfort. To determine unpleasant local conditions, the *PD (Percentage Dissatisfied) index* is used. Local and global comforts are not necessarily in agreement. People may be dissatisfied due to general thermal comfort (PMV) and/or dissatisfied by the local thermal discomfort parameters (draught, radiant asymmetry, and so on.). At the present time there is no method for combining the percentages of dissatisfied people to give an accurate prediction of the total number of people finding the environment unacceptable [de Dear, 2004].

2.11.5.1 Global comfort level: PMV

Following the indications of Fanger [Fanger, 1970], which are now standardized by the ISO [ISO 7730, 1994], the PMV value can be obtained by means of equation **17**. The PMV depends on several factors: metabolic rate (M), effective mechanical power (W), clothing insulation (I_{cl}), clothing surface area factor (f_{cl}), air temperature (t_a), mean radiant temperature ($\overline{t_r}$), relative air velocity (v_{ar}), water vapour partial pressure (humidity) (p_a), heat transfer coefficient (h_c) and clothing surface temperature (t_{cl}).

$$PMV = \left[0{,}303 * \exp\left(-0{,}036 * M\right) + 0{,}028\right] * \left\{ \begin{array}{l} \left(M - W\right) - 3{,}05 * 10^{-3} * \left[5733 - 6{,}99\left(M - W\right) - p_a\right] - 0{,}42 * \left[\left(M - W\right) - 58{,}15\right] \\ -1{,}7 * 10^{-5} * M * \left(5867 - p_a\right) - 0{,}0014 * M * \left(34 - t_a\right) \\ -3{,}96 * 10^{-8} * f_{cl} * \left[\left(t_{cl} + 273\right)^4 - \left(\overline{t_r} + 273\right)^4\right] - f_{cl} * h_c * \left(t_{cl} - t_a\right) \end{array} \right\} \qquad \textbf{(17)}$$

where

$$t_{cl} = 35{,}7 - 0{,}028 * \left(M - W\right) - I_{cl} * \left\{3{,}96 * 10^{-8} * f_{cl} * \left[\left(t_{cl} + 273\right)^4 - \left(\overline{t_r} + 273\right)^4\right] + f_{cl} * h_c * \left(t_{cl} - t_a\right)\right\}$$

$$h_c = \begin{cases} 2{,}38 * \left| t_{cl} - t_a{}^{0,25} \right| & for \quad 2{,}38 * \left| t_{cl} - t_a \right|^{0,25} > 12{,}1 * \sqrt{v_{ar}} \\ 12{,}1 * \sqrt{v_{ar}} & for \quad 2{,}38 * \left| t_{cl} - t_a \right|^{0,25} < 12{,}1 * \sqrt{v_{ar}} \end{cases}$$

$$f_{cl} = \begin{cases} 1{,}00 + 1{,}290 * I_{cl} & for \quad l_{cl} \leq 0{,}078 m^2.K / W \\ 1{,}05 + 0{,}645 l_{cl} & for \quad l_{cl} > 0{,}078 m^2.K / W \end{cases}$$

Metabolic rate and heat production are tabulated for various activities in the standards [ISO 7730, 1994] (**table 1** and **2** respectively). The first 3 cases are typical of sedentary behaviour, having the lowest values. The third category, with slightly higher values, includes activities such as working, eating or playing with the entertainment system. Clothing insulation and clothing surface area can be estimated as discussed in section 2.9. Heat transfer coefficient and clothing surface temperature are determined by the formula **17**, which is solved by iteration. Mean radiant temperature can be determined based on the instructions of ISO 7726 [ISO 7726, 1998]. Air temperature and water vapour partial pressure (humidity) are measured with standard sensors. Relative air velocity can be obtained by means of equation **10** [ISO 11079, 1993]. Estimation of I_{cl} and M ought to be particularly precise to achieve a comfort assessment within 0.3 PMV [Havenith, 2002]. Havenith observed that body motion and air movement can not be neglected when assessing I_{cl} and that more details about the activities ought to be considered when M is below 2 met.

In lab studies, Tanabe et al. [Tanabe, 1994] found that PMV can be easily calculated when using their manikin-based equivalent temperature as air and mean radiant temperature. Air velocity should be considered still, hence natural convection, and the relative humidity to be 50%. The relation between the equivalent temperature and PMV appears to be linear, with this being dependent on the clothing and activity level.

2.11.5.2 Global discomfort - PPD

PPD predicts the percentage of people within a large group that are uncomfortable with the thermal environment. Dissatisfied are those people who would vote their thermal sensation as not being -1, 0 or +1. The number of people dissatisfied is never zero as no thermal environment can satisfy everyone because of individual differences in experiencing thermal environments [Fanger, 1970]. PPD would be 5% even when PMV is equals to zero, 10% when PMV ranges from -0.5 to +0.5. PMV and PPD are related by equation **18**, also represented in **Figure 5**.

$$PPD = 100 - 95 * \exp\left(-0.03353 * PMV^{4} - 0.2179 * PMV^{2}\right) \tag{18}$$

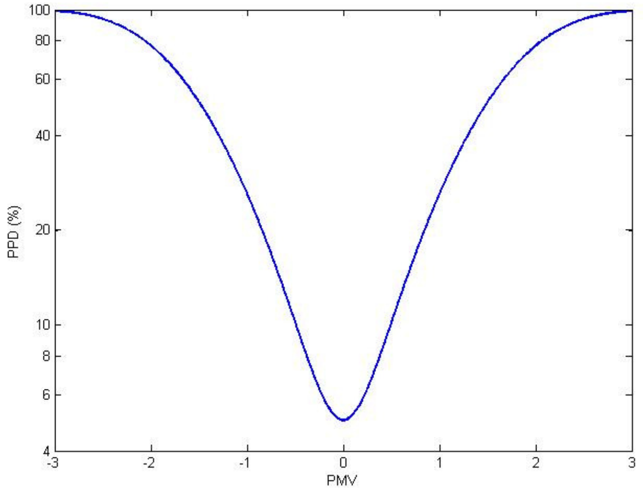


Figure 5: Relation between PMV and PPD

2.11.5.3 Local comfort - PD

Thermal dissatisfaction can be caused by unwanted cooling or heating of one particular part of the body, known as *local discomfort*. Local discomfort might be caused by several aspects: draughts, vertical air temperature difference, warm and cold floors, warm and cool walls, and warm and cool ceilings [ISO 7730, 1994].

The **discomfort due to draught** may be expressed as indicated in equation **19**.

$$DR = \left(34 - t_{a,l}\right) * \left(\overline{v_{a,l}} * Tu + 3{,}14\right)$$

where:

$t_{a,l}$ is the local air temperature, in ˚C, 20 to 26 ˚C

$v_{a,l}$ is the local mean air velocity, in m/s, <0,5m/s **(19)**

Tu is the local turbulence intensity, in percent, 10% to 60%
(if unknown, 40% may be used)

The **local discomfort caused by vertical air temperature difference** can be determined by equation **20**. **Figure 6** presents the local discomfort for several values of temperature difference.

$$PD = \frac{100}{1+\exp\left(5{,}76-0{,}856*\Delta t_{a,v}\right)} \qquad if \qquad \Delta t_{a,v} < 8°C \qquad \textbf{(20)}$$

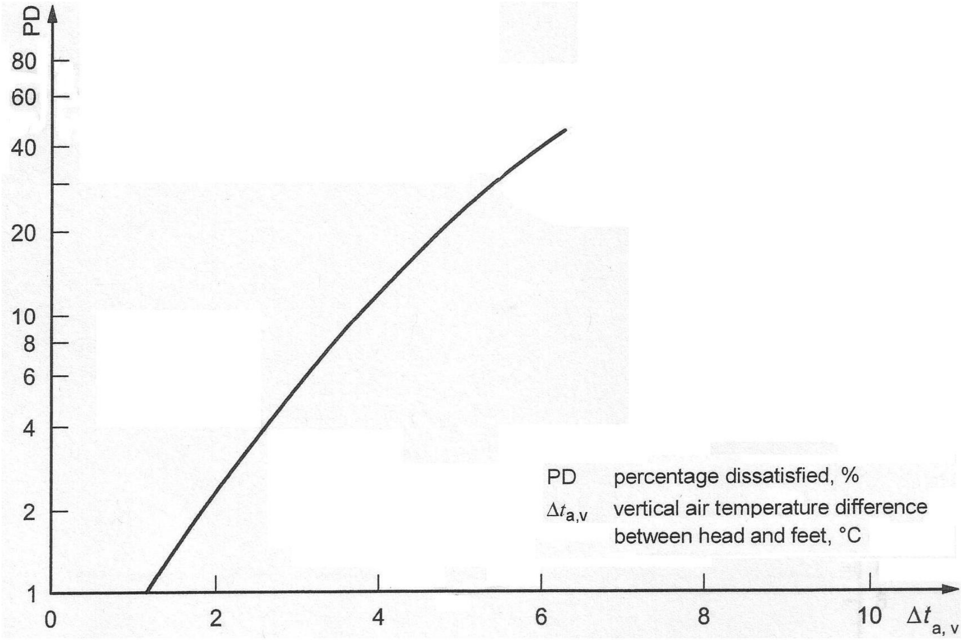


Figure 6: Local discomfort caused by vertical air temperature difference (ISO 7730)

Local thermal discomfort caused by warm and cold floors can be determined by equation **21**. **Figure 7** presents the local discomfort for several values of floor temperature. Optimal temperature appears between 24 and 25 °C.

$$PD = 100 - 94*\exp\left(-1{,}387+0{,}118*t_f - 0{,}0025*t_f^2\right) \qquad \textbf{(21)}$$

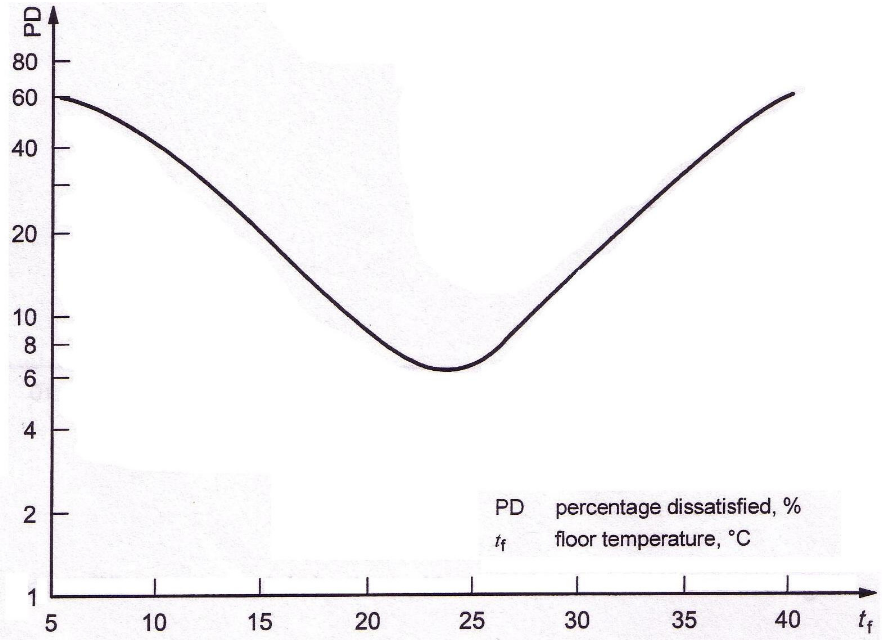


Figure 7: Local discomfort caused by warm and cold floors (ISO 7730)

Discomfort caused by radiant asymmetry can be determined by equations **22** to **25**. Radiant asymmetry has no significant impact on the operative temperatures preferred by seated people in 0.6 clo clothing, but did at a comfort level as observed by Fanger et al. [Fanger, 1985]. Fanger established the curves of percentage of people dissatisfied due to radiant asymmetry of cool walls, warm walls, and cool ceilings (**Figure 8**). Warm walls were observed to cause less discomfort than cool walls, but the opposite for ceilings. To maintain the PPD at a 5% the maximum asymmetry are 10°C in a cool wall, 23°C at a warm wall, 14°C under a cool ceiling, and 4°C under a warm ceiling.

i) Warm ceiling

$$PD = \frac{100}{1+\exp\left(2{,}84-0{,}174*\Delta t_{pr}\right)}-5{,}5 \qquad if \qquad \Delta t_{pr} < 23°C \qquad \textbf{(22)}$$

ii) Cool wall

$$PD = \frac{100}{1+\exp\left(6{,}61-0{,}345*\Delta t_{pr}\right)} \qquad if \qquad \Delta t_{pr} < 15°C \qquad \textbf{(23)}$$

iii) Cool ceiling

$$PD = \frac{100}{1+\exp\left(9{,}93-0{,}50*\Delta t_{pr}\right)} \qquad if \qquad \Delta t_{pr} < 15°C \qquad \textbf{(24)}$$

iv) Warm wall

$$PD = \frac{100}{1+\exp\left(3{,}72-0{,}052*\Delta t_{pr}\right)}-3{,}5 \qquad if \qquad \Delta t_{pr} < 35°C \qquad \textbf{(25)}$$

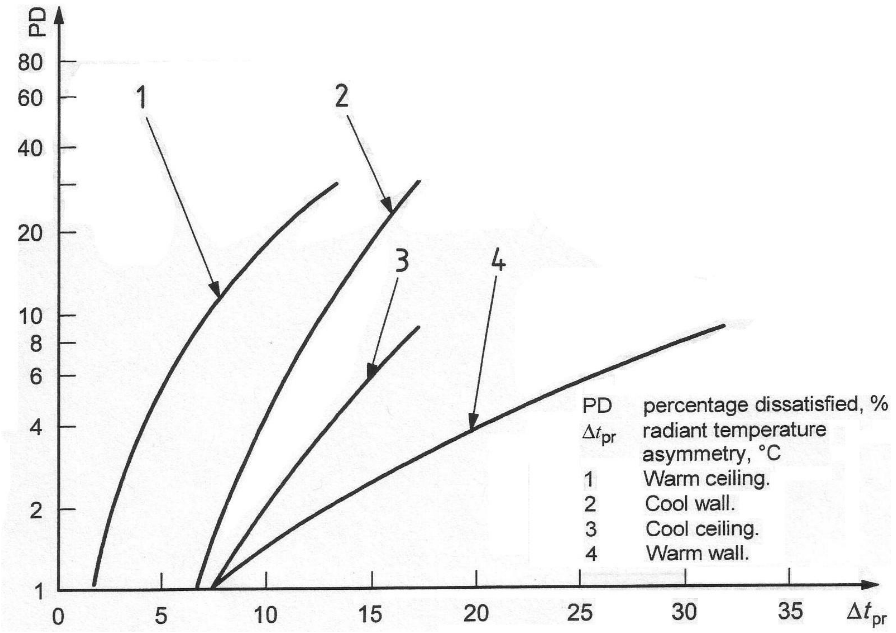


Figure 8: Local thermal discomfort caused by radiant temperature asymmetry (ISO 7730)

Formulas given by ISO 7730 [ISO 7730, 1994] refer to homogeneous and steady-state environments, which is not always the case. Steady-state can be considered when:

- the peak-to-peak variation is less than 1K in temperature cycles.
- the temperature change for drifts or ramps is lower than 2.0K/h.

2.11.6 Comfort zone

At international level, International Organization for Standardization (ISO), European Committee for Standardization (CEN) and American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) are continuously writing and reviewing standards relating to the indoor environment. Standards such as EN ISO 7730 [ISO 7730, 1994], CR1752 [CEN, 1998] and ASHRAE 55–92R [ASHRAE, 2004] enclose the requirements for acceptable thermal climate, both for global comfort (body as a whole) and to avoid local thermal discomfort. These standards are discussed by Olesen [Olesen, 2004] and Oseland [Oseland, 1997] as partially reported in this section.

Optimum comfort conditions outlined in at ISO 7730 were initially based on Fanger's PMV model and later on adjusted using the field data collected by De Dear [de Dear, 1998a]. De Dear collated into a database dozens of thermal comfort field studies done at 160 different buildings (mainly commercial offices located in a wide crossection of climate-zones across the globe) where approximately 22,000 standardized comfort questionnaires were completed by occupants as their immediate workstation microclimate was monitored. De Dear and Brager [de Dear, 1998b] found close agreement between comfort temperatures (preferred indoor temperatures) in the centrally controlled HVAC buildings, and the optimal temperature predicted by the comfort indices such as PMV-PPD [de Dear, 2001], even in a broad range of external climatic contexts. In centrally controlled HVAC buildings the indoor climates were observed to be relatively static through time hence can be considered to be steady-state.

The American standard ASHRAE 55 was originally based on Gagge's physiological studies and two-node thermoregulation model [Gagge, 1971] and comfort data from field studies [Nevins, 1973a]. The definition of the boundaries for comfort was changing until the latest version in 2004, where lower limit for humidity was removed, besides the potential excessive drying of the skin and mucous membranes. This value was removed as it is not technically a factor for thermal comfort [PLEA, 2007].

ASHRAE 55 and ISO 7730 currently provide very similar ranges of environmental conditions for thermal comfort. They specify ranges of PMV, PPD, t_o, v_a, and H for general thermal comfort; and maximum draught, turbulence, vertical air temperature differences, radiant temperature asymmetry, and surfaces temperature for local thermal comfort. Today no method exists for combining these percentages of people dissatisfied in order to give a good prediction of the total number of persons finding the environment unacceptable [Olesen, 2004]. Both standards assume indoor environments, sedentary activity and typical clothing of 1.0 clo for winter and 0.5 clo for summer.

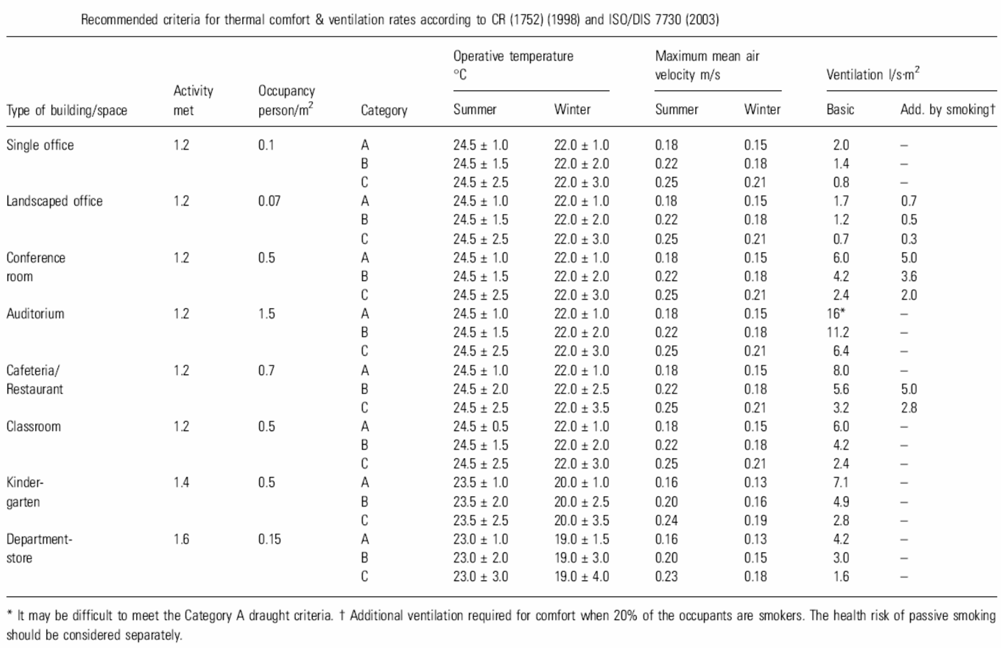
Recommendations are given by standards ISO 7730 and CR 1752 [ISO 7730, 2005] [CEN, 1998] for good acceptance within 3 classes of environments (**Table 12**). Each category corresponds to a different allowance of percentage of people dissatisfied. Optimal temperature is the same for all 3 classes but the acceptable range varies. **Table 13** includes the parameters causing local discomfort (radiant temperature asymmetry, vertical air temperature differences and floor surface temperatures). Some of the classes for local thermal comfort are similar because the existing data do not support limits even lower. Preferred temperatures were observed to be dependent on the kind of room and its occupancy, and so different ranges of temperature, maximum air velocity and ventilation are given **Table 14**.

Category	Thermal state of the body as a whole		Operative temperature °C		Max. mean air velocity m/s	
	PPD %	PMV	Summer (0,5 clo) Cooling	Winter (1 clo) Heating	Summer (0,5 clo) Cooling	Winter (1 clo) Heating
A	< 6	-0.2 < PMV < + 0.2	23.5 – 25.5	21.0 – 23.0	0.18	0.15
B	< 10	-0.5 < PMV < + 0.5	23.0 – 26.0	20.0 – 24.0	0.22	0.18
C	< 15	0.7 < PMV < + 0.7	22.0 – 27.0	19.0 – 25.0	0.25	0.21

Table 12: Three categories of thermal environment. Percentage of dissatisfied due to general comfort and local discomfort [ISO 7730, 2005][CEN, 1998]

Category	Vertical air temp. diff. K	Floor surface temperature ℃	Radiant temperature asymmetry K			
			Warm ceiling	Cool ceiling	Cool wall	Warm wall
A	< 2	19 - 29	< 5	< 14	< 10	< 23
B	< 3	19 - 29	< 5	< 14	< 10	< 23
C	< 4	17 - 31	< 7	< 18	< 13	< 35

Table 13: Recommended categories for local thermal discomfort parameters



Recommended criteria for thermal comfort & ventilation rates according to CR (1752) (1998) and ISO/DIS 7730 (2003)

Type of building/space	Activity met	Occupancy person/m^2	Category	Operative temperature °C		Maximum mean air velocity m/s		Ventilation l/s·m^2	
				Summer	Winter	Summer	Winter	Basic	Add. by smoking†
Single office	1.2	0.1	A	24.5 ± 1.0	22.0 ± 1.0	0.18	0.15	2.0	–
			B	24.5 ± 1.5	22.0 ± 2.0	0.22	0.18	1.4	–
			C	24.5 ± 2.5	22.0 ± 3.0	0.25	0.21	0.8	–
Landscaped office	1.2	0.07	A	24.5 ± 1.0	22.0 ± 1.0	0.18	0.15	1.7	0.7
			B	24.5 ± 1.5	22.0 ± 2.0	0.22	0.18	1.2	0.5
			C	24.5 ± 2.5	22.0 ± 3.0	0.25	0.21	0.7	0.3
Conference room	1.2	0.5	A	24.5 ± 1.0	22.0 ± 1.0	0.18	0.15	6.0	5.0
			B	24.5 ± 1.5	22.0 ± 2.0	0.22	0.18	4.2	3.6
			C	24.5 ± 2.5	22.0 ± 3.0	0.25	0.21	2.4	2.0
Auditorium	1.2	1.5	A	24.5 ± 1.0	22.0 ± 1.0	0.18	0.15	16*	–
			B	24.5 ± 1.5	22.0 ± 2.0	0.22	0.18	11.2	–
			C	24.5 ± 2.5	22.0 ± 3.0	0.25	0.21	6.4	–
Cafeteria/ Restaurant	1.2	0.7	A	24.5 ± 1.0	22.0 ± 1.0	0.18	0.15	8.0	–
			B	24.5 ± 2.0	22.0 ± 2.5	0.22	0.18	5.6	5.0
			C	24.5 ± 2.5	22.0 ± 3.5	0.25	0.21	3.2	2.8
Classroom	1.2	0.5	A	24.5 ± 0.5	22.0 ± 1.0	0.18	0.15	6.0	–
			B	24.5 ± 1.5	22.0 ± 2.0	0.22	0.18	4.2	–
			C	24.5 ± 2.5	22.0 ± 3.0	0.25	0.21	2.4	–
Kinder- garten	1.4	0.5	A	23.5 ± 1.0	20.0 ± 1.0	0.16	0.13	7.1	–
			B	23.5 ± 2.0	20.0 ± 2.5	0.20	0.16	4.9	–
			C	23.5 ± 2.5	20.0 ± 3.5	0.24	0.19	2.8	–
Department- store	1.6	0.15	A	23.0 ± 1.0	19.0 ± 1.5	0.16	0.13	4.2	–
			B	23.0 ± 2.0	19.0 ± 3.0	0.20	0.15	3.0	–
			C	23.0 ± 3.0	19.0 ± 4.0	0.23	0.18	1.6	–

* It may be difficult to meet the Category A draught criteria. † Additional ventilation required for comfort when 20% of the occupants are smokers. The health risk of passive smoking should be considered separately.

Table 14: Recommended criteria for thermal comfort and ventilation rates according to ISO 7730 and CR 1752 [ISO 7730, 2005][CEN, 1998]

Air velocity offsets the thermal sensation either improving comfort under warm conditions or leading to draught sensation. Displacement of the upper limit temperature for comfort can be obtained based on computer model for constant total heat transfer from the skin, e.g. by means of equation **26** included both in ASHRAE Standard 55 and ISO 7730 (**Figure 9**). Alternatively experimental expressions are given by Fountain et al. [Fountain, 1994], who investigated the effect and preference of different air supplies.

$$DR = ((34 - t_a)*(v_a - 0.05)^{0.62})*(0.37*v_a*Tu + 3.14) \qquad \textbf{(26)}$$

where DR is the percentage of people dissatisfied due to draught, ta is the local air temperature, v_a is the local mean air velocity and Tu is the local turbulence intensity.

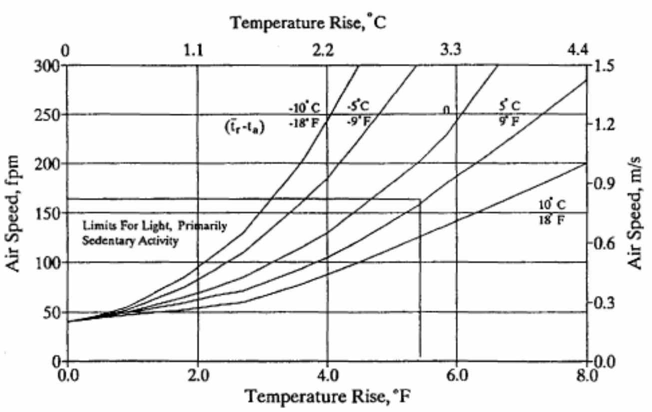


Figure 9: Air speed required to offset increased temperature (from ASHRAE Standard 55)

Poor ventilation increases the percentage of people dissatisfied even for the particular case of 0% of smokers among the occupancy of the room (**Figure 10**). Minimum ventilation rates are established for different classes (A, B and C) and increase with the percentage of smokers within the room (see **Table 15**). The required ventilation rate (Q) is an addition of the minimum Q required per person (due to the pollution and odour emitted from the person and his activity) and the minimum Q required per square meter of floor area (taking care of emissions from the building, furnishing or HVAC system) [ASHRAE, 2003]. It can be obtained by equation **27** as indicated in ISO 7730.

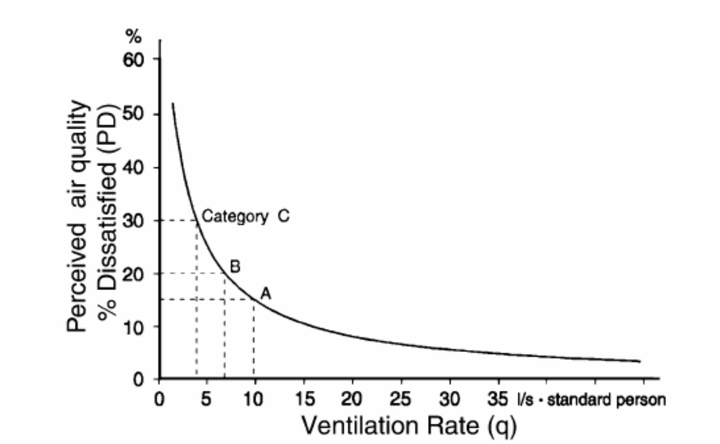
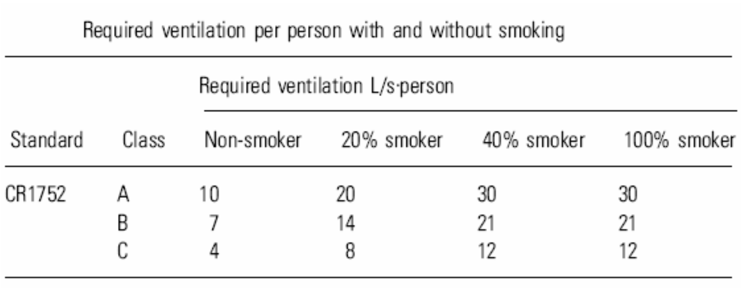


Figure 10: Dissatisfaction at different ventilation rates (reproduced from [Olesen, 1973]


Required ventilation per person with and without smoking

Standard	Class	Required ventilation L/s·person Non-smoker	20% smoker	40% smoker	100% smoker
CR1752	A	10	20	30	30
	B	7	14	21	21
	C	4	8	12	12

Table 15: Required ventilation per person with and without smoking

$$Q = G / ((Ci - Co)*E_v*s)$$

where G = Total emission rate mg/s; Ci = Concentration limit mg/l; **(27)**

Co = Concentration in outside air mg/l; and E_v = Ventilation effectiveness

The effect of absolute humidity on general thermal comfort is rather limited at moderate activity levels and temperatures (<26°C). Typically a 10% increase of H rises the operative temperature on 0.3°C. For higher temperatures and activities, the influence is greater. Similarly PMV is not influenced significantly by relative humidity unless under very cold conditions [Fermanel, 1999]. Humidity comfort zones are wide when based on the maintenance of acceptable thermal conditions (thermal sensation, skin wetness, skin dryness, and eye irritation). Comfort is very good when T ranges 19-22ºC and H ranges 40-60%. Correct comfort occurs at T of 17.5-23.5ºC and H=30-65%.

Strong thermal discomfort exists within the vicinity of the stove high-temperature surface [Ghali, 2008]. Local discomfort is defined as a deviation of SD>1.1ºC from temperature at comfort, accordingly with the limits established by Fanger for asymmetric thermal radiation [Fanger, 1985] as indicated by Ghali.

Body temperature must be kept within certain range so people do not feel uncomfortable. Average human core temperatures is about 36.1-37.8°C while skin temperature is about 33.3°C [Sharon, 2007]. For people with light clothing (0.6 clo) when subjected to their preferred environmental temperature (25.6ºC), skin and rectal temperature were 33.5ºC and 36.9ºC respectively [Olesen, 1973]. This is for whole-body thermal comfort. When regarding local thermal comfort, the topography of local temperatures and vasomotor activity need to be observed [Hensel, 1973].

Currently it is under discussion whether people could adapt to higher indoor temperatures during summer in naturally ventilated (free running) buildings, or the benefits of increasing air velocity, humidity and thermal comfort.

Oseland [Oseland, 1997] investigated the accuracy of temperature predictions for comfort given by the standards ISSO 7730 and ASHRAE 55. He observed those standards over-predict by up to 3ºC the temperatures for comfort and suggest that empirical models should be used rather than pure theoretical ones.

2.11.7 Towards an comfort level assessment system

Thermal comfort has been empirically related to the environmental parameters since Houghten and Yaglou´s work in 1923 [Nevins, 1973a]. Since then, numerous authors have contributed to a better understanding of the thermal sensation and thermal comfort, such as Fanger or de Dear whose work contributed to the creation of international standards such as ASHRAE 55 or ISO 7730. Furthermore experiments were carried out at Kansas State University to investigate the thermal comfort response of large number of subjects varying most of the parameters involved in thermal comfort [Nevins, 1973a]. Also different comfort studies were performed at Berkeley University by Arens, Wang and Zhang. Arens and Wang investigated the local thermal sensations and comfort at various uniform environmental conditions and related with the whole body thermal sensation and comfort perceived for individual. They observed that the overall sensation and comfort follow the warmest local sensation (head) in warm environments and the coldest (hands and feet) in cool environments [Arens, 2006a], and their change is stronger when only a local part of the body is cooled or warmed rather than whole-body temperature step-changes [Arens, 2006b]. Whole-body thermal sensation was found to be specially correlated with temperature at fingers or finger-forearm skin temperature gradient [Wang, 2007], both for steady and transient conditions. Positive gradient is observed in those people feeling warm or hot, while the gradient is negative when feeling cold. Similarly, finger temperature above 30ºC is related with warm sensation, while for values below that threshold there is possibility of discomfort due to cold.

Following Arens and Wang's investigations about the relation between local skin temperature and over-all thermal sensation and comfort level, Zhang et al. [Zhang, 2010d] developed at the same university a task–ambient conditioning (TAC) system which provides comfort by either heating feet and hands or cooling hands and face. They observed that this system maintains good comfort level for room temperatures ranging 18-30ºC and saves about 40% of the energy annually dedicated to heating and cooling within a building.

Shivering and sweating are clearly two uncomfortable states for the vast majority of the people and so they ought to be avoided. The onset of either of them is defined by the core and skin temperature [Cheng, 1995]. Cheng *et al.* proved experimentally that the relation between core and skin temperature is linear at the thresholds of vasoconstriction and shivering, and not dependent on the gender of the subjects. They estimate the average contribution of skin temperature to those states in a 20%.

2.11.8 Thermal comfort studies into vehicle cabins

The comfort expectations experienced by vehicle passengers have significantly grown due to the rising mobility and travelling time [Silva, 2002]. This has lead to a series of investigations on thermal comfort within vehicle cabins.

Burch *et al.* [Burch, 1991] developed a model for thermal exchange between body and environment, accounting for sensible and latent heat losses at different locations, skin temperatures and skin wettedness. They used the thermal sensation for estimation of the thermal comfort as defined in equation **28**. Also they determined experimentally the local air velocities on the body of sitting passenger (**Table 16**).

$$TS =[0.303 \exp(-0.036*M/A_b) +0.028]*L \tag{28}$$

where

A_b is the total surface area of the body

M is the metabolic rate

L is the thermal load on the body

Region	Air velocity (m/s)
Head	0.13
Trunk	0.11
Right shoulder	0.12
Left shoulder	0.13
Legs	0.11
Right knee	0.18
Left knee	0.21
Right ankle	0.66
Left ankle	0.62

Table 16: Local air velocities on a body in seated position inside a vehicle cabin

Martinho *et al.* [Martinho, 2004] studied the airflow in a vehicle cabin with the typical dimensions and geometry of a multi-purpose vehicle. They evaluated the thermal comfort through the equivalent temperature index. Their tests were carried out with and without the presence of a thermal manikin, with different values of air velocity and temperature and with different regulation of the air inlets. They determined the equivalent temperature for each of 16 parts of the body by two distinct forms: from the measurements performed by the thermal manikin and from the physical parameters of the airflow, i.e. air velocity and temperature.

Kaynakli et al. [Kaynakli, 2005a] modelled the thermal interactions between a human body and the interior environment of an automobile, based on the heat balance equation for human body, combined with empirical equations defining the sweat rate and mean skin temperature. Transient conditions were simulated and the effects of both heating and cooling processes on the thermal comfort inside the automobile were investigated. Segmental analysis was carried out for determination of local discomforts. 16 segments were considered: feet, fibulas, thighs, pelvis, head, hands, forearms, chest, and back.

Mezrhab et al. [Mezrhab, 2006] described a numerical method to study thermal comfort response inside the car compartment according to climatic conditions and materials within vehicle. They also investigated the effects of solar radiation, types of glazing, car colour and radioactive properties of materials constituting the compartment. Their model is based on the nodal method and the finite difference method. Its specifications are: (i) the transient mode, (ii) the taking into account the combined convection, conduction and radiation heat transfer, (iii) the coupling of two spectral bands (short-wave and long-wave radiation) and two solar fluxes (beam and diffuse). It subdivides the compartment into several solid nodes (materials constituting the compartment) and fluid nodes (volumes of air inside the compartment). Then it establishes the heat balance for each node and predicts the evolution of its temperature.

Numerical simulations of interaction between environment within a cabin and its occupants based on computational fluid dynamics (CFD) enable the assessment of the potential thermal comfort for different designs prior to their construction [Nilsson, 2006]. This permits the selection of appropriate designs. Van Treeck et al. [Van Treeck, 2006] developed a computational steering environment (CSE) which simulates the turbulent convective flows and the local interaction of the environment and occupants; and applied it to the separator room of a ferry and a train’s passenger carriage.

Cengiz et al. [Cengiz, 2007] evaluated the thermal comfort of drivers under real traffic conditions. They observed that traffic conditions affect the comfort level directly. They studied three different seat cover materials but found not relation with the thermal comfort level. The drivers felt the warmest around their waist.

3 Experimental setup

The present thesis investigates the following physiological aspects related to human thermoregulation: (1) skin temperature mapping, (2) external parameters affecting core temperature, skin temperature and thermal comfort level, (3) the relation between the core temperature and skin temperature and influence of external conditions, (4) relation between thermal comfort level and the skin temperature and influence of external conditions, (5) evolution on time of physiological signals –skin temperature and core temperature- and psychological signals – thermal sensation and comfort level- under steady conditions, and (6) identification of new methods for non-intrusive core temperature monitoring. Several experiments were carried out with similar setup, detailed in this chapter. Studied parameters are environmental temperature and humidity, gender, BMI, age, activity level, and clothing. They were chosen as there is indication in the literature that they affect the core and/or skin temperature.

3.1 Subject groups

The population investigated was from two specific groups: (1) children under the age of 2 years, and (2) self clothed adults at low activity levels. All sub studies were approved by QMUL ethics committee, references QMREC2008/31 and QMREC2008/72. Respective forms are attached in **appendices C** and **D**. Adult volunteers were approached at the university through posters and general emails. Children were recruited by approaching their parents at nurseries. Ethical regulations were complied with.

3.2 Measurement rooms

All measurements were taken indoors, where climatic conditions are easier to control. The effect of radiant temperature was kept at a minimum by using blinds on the windows and keeping subjects away from radiators or cold surfaces. There was no significant air velocity as drafts affecting the volunteers, both from doors or air conditioning systems, were avoided. Hence, factors as wind chill or high radiant temperature due to direct exposure to the sun were not considered.

Different room temperatures for the adults-cohort, ranging between 18 and 31ºC, were used in order to study how temperature affects both physiological and psychological parameters. Temperature was controlled either (1) by opening windows or using heaters simulating natural-ventilated buildings, or (2) by air-conditioning systems. A finer environmental control system (e.g. better control of the temperature, more stable conditions, greater uniformity of conditions within the room) was desirable but not available. Stratification per room temperature is given in each of the chapters accordingly. Room temperature for the children-cohort could not be modified as nurseries, where measurements for this cohort took place, need to maintain it within a narrow range. During our experiments the observed mean environmental temperature was 23.7°C (1.7°C) and average humidity was 55.1 (6.8) %.

3.3 Selection of skin locations

The skin temperature measuring locations were selected according to the 14-points suggested by International Standard ISO 9886 [ISO 9886, 2004] (see **Table 5** and **Figure 3**) and their convenience. For the baby's cohort, all 14 standard points were used and 2 additional ones included (locations 15 lateral of the neck and 16 left wrist) as they are very visible, hence convenient locations for placing monitoring sensors (**Figure 11**). For the adult's cohort (**Figure 12**), locations in the back of the body were withdrawn as volunteers were seating hence they were not practical. An extra point (knees) was added as pilot studies established that its skin temperature is one of the most accurately predictable, being also closely represented by the temperature measured on the clothing covering the knee. Skin temperature was measured both in the left and right side of the body to minimize possible effect of drafts.

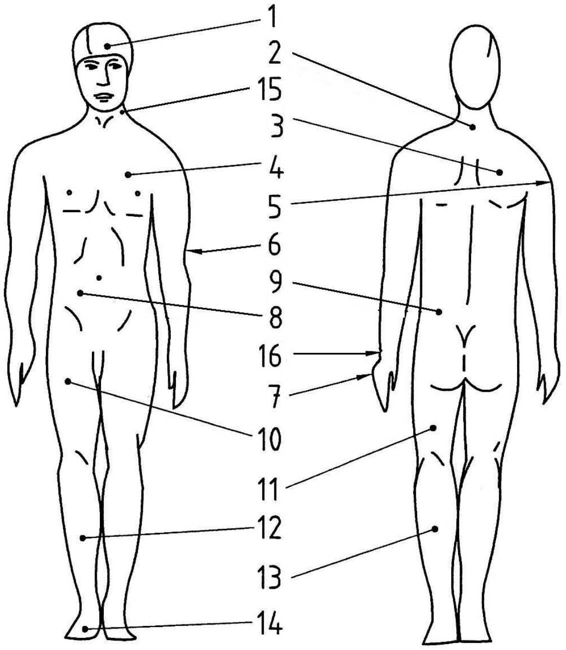


Figure 11: Location of measuring for baby's cohort (figure adapted from ISO 9886:2004)

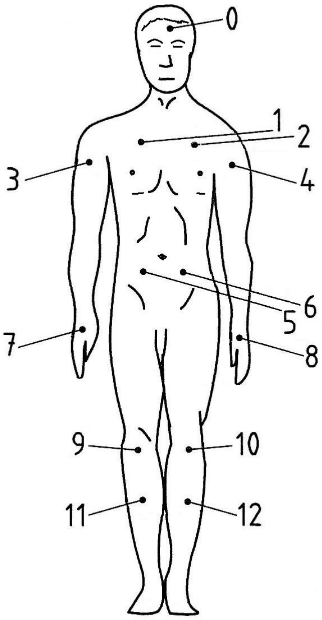


Figure 12: Measuring sites for adults

3.4 Equipment

Tympanic temperature was used as core temperature as it provides a reliable and accurate indication of the core temperature in a hygienic non-invasive way. It was measured using an infrared (IR) sensor (OMRON Healthcare Co., Ltd., model MC-510-E2) of 0.1°C accuracy (**Figure 13**). A special ear thermometer for babies was chosen. Consistent measurements of the tympanic temperature were obtained by recording the maximum temperature value in a 10 seconds application while inclining the sensor under different angles, as recommended by the manufacturer. This enhances the possibilities of detecting the tympanic area.

Skin temperature was measured using an infrared sensor (Medscope Ltd., model TH03F) of accuracy 0.1ºC (**Figure 14**). This sensor is fast, safe and hygienic as contact is not required.

Both sensors are approved by in the UK's National Health System (NHS). To guarantee the validity of the measurements, climatic conditions were kept constant during data collection, with air temperature in the range of 18 to 31˚C, air velocity less that 0.2 m/s and mean radiant temperature close to air temperature.

Auditory channel temperature was measured using an infrared camera (thermal imager Fluke TiR1, see **Figure 15**). This allows contactless temperature identification.

Five meteorological station units were used to monitor the humidity and temperature conditions in different areas of the room where the experiments took place. These units were distributed through the room so that the average temperature and relative humidity of the non uniform environment could be calculated. Radiant temperature and air velocity measurement devices were desirable in order to perform a broader study were these parameters were taken into account; they were however not available.

Specifications of the measuring devices are presented in **Appendix E**.

Sensors used on the project

Figure 13: Ear thermometer

Figure 14: Skin thermometer

Figure 15: Thermal imager Fluke TiR1

Additionally, adults were asked to complete questionnaires where they indicated their *thermal sensation* in the 7-point ASHRAE scale (**Table 11**) and the corresponding *level of comfort* in a 0 to 5 scale (from 0 which corresponds to least discomfort or "comfortable" to 5 which corresponds to the most discomfort or "intolerance") (see **Appendix F**).

3.5 Procedure

Prior to the subject's arrivals, the room was prepared such that temperature was homogeneous. Drafts were minimized by closing doors and windows; blinds were used to prevent sunlight and so avoid room temperature deviation due to radiant temperature. For the adults' cohort, desired room temperature was set up.

Volunteers were allowed into the test room, where they remained for a minimum of 15 minutes before the first measurement was taken. During this time, the subjects had time to adapt to the environment, reaching stable skin temperatures as shown by Nagano et al. [Nagano, 2005]. While not adapted, random temperature fluctuations occur such that measurements are not comparable [Houdas, 1972]. Volunteers were asked to have their forehead exposed, as hair is known to decrease the heat transfer coefficient [de Dear, 1997]. Children moved to their will while adults were required to remain seated.

Volunteers were addressed several times and their skin temperatures and core temperature taken. Skin temperature at exposed locations was measured first, followed by temperature on the clothed areas and then underneath. Finally core temperature was taken. In order to reduce the error, core temperature was measured twice in each occasion while the skin temperature was measured three times and averaged. Intravariation was small, about the accuracy of the measurement device, 0.1ºC. The inter-variation was observed to be the same, and so attributed to the accuracy of the measurement. No distinction among data from different observers was further done, but all analyzed together.

The individual characteristics –gender, age and BMI- were recorded. Also activity, ingestion of food prior to the measurements and clothing were observed during each measurement session. Activity for the children cohort was classified as *sleeping* or *awake* status, as they do not have otherwise a great difference in the metabolic rate. Low activity was observed for all adults as they were required to remain seated.

In the babies' study, 3 to 7 measurement sessions were performed in each volunteer allowing a minimum of one hour between them. In the adults' study, the first measuring sessions took place after 15 minutes and they continued every half an hour for periods up to 3 hours.

Auditory channel temperature was occasionally identified and measured in adults by using an IR thermal camera. As this measurement is non-intrusive it does not affect the ear channel temperature. The IR camera was located at approximately 20 centimetres from the ear channel. Volunteers' head was gently turned and tilted slightly in order to get maximum visibility of the ear channel, hence the maximum temperature value. Auditory channel temperature was taken right before measuring the core temperature.

Room temperature and humidity were periodically monitored at several locations across the room to ensure all sessions were performed in a neutral environment to avoid bias.

Adults were asked to complete questionnaires where they indicated their *thermal sensation* and the corresponding *level of comfort* as part of the measurement session. This method of self-reporting subjective measurements has been used in studies enclosed in the ISO standards. In our opinion, the use of interactive systems where the volunteer could change the temperature and rate of the air supply or control the heating would be desirable, but was not used in these experiments as not available.

4 Infants temperature monitoring: Fever recognition in children under 2

Feverish illness in young children usually indicates an underlying infection, caused by a self-limiting viral infection or a more serious bacterial infections such as meningitis or pneumonia which can be life-threatening, as pointed by the National Collaborating Centre for Women's and Children's Health [NICE, 2007]. In general, infections remain the leading cause of death in children under the age of 5 years.

Fever is very common in young children, with between 20 and 40% of parents reporting it each year, probably the commonest reason for a child to be taken to the doctor, and the second most common reason for a child being admitted to hospital. Even when the fever is reported by the parents or carers, fever ought to be taken seriously by healthcare professionals who are required to set a face-to-face visit within 2 hours when the children have any "red" features, even if they are not considered to have an immediately life-threatening illness [NICE, 2007].

Core body temperature can be accurately measured by using traditional techniques described in Chapter 2.2. These methods have been studied and approved, and they are used widely from hospitals to home environments. However, in normal circumstances, they are only used to detect fever when some other symptoms are evident. This is not sufficient to monitor children, especially in schools or nurseries where the ratio of children to adults is considerable, knowing that adults can detect fever but children, and especially babies, cannot detect or indicate this condition. Therefore the study and development of a non-intrusive indicator that provides reliable means for fever detection is of practical importance.

This chapter studies the possibility of a novel core temperature monitoring method for children under the age of 2 based on the relation between core and skin temperatures at different locations on the body. Skin temperature is not as reliable as the core temperature, but it is more accessible and allows non-intrusive measurement, which makes continuous monitoring a possibility. Early detection of fever could potentially save youngster’s life to conditions such as meningitis.

4.1 Study design

This study explores the relationship of core and local skin temperatures in children under the age of 2 years. Measurements of local skin temperature could provide estimated values of core temperature. Skin temperature can be identified by using a thermometer over a chosen location on the body. If this sensor is embedded in the clothing (see **Figure 16**), the local skin temperature monitoring is performed while the child is wearing the garment (see **Figure 17**). A binary sensor is proposed to identify when the local skin temperature is over a given threshold. If that threshold matches with the onset of fever, then one of the states of the sensor can identify the occurrence of fever. The use of wires and batteries is not convenient; hence a thermocromic pigment applied over a selected area of the fabric could be used. The pigment changes colour when threshold is exceeded.

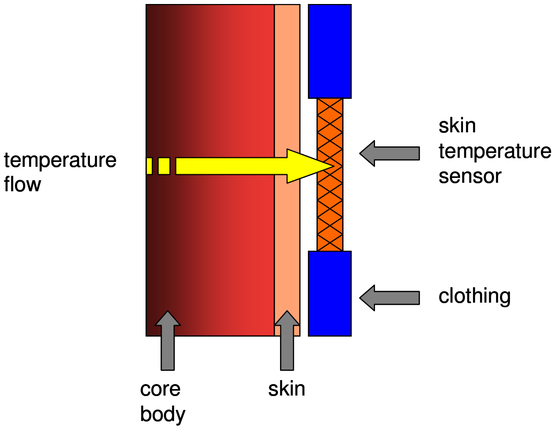


Figure 16: Skin temperature sensor applied over the skin

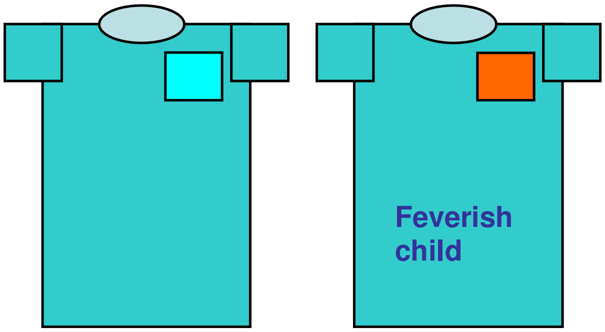
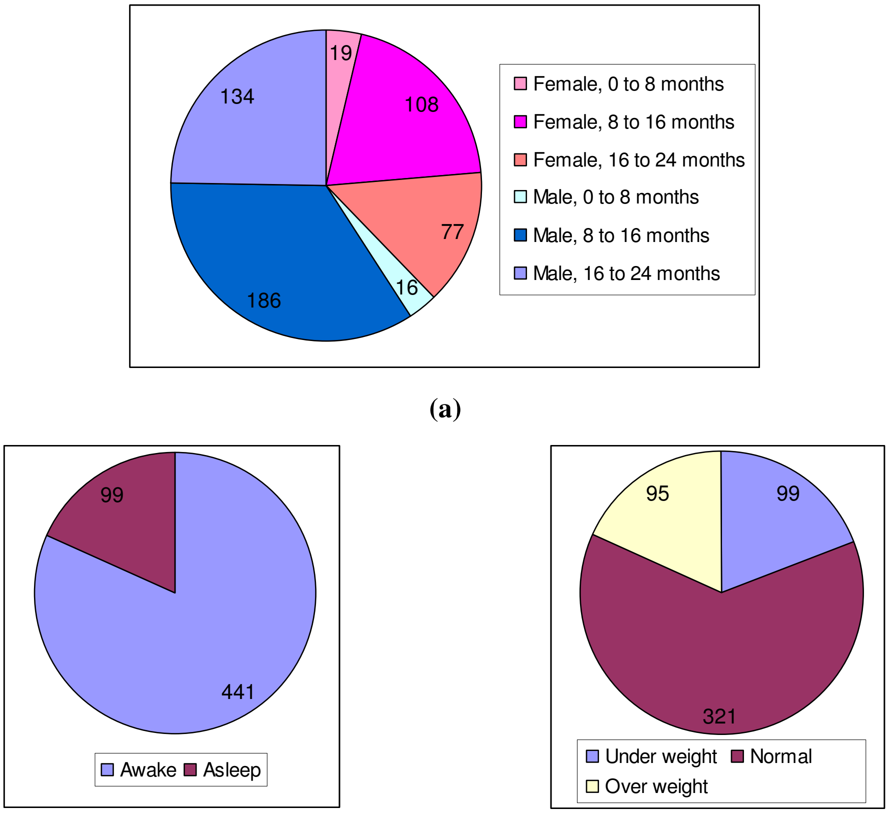


Figure 17: Possible location and states of the fever sensor on the garment

4.1.1 Group stratification

A total of 540 measurement sessions were taken from 138 subjects following the experimental procedure detailed in Chapter 2. Several cohorts, specified in **Figure 18**, were defined depending on gender, age, constitution and status of the subject.

Status was defined as *sleeping* or *awake*, due to the difference in the metabolic rate. While awake, babies' activities had a similar level of metabolic rate, hence no need for a further breakdown.



(a)

(b) **(c)**

Figure 18: Group stratification

The constitution of the subjects in this project was assessed through the Body Mass Index (BMI), as explained in the section 2.5.2.3. There are standard ranges that define whether a person is *underweight*, *normal* or *overweight* [WHO, BMI]. However, fixed limits do not apply for very young children. The sample of babies on the present investigation was diverse, and also contained different races and nationalities. Three different categories were defined with cuts at 16.53 and 19.25 kg/m^2, based on the percentiles 20 and 80 of the BMI distribution of this particular sample. Those categories were tagged as *underweight*, *normal* or *overweight,* but they are not necessarily in accordance with any tabulated values.

4.2 Data analysis

4.2.1 Body and local skin temperature characterization

The normality of the distribution of core temperature and each of the local skin temperatures was studied applying a maximum absolute value of 2 both for Skewness and Kurtosis. This was performed on the whole data set and furthermore on each of the cohorts created when observing gender, age, BMI, clothing, status, use of blanket while sleeping and fever occurrence. Most probable core and local skin temperature values (mean and standard deviation) were given for each of the cohorts.

The relevance of each parameter was then tested separately at each location. The complete data set was split into cohorts attending to each of the studied parameters and their individual distributions statistically compared. If the distributions were different it was concluded that the factor was relevant. In those cases where the distribution of the whole dataset and each of the cohorts were normal, one of the versions of ANOVA test was used to compare the means in conjunction with the Levene statistic to test the homogeneity of variances. When the variances are proved to be equivalent the original ANOVA test was used to compare the means. Otherwise, robust test of equality of means (Welch and Brown-Forsythe tests) were used. In those cases where normal distributions were not guaranteed, alternative non-parametric tests were used which do not assume normality or equal variances among the groups. These were Mann-Whitney U test (compare distributions of only 2 groups) and Kruskal-Wallis 1-way ANOVA (3+ groups).

4.2.2 Body and skin temperature relation

The correlation of core temperature and each of the local skin temperatures was investigated, as only those locations which have a strong relation with the core temperature are useful for body temperature monitoring. Linear regressions of core versus skin temperature were obtained and the R^2 value computed. Ideally the slope should be high, i.e. indicating a strong relation between the two parameters, and the R^2 close to 1. Locations with low correlation values were withdrawn.

Fever was then defined as core temperature over a certain threshold. Subjects were divided into 2 cohorts depending on whether they were feverish (i.e. core temperature was over or below that value) and the local skin temperatures where fever is a relevant factor were identified by statistical tests similar to the previously used.

4.2.3 Identification of suitable locations

Suitable and non-suitable locations for the monitoring of core temperature were selected according to 3 conditions. First, it was checked whether the temperatures follow normal distributions, which is necessary for the subsequent analysis. Secondly, locations which depend on many parameters were withdrawn, as they would require the use of a great number of skin temperature thresholds for the identification of children with a fever. Ideally only one threshold would be required per location. Finally, locations at which skin temperature had a weak relation with the core temperature were withdrawn, as they do not reflect the core body temperature of the infants.

4.2.4 Identification of febrile babies using local skin temperatures

Locations which were classified as suitable for the identification of febrile babies were subjected to the following analysis. Subjects were separated into several cohorts, according to the relevant factors of each local skin temperature. Then, each of those groups were split into 2 cohorts, $T_c<37.3ºC$ and $T_c\geq37.3ºC$. Skin temperature distribution for each group was characterized. Next, following the theory about overlapping distributions (**appendix G1-2**), a range of thresholds for the identification of febrile babies are studied, calculating the percentage of detected false positive cases of fever (alpha error) and the percentage of missed true positive cases of fever (beta error) for each of them. Those values are presented in alpha-beta graphs, with a set of 1 alpha curve and 1 beta curve per defined group. If a unique threshold for more than one of the studied groups is preferred, the new error curves can be obtained by simple extrapolation from the individual ones, as shown in **appendix G3**.

One encountered problem was the characterization of the skin temperature in febrile groups, especially at body locations where the skin temperature depends on many factors, as the groups get sparse. When the number of samples for a febrile group is not sufficient, its characterization was estimated based on the data of non febrile children. First, the mean and standard deviation of the non febrile cohorts are obtained, for example μ_{awake}, σ_{awake}, μ_{asleep} and σ_{asleep}. Then the change of the skin temperature is characterized by parameters A and B, detailed below. Finally same change is assumed to occur within the febrile groups, hence they are applied to get the estimation of the mean and SD for the sparse cohort. A variation of this method is the estimation of the change between a whole group and one of its cohorts, for which similar procedure were followed.

$$A = \mu_{awake} - \mu_{asleep}$$

$$B = \sigma_{awake}/\sigma_{asleep}$$

4.3 Results

4.3.1 Core temperature characterization

4.3.1.1 Expected value

An abnormal body temperature, either high or low, might be indicative of a health problem or uncomfortable circumstance. Under the specific environmental conditions the normal range of body temperatures was identified for this group of people. The core temperature distribution is presented in **Figure 19**, full characterization in **Appendix I Table I1**. The distribution is normal (Kurtosis = 0.84 and Skewness = 0.14), confirming that the obtained data for core temperature are reliable, samples sufficient and methodology appropriate. The distribution is slightly negative skewed due to a lack of feverish or sick children in the nursery, which makes the sample population not completely random. However the distribution is still normal as the percentage of sick children in real life is fairly small. This effect is also predictable in the skin temperature distribution at each location. The expected core temperature in babies is 36.59 ± 0.02, the range of values being fairly tight due to a quite small standard deviation of 0.40°C. More precise expected values are reported for smaller cohorts in the next section.

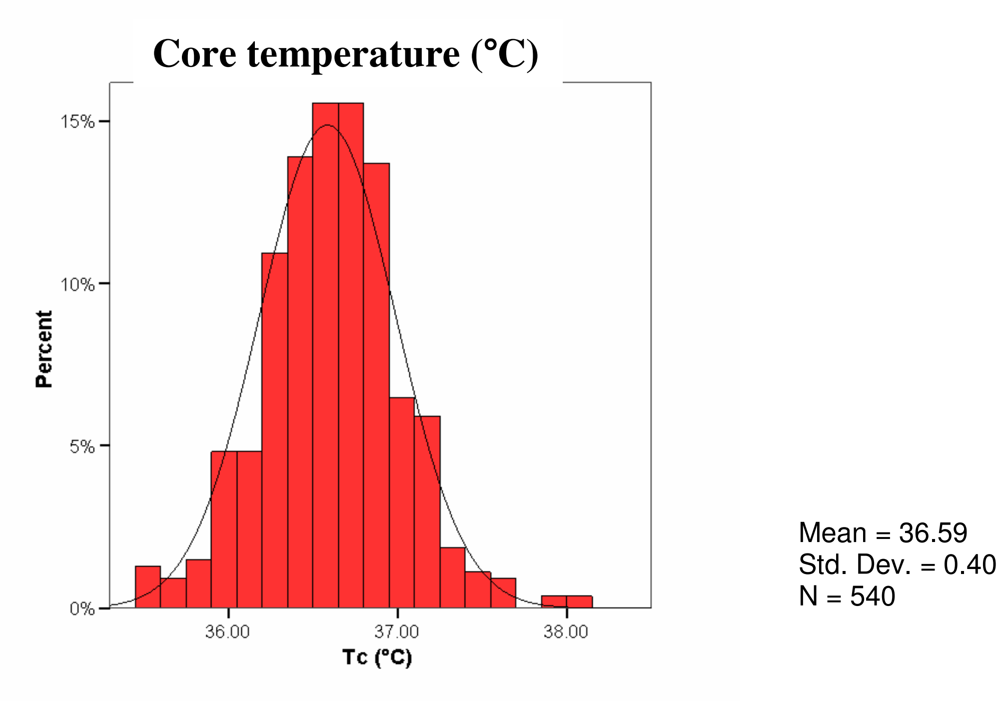


Figure 19: Core temperature distribution

4.3.1.2 Relevant factors of the core temperature

4.3.1.2.1 Gender

Subjects were separated into two gender based cohorts, and their distribution characterization obtained (see **Appendix I Table I2**). Core temperature distribution was observed to be normal for each group and of equal variances according to the Levene test. They were compared using ANOVA and found to be different (F(1,538)=12.36, p=0.000), hence gender is a relevant factor. Core temperature was found to be on average higher for female than for male babies by approximately 0.1°C. However this is a very small difference in the context of our study (within the measurement accuracy), for which further analysis of core temperature regarding the gender is withdrawn.

4.3.1.2.2 Age

Subjects were separated into three age categories based cohorts, presented in **Figure 18-a**, and their distribution characterization obtained (see **Appendix I Table I3**). Core temperature distribution was observed to be normal for each group but their variances different according to the Levene test. They were compared using robust tests of equality of means (Welch and Brown-Forsythe) and found to be equal (p=0.403), hence age is not a relevant factor.

4.3.1.2.3 Constitution

Subjects were separated into three BMI categories based cohorts, presented in **Figure 18-c**, and their distribution characterization obtained (see **Appendix I Table I4**). Core temperature distribution was observed to follow a not normal distribution for the heavy group. Hence groups were compared using non-parametric Kruskal-Wallis test which does not assume normality or equal variances. Distributions were found to be equal (p=0.654), hence BMI is not a relevant factor.

4.3.1.2.4 Status

Activity level affects the core temperature as discussed in the literature review, section 2.5.3.1. This study considered two different statuses, those are awake and light sleep. Light sleep takes place when the subjects sleep for short periods of time, i.e. 1 to 2 hours. Deep sleep was not investigated as all measurements were taken during the day.

Subjects were separated into two attending to their status, presented in **Figure 18-b**, and their distribution characterization obtained (see **Appendix I Table I5**). Core temperature distribution was observed to follow a not normal distribution for the sleeping group. Hence groups were compared using non-parametric Mann-Whitney U test which does not assume normality or equal variances. Distributions were found to be different (p=0.000), hence status is corroborated as a relevant factor. A difference of 0.32 ± 0.04 ºC was observed between the means. This is quite a large difference as the core temperature is in general within a small range of values.

4.3.1.2.5 Blanket influence in sleeping babies

The influence of the use of a blanket while asleep on the core temperature was investigated. The subjects were separated into two categories: sleeping with and without a blanket (see **Appendix I Table I6**). Core temperature distribution was observed to follow a not normal distribution for the group sleeping without blanket. Hence groups were compared using non-parametric Mann-Whitney U test. Distributions were found to be different (p=0.037), hence the use of blanket is corroborated as a relevant factor. The mean temperature is slightly higher when babies are not covered with a blanket; opposite to the intuitive belief that cover increases the core temperature. The heat loss leads to a higher metabolic rate, core temperature increases to keep surface temperature. When sleeping with a blanket the babies's metabolic rate is lower, hence they sleep deeper.

4.3.2 Skin temperature characterization

In parallel to the core temperature analysis, the skin temperature was investigated at 16 locations on the body.

4.3.2.1 Expected values

Each local skin temperature distributions were characterized regardless of any other parameter (**Appendix I Tables I7-11**). The majority of the locations have a normal or nearly normal temperature distribution. Minor deviations were found at *T14* (right instep) and *T8-S* (right abdomen – over clothing) whose distributions are not perfectly symmetric. Scarcely populated right wing, due to the lack of sick children at the nurseries, is presented in most of the locations but *T1*, *T2*, *T6* and *T8-S*. Only temperature distributions at locations on the neck (*T2*, *T15* and *T15S*) were found to be non-normal due to high Kurtosis, i.e. they are more pointed than normal distribution.

The expected temperatures are presented at their specific locations in the **Figure 20**. Standard deviation or range of temperatures varies with the location, with it being the smallest at *T1*, *T2*, *T3*, *T8* and *T15* and the largest at *T7*, *T12*, *T13*, *T14*, *T16*, *T4-S*, *T5-S* and *T15-S*.

Temperature at locations *T4* (left upper chest), *T5* (right arm in upper location), *T8* (right abdomen) and *T15* (neck in lateral location), were measured both on the skin and on the clothing. Distributions were found to have similar shape in both cases, being normal at locations 4, 5 and 8 and much more pointed than normal at location 15. However, mean and standard deviation of the skin temperature distribution change when measured on top of the clothing. On average, the temperature decreases by 3.3°C when measured over clothing and the standard deviation increases by a factor of 1.8.

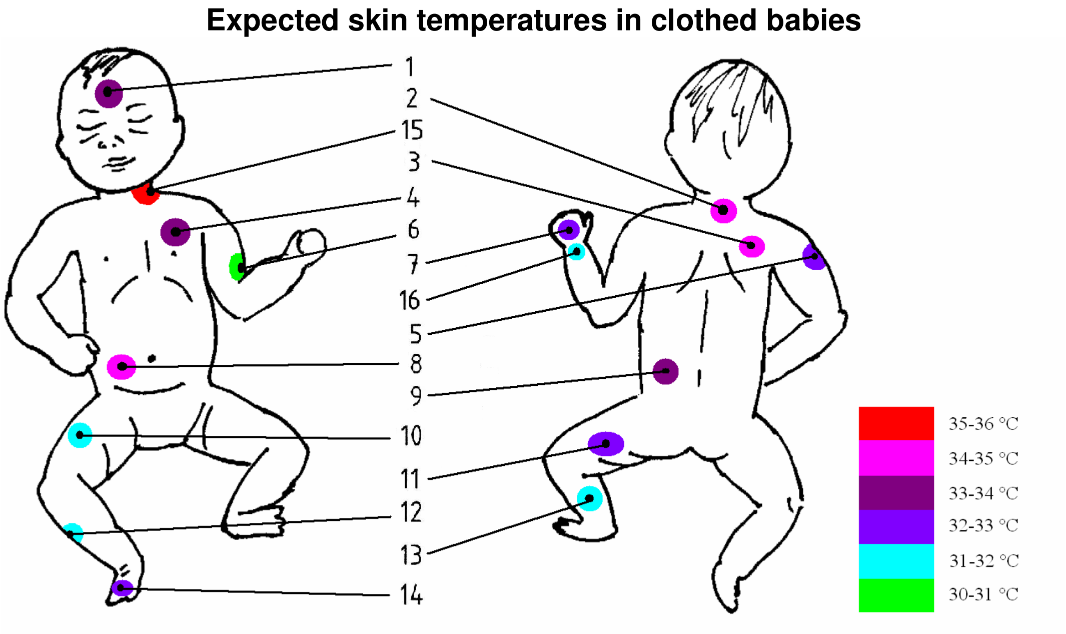
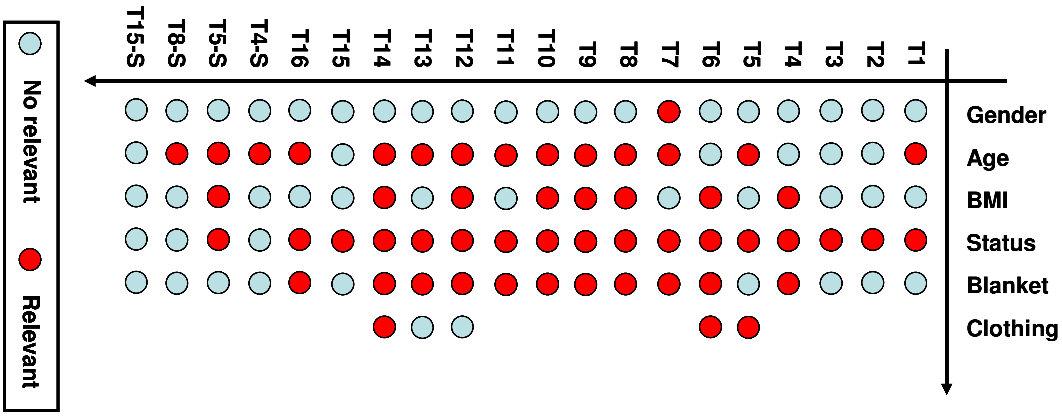


Figure 20: Representation of the expected local skin temperatures

4.3.2.2 Relevant factors of the skin temperature

Identical analysis to that carried out for core temperature was also used to identify the relevant parameters of each of the 16 local skin temperatures under investigation. Subjects were separated in several cohorts attending to each of the parameters under study and their normality (**Appendix J Table J1**) and homogeneity of variances studied. Temperature distributions were obtained (see **Appendix I Tables I12-17**) and accordingly compared by the appropriated statistical test. The tests used in each case and the parameters found to be relevant for each local skin temperature are given in **Appendix J Table J2**. A summary of the relevant parameters in each case is given in **Figure 21**. They are further discussed in the following sections.



○ No relevant ● Relevant

	T15-S	T8-S	T5-S	T4-S	T16	T15	T14	T13	T12	T11	T10	T9	T8	T7	T6	T5	T4	T3	T2	T1
Gender	○	○	○	○	○	○	○	○	○	○	○	○	○	●	○	○	○	○	○	○
Age	○	●	●	●	●	○	●	●	●	●	●	●	●	●	○	●	○	○	○	●
BMI	○	○	●	○	○	○	●	○	●	○	●	●	●	○	●	○	●	○	○	○
Status	○	○	●	○	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Blanket	○	○	○	○	●	○	●	●	●	●	●	●	●	●	●	○	●	○	○	○
Clothing							●	○	○						●	●				

Figure 21: Summary of relevant parameters for each of the local skin temperatures.

4.3.2.2.1 Gender

Gender was found relevant only at the hands temperature or T7 (F(1, 487)=6.983, p=0.008). This exception is perhaps due to the great standard deviation of temperature at this location.

4.3.2.2.2 BMI

Regarding the constitution, a consistent decrease of skin temperature was detected in most of the locations as the BMI of the subjects increased. This was expected as the adipose tissue acts as an insulator, protecting the temperature of the internal organs from the environment. Hence it reduces the transfer of heat to the skin. Locations where skin temperature is affected by BMI are *T4, T6, T8, T9*, *T10*, *T12* and *T14*, where temperature deviations ranged from 0.5 to 0.8°C. Those locations are at the upper arm, lower limbs, abdomen and back, where the increase of the BMI is more visible.

4.3.2.2.3 Age

Regarding the age, **Figure 22** presents the deviation of mean values of cohorts 1 and 3 from mean value of cohort 2, showing that locations *T5*, *T8* and *T9* have very similar values (within 0.3ºC) although according to the statistical tests the distributions are different. Considering both the statistical test results and the deviations of means, it is concluded that temperature at locations on trunk and upper arms do not depend on the age of the children. However, temperature on forehead (*T1*), lower limbs (*T10*, *T11*, *T12*, *T13*, *T14*) and lower arms (*T7* and *T16*) change with age. For these locations, age should be considered.

Similar to our findings, Svedberg et al. [Svedberg, 2005] detected a lower mean skin temperature in the extremities of non-walking children between 2 and 7 years. It seems that the non development of the muscles and poor blood circulation leads to lower skin temperature on the legs. Similar reasoning is likely to apply to the increase with the age of skin temperature at hand and wrist.

Temperature at the surface of the clothing is different for each of the age categories. Differences on the wore outfit were detected on the youngest children respect the other cohorts, which is likely to be partly the cause of those temperature differences.

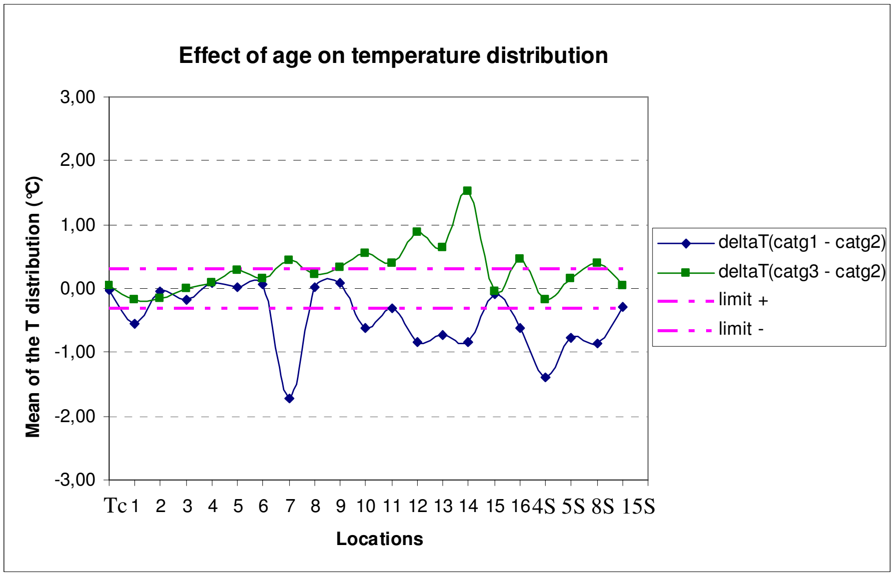


Figure 22: Mean temperature deviation of categories 1 and 3 with respect to mean for category 2. Limit values identify differences on the temperature of ±0.3ºC.

4.3.2.2.4 Status and use of blanket while sleeping

Regarding the status of the children, statistical tests confirmed that skin temperature distributions are statistically different at each location, hence status is relevant. When the temperature is measured over the clothing, no significant difference is observed except in *T5S*. Typical exposed locations on the body like forehead and right scapula appears to decrease in temperature when the baby starts to sleep, probably due the decrease in the level of activity. The temperature increases at the rest of the locations between 0.5°C and 1°C, probably partly due to the use of blankets, as the thermal clothing insulation factor increases. Further analysis of the combined effect of status and the use of blanket while sleeping is carried out.

For subjects who were sleeping, the effect of using a blanket was studied. Statistical tests showed no significant difference in temperature mainly at exposed parts like *T1* (forehead), *T2* (back of the neck), *T3* (right scapula), *T5* and *T5S* (upper arm at skin and clothing surface) and *T15* (neck in lateral location). However, a significant increase on the temperatures were found at locations which are typically covered by the blanket, like lower trunk and legs, partially caused by the increase of thermal clothing insulation in the area.

In order to investigate the more relevant cause of skin temperature change in sleeping babies, independent effect of both status and extra clothing while sleeping were studied.

Temperature distributions for awake babies were compared separately with two cohorts, sleeping babies when covered and not covered by a blanket. It was found that the temperature increases by around 1°C mainly due to the use of a blanket at locations typically covered by the blanket, which were *T4*, *T6*, *T8*, *T9*, *T10*, *T11*, *T12* and *T13*. An increase on the temperature as a combination of the use of blanket and the status was observed at locations on the extremes of the limbs, i.e. *T7*, *T14* and *T16*), although the effect of status is less significant. Skin temperature decreases due to the status at typically exposed parts of the body (*T1*, *T3* and *T15*) by about 0.5°C while sleeping. This decrease is surely due to the decrease of the activity level and heart rate. Finally, in case of the location being covered, the blanket might compensate the decrease of temperature due to the status, as it happens at location *T5* (right arm in upper location). No dependency with the use of blanket was observed at T2 or T5S. Statistics for locations *T4S*, *T8S* and *T15S* are missing due to lack of sufficient samples.

4.3.2.2.5 Clothing

The effect of clothing was studied at locations *T5* (right arm in upper location), *T6* (left arm in lower location), *T12* (right shin), *T13* (left calf) and *T14* (right instep). The rest of the locations were typically covered or exposed, hence this analysis is not relevant. Statistical tests showed significant difference in temperature at *T5*, *T6* and *T14*, temperature being greater when covered. However, no significant increase was found at locations *T12* and *T13*, perhaps due to the opening of the trousers which allows air circulation, reducing the thermal clothing insulation in the area. The effect of different clothing, assessed as number of layers that cover the skin location, was investigated (**Figure 23)** and found to be significant and positive. The greatest increase occurs with the first layer being placed over the skin.

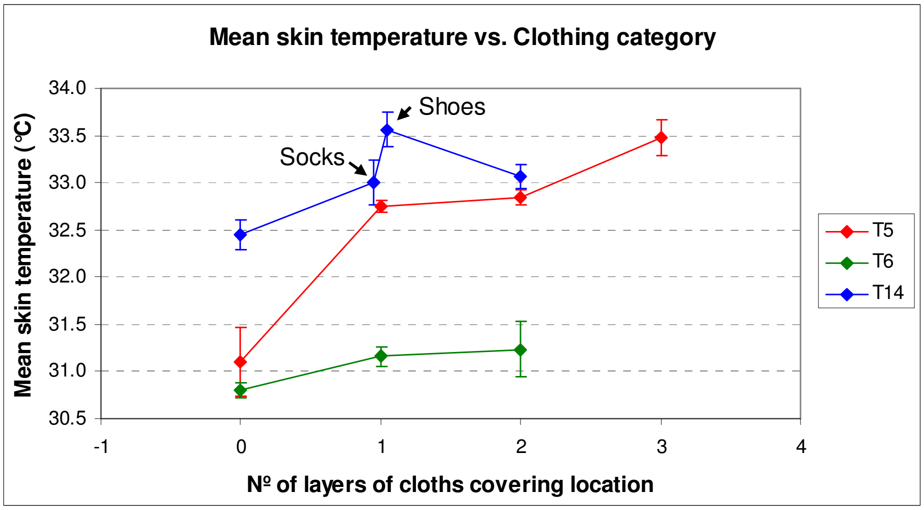


Figure 23: Mean skin temperature at locations *T5*, *T6* and *T14* versus number of layers covering the location. For *T14*, two cases of only one layer were considered, socks and shoes.

4.3.3 Relation between core and skin temperature

The relation between local skin temperatures and core temperature was investigated for all listed body points. As an example, the scatter diagram for the forehead temperature (*T1*) is presented in **Figure 24**, where a large scattering can be observed. This is common to all local skin temperature measurements, especially at typically clothed locations. Linear regressions of core versus local skin temperatures were derived for each location, and are presented in **Appendix K Table K1**. Locations *T5*, *T6*, *T12*, *T13* and *T14* were studied separately when covered and exposed, as both cases were likely. Clothing was found to affect the relation between core and local skin temperature.

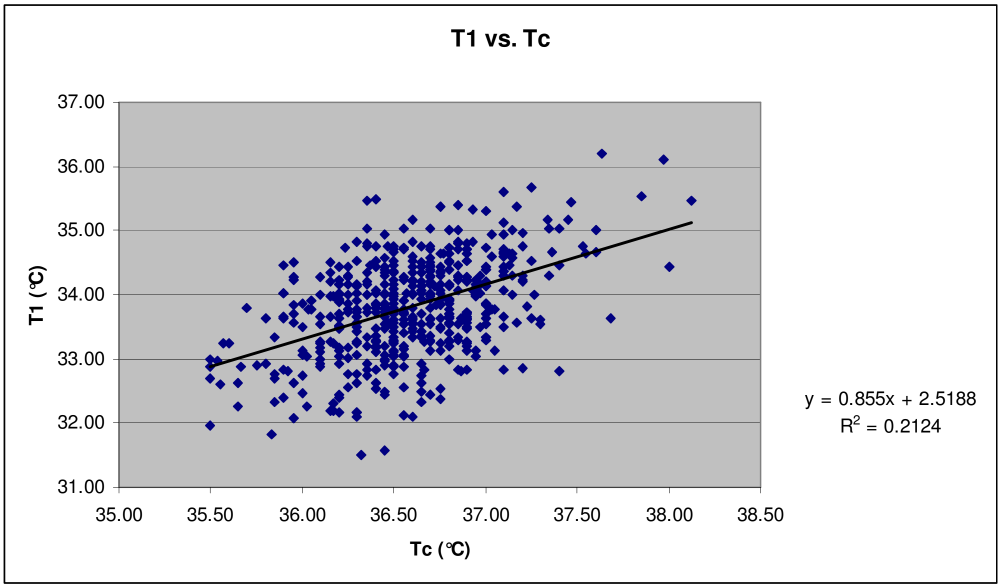


Figure 24: Forehead temperature versus core temperature

The strength of relation between core and skin temperature is dependent on the location. Suitable locations to obtain the core temperature are listed below, ordered by the potential strength. However, further statistical analysis needs to be done.

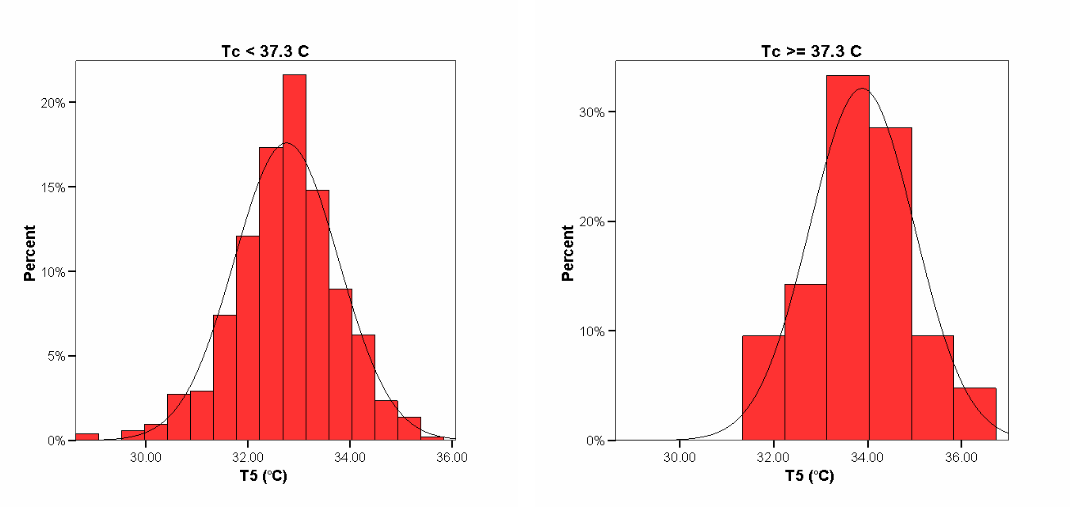
• T1: Forehead • T3: Right scapula	Around 0.8℃ of skin temperature increase when core temperature increases by 1℃
• T7: Left hand • T2: Back of the neck • T5: Right arm in upper location • T15: Neck in lateral location	Around 0.6℃ of skin temperature increase when core temperature increases by 1℃
• T13: Left calf • T14: Right instep • T11: left posterior thigh • T16: Left wrist • T12: Right shin	Around 0.5℃ of skin temperature increase when core temperature increases by 1℃
• T9: Left paravertebral	Around 0.3℃ of skin temperature increase when core temperature
• T6: Left arm in lower location • T10: Right anterior thigh • T8: Right abdomen	Only around 0.15℃ of skin temperature increase when core temperature increases by 1℃
• T4: Left upper chest	Less than 0.1°C of skin temperature increase when core temperature increases by 1°C

4.3.3.1 Fever definition

Five different limits for core temperature (Tc_{limit}) were investigated: 36.9°C, 37.0°C, 37.1°C, 37.2°C and 37.3°C. No higher values were studied due to the lack of enough number of samples of high fever. 37.3 ºC was selected as being more convenient for the identification of a fever.

Subjects were separated into 2 cohorts according to the Tc_{limit} of 37.3ºC, and their local skin temperature distributions obtained. **Figure 25** shows the two normalised skin temperature distributions at *T5*. **Appendix K Tables K2-3** encloses the characterization of all local skin temperature distributions and the difference of the mean values, ordered from maximum to minimum and with a colour scale.

Temperature distribution on the right arm in upper location for two ranges of core temperature



(a) **(b)**

Figure 25: Normalized temperature distribution on the right arm in upper location for two cohorts. a) *Tc< 37.3°C*. b) *Tc≥ 37.3°C*.

Skin temperature distributions were statistically compared attending to the occurrence of fever. Statistical tests used at each location and results are summarized in **Appendix K Table K4**). Results show that locations *T1*, *T2*, *T3*, *T5*, *T6*, *T7*, *T8*, *T9*, *T10*, *T11*, *T15* and *T16* present significant differences for the specific core temperature limit of 37.3°C, and so they are further studied. Locations *T4*, *T12*, *T13* and *T14* do not present significant differences in temperature, neither locations on the clothing (*T4S*, *T5S*, *T8S*, *T15S*), probably due to the lack of good contact between the clothing and the skin.

4.3.4 Non suitable locations

Several locations had to be withdrawn as they do not satisfy one or several of the required conditions for serving as a good estimator of core temperature. Those conditions are (i) temperature distribution must be normal, (ii) correlation with the core temperature must be significant, and (iii) skin temperature can not be dependent on many factors to avoid large number of thresholds.

Locations *T2* and *T15* (back of the neck and lateral) had temperature distributions more pointed than normal distribution, hence were withdrawn. Locations *T4, T12, T13* and *T14* (left upper chest, right shin, left calf and right instep) do not have sufficient strong relation with the core temperature, hence were withdrawn, as discussed in section 4.3.3.

Location *T10* depend on a high number of factors, hence they were withdrawn due to difficulties at selecting a proper threshold. Temperature at location *T10* depends on status (2 categories), age (3 categories) and constitution (3 categories), requiring a total of 18 different thresholds, one for each combination of status, age and constitution. Other locations already withdrawn depend as well on many factors, such as *T12* and *T14* making them even more suitable.

4.3.5 Suitable locations to non-invasive core temperature monitoring

4.3.5.1 Forehead (*T1*)

Forehead is a suitable location for the non-invasive monitoring of the core temperature. It is one of the recommended locations, as it presents a perfectly normal distribution of the skin temperature (see section 4.3.2) and holds a strong relation between skin and core body temperature (see section 4.3.3). Forehead skin temperature depends on the status and age of the baby. Characterization for each of the 6 subgroups of interest is included in **Appendix L Table L1**. Curves of alpha and beta errors are presented in **Figure 26** for 3 main groups.

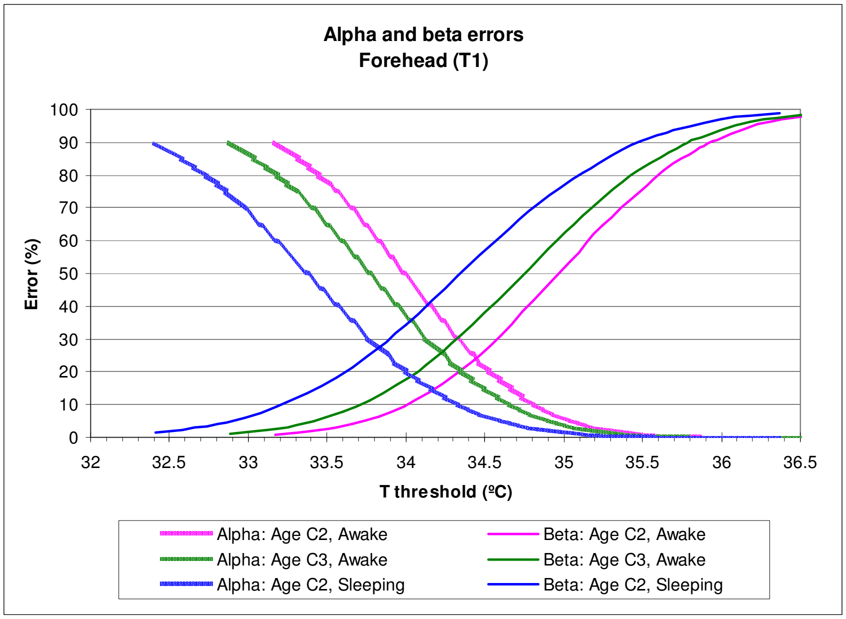


Figure 26: Alpha (detected false positives) and beta (missed true positives) errors for different skin temperature thresholds at the forehead for 3 given cohorts.

4.3.5.2 Right scapula (*T3*)

Right scapula is also a suitable and recommended location, as its skin temperature follows a normal distribution (see section 4.3.1.1) and has the second strongest relation with the core temperature (see section 4.3.3). Skin temperature at *T3* depends on the status of the baby. Characterization for each of the 2 subgroups of interest is included in **Appendix L Table L2**. Curves of alpha and beta errors are presented in **Figure 27.**

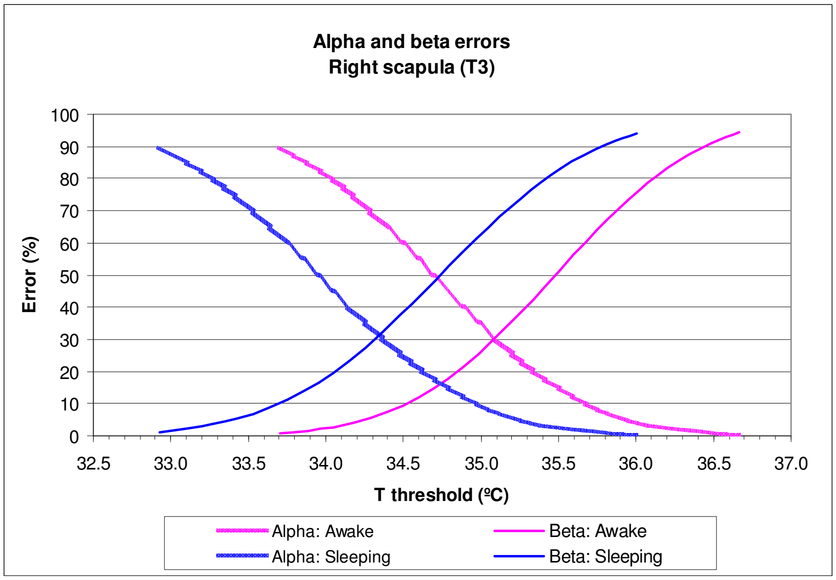


Figure 27: Alpha (detected false positives) and beta (missed true positives) errors for different skin temperature thresholds at the right scapula.

4.3.5.3 Right arm in upper location (*T5*)

Skin temperature at *T5* follows a normal distribution (see section 4.3.2) and has a strong relation with the core temperature, being one of the top 5 locations (see section 4.3.3). This temperature depends on the status of the baby as characterized in **Appendix L Table L3**. Curves of alpha and beta errors are presented in **Figure 28**. Only samples of temperature in covered skin have been taken into account.

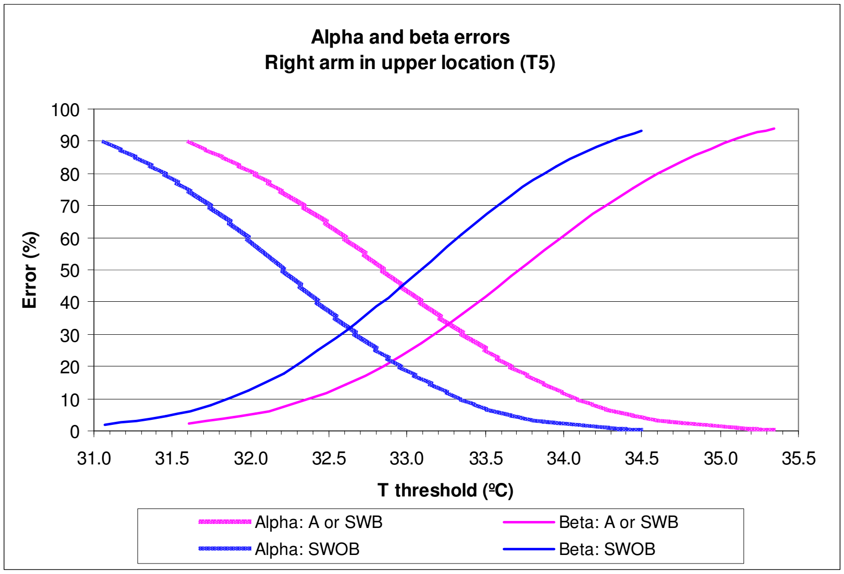


Figure 28: Alpha (detected false positives) and beta (missed true positives) errors for different skin temperature thresholds at the right arm in upper location. (*A* or *SWB*) awake or sleeping with a blanket; (*SWOB*) sleeping without a blanket.

4.3.5.4 Left arm in lower location (*T6*)

T6 or left arm in lower location could also be used for fever identification, as the skin temperature follows a normal distribution (see section 4.3.2) and relates to the core temperature, although mildly (see section 4.3.3). Hence, this location is studied although it might not be one of the best. Skin temperature at *T6* depends on status of the baby. Characterization for each of the 2 subgroups of interest is included in **Appendix L Table L4**. Curves of alpha and beta errors are presented in **Figure 29**.

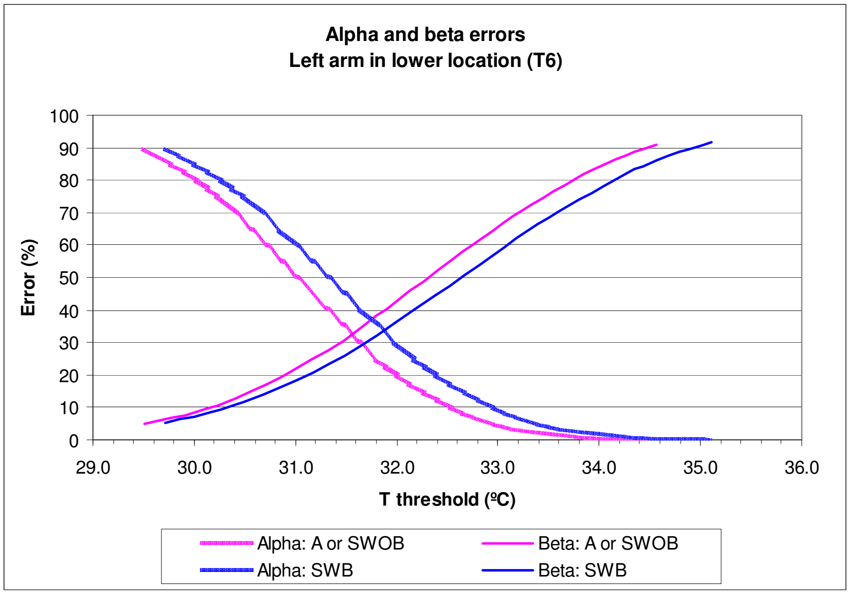


Figure 29: Alpha (detected false positives) and beta (missed true positives) errors for different skin temperature thresholds at the left arm in lower location. (*A* or *SWOB*) awake or sleeping without blanket; (*SWB*) sleeping with a blanket

4.3.5.5 Left hand (*T7*)

Left hand or location *T7* may also be recommended as the skin temperature distribution seems close to normal (see section 4.3.2) and holds quite strong relation with the core temperature, being one of the top 5 locations (see section 4.3.3). Skin temperature at *T7* depends on the status and age of the baby. Characterization for each of the 9 subgroups of interest is included in **Appendix L Table L5**. Curves of alpha and beta errors are presented in **Figure 30** for 3 main cohorts. The standard deviation of skin temperature distribution on the hand is greater that for other locations, which is beneficial as the alpha-beta curves will be wider.

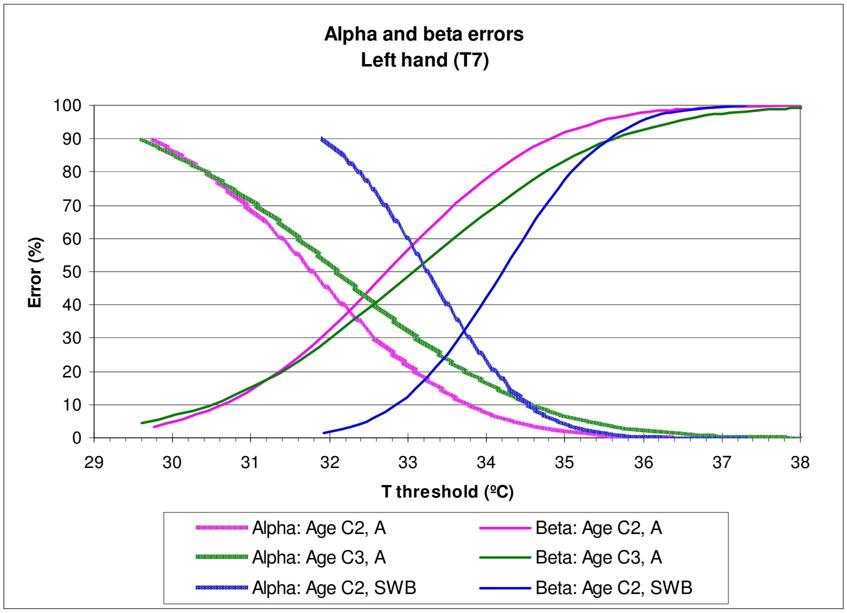


Figure 30: Alpha (detected false positives) and beta (missed true positives) errors for different skin temperature thresholds at the left hand. (A) awake; (SWB) sleeping with a blanket

4.3.5.6 Right abdomen (*T8*)

T8 or right abdomen is also a suitable location, although not the best choice, as the skin temperature follows a perfectly normal distribution (see section 4.3.2) but it only relates mildly to the core temperature (see section 4.3.3). *T8* depends on the status. Characterization for each of the 2 subgroups of interest is included in **Appendix L Table L6**. Curves of alpha and beta errors are presented in **Figure 31**.

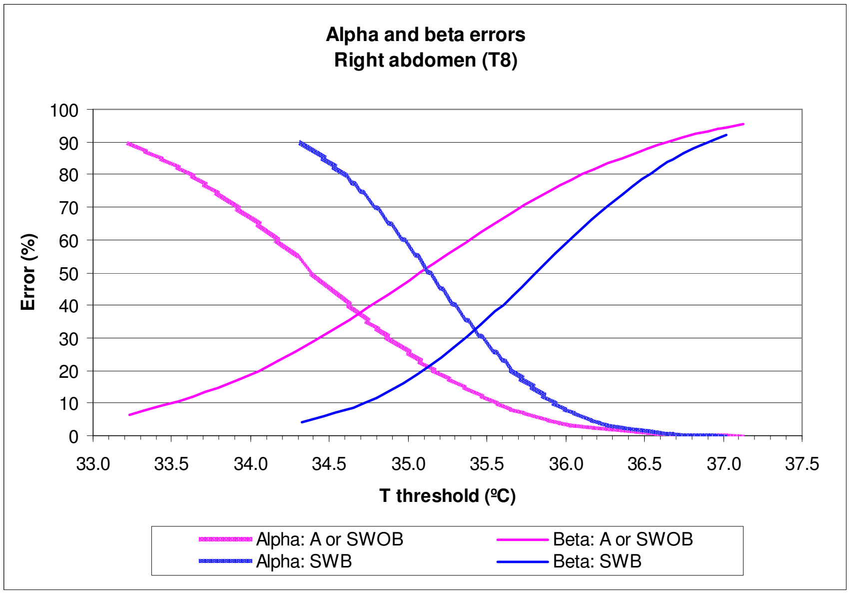


Figure 31: Alpha (detected false positives) and beta (missed true positives) errors for different skin temperature thresholds at the right abdomen. (*A* or *SWOB*) awake or sleeping without a blanket; (*SWB*) sleeping with a blanket

4.3.5.7 Left paravertebral (*T9*)

Location *T9* or left paravertebral is also a suitable location, as its skin temperature follows a normal distribution (see section 4.3.2) and relates to the core temperature (see section 4.3.3). Skin temperature distribution at *T9* depends on the status and constitution of the baby. Characterization for the 6 subgroups of interest is included in **Table L7**. Curves of alpha and beta errors are presented in **Figure 32** for 3 main groups.

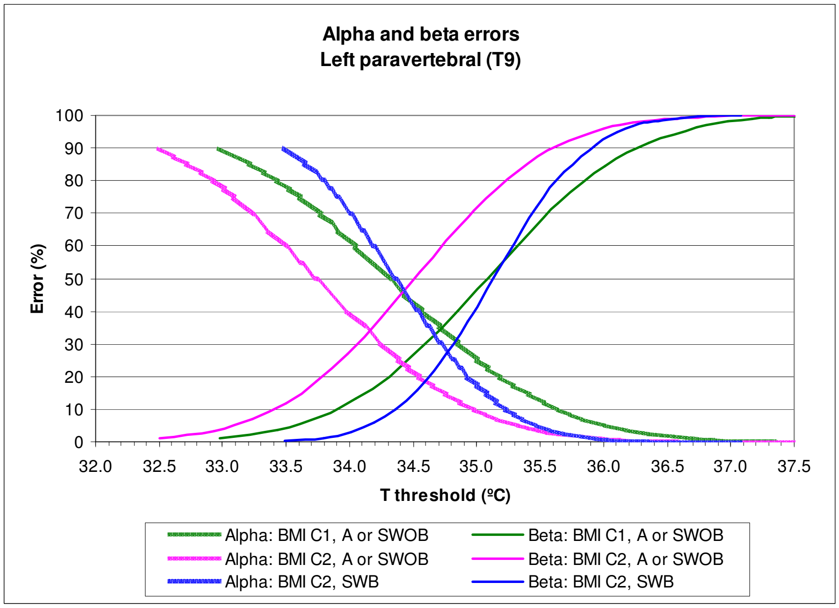


Figure 32: Alpha (detected false positives) and beta (missed true positives) errors for different skin temperature thresholds at the left paravertebral. (*A* or *SWOB*) awake or sleeping without a blanket (*SWB*) sleeping with a blanket.

4.3.5.8 Left posterior thigh (*T11*)

T11 or left posterior thigh could be suitable location as the skin temperature follows a normal distribution (see section 4.3.2) and holds a relation with the core temperature, although it is not one of the strongest ones (see section 4.3.3). The skin temperature at *T11* depends on the status and age of the baby. Characterization for each of the 4 subgroups of interest is included in **Appendix L Table L8**. Curves of alpha and beta errors are presented in **Figure 33** for 3 main groups.

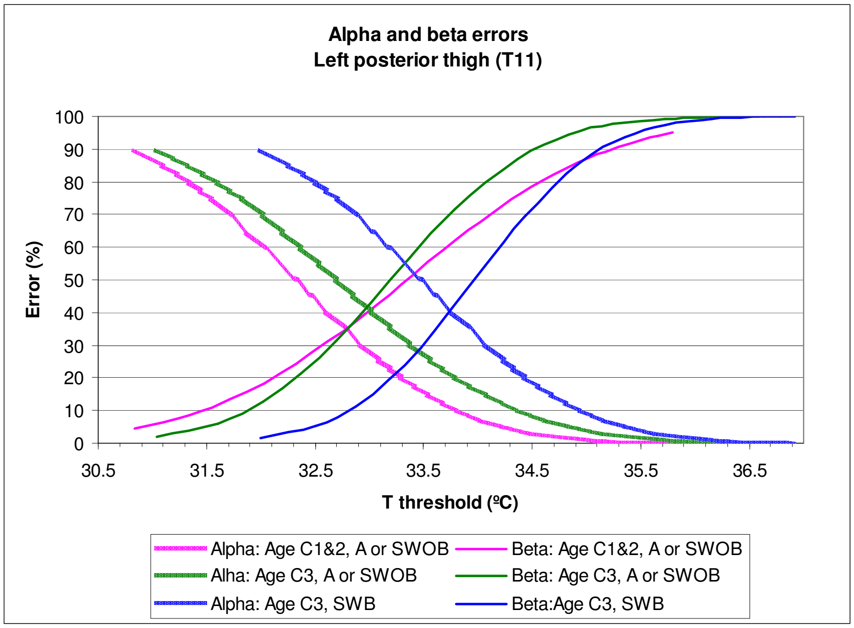


Figure 33: Alpha (detected false positives) and beta (missed true positives) errors for different skin temperature thresholds at the left posterior thigh. (*A* or *SWOB*) awake or sleeping without blanket (*SWB*) sleeping with a blanket

4.3.5.9 Left wrist (*T16*)

Left wrist or location *T16* is also a suitable location, although not one of the best choices, as the skin temperature follows a normal distribution (see section 4.3.2) and it relates with the core temperature but not as strongly as other locations (see section 4.3.3). Skin temperature distribution at *T16* depends on the status and age of the baby. Characterization for each of the 9 subgroups of interest is included in **Appendix L Table L9**. Curves of alpha and beta errors are presented in **Figure 34** for 3 main groups. The standard deviation of skin temperature distribution at the wrist is greater that for other locations, which is beneficial as the alpha-beta curves will be wider.

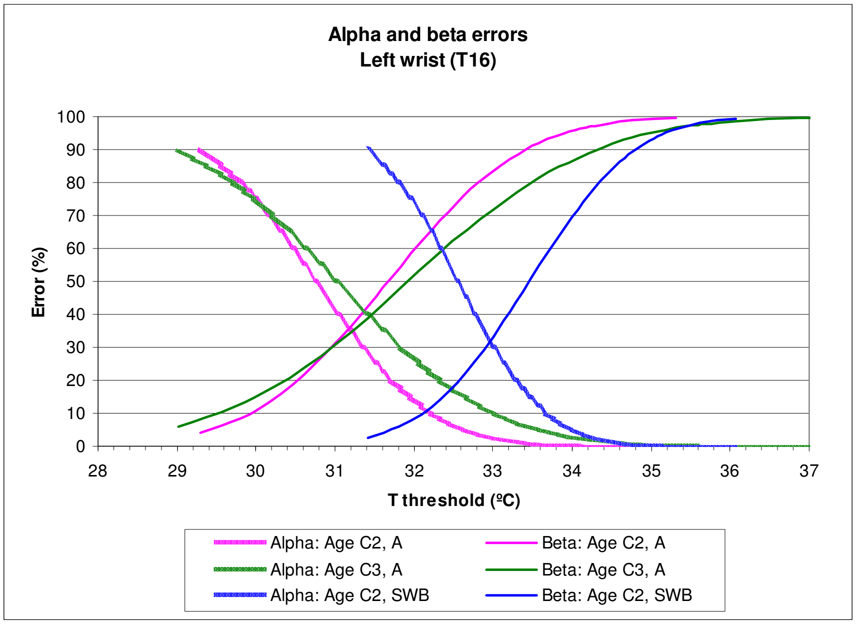


Figure 34: Alpha (detected false positives) and beta (missed true positives) errors for different skin temperature thresholds at the left wrist. (*A*) awake; (*SWB*) sleeping with a blanket.

4.4 Discussion

4.4.1 Classification of the suitable locations

Several skin locations were found to be suitable for the monitoring of core temperature, as detailed in section 4.3.5. Each location can be characterized according to different features, as detailed below:

- Mean temperature: the most likely temperature at that location.
- Standard deviation: width of the temperature distribution.
- Temperature at α =10%: average of *limit temperature* for all the studied subgroups when alpha error is 10%.
- Amplitude of the error curve: range of *limit temperature* in which α decreases from 90 to approximately 0%.
- Range of T limit values at α =10%: maximum difference in *temperature limits* for the studied cohorts when α is 10%.

A summary of those characteristics are given for each location in **Table 17**. A rank of the more convenient locations was derived attending to their characteristics and the strength of relation with core temperature (see last column in **Table 17**). High amplitudes in the error curves are preferred as a small change of the temperature limit will not affect the percentage of error so strongly. Small ranges of temperature limit within cohorts are preferred as an average of the *temperature limit* could be used without generating big errors in the estimation of α and β. Finally, and more important, a strong correlation with core temperature is necessary.

Location	**Mean temperature (°C)**	**Standard deviation (°C)**	**Temperature at α =10% (°C)**	**Amplitude of error curve (°C)**	**Range of T limit values at α =10% (°C)**	**Rank**
T1	33.8	0.75	34.3	3.0	1.1	3
T3	34.6	0.84	35.0	3.1	0.7	2
T5	32.8	1.05	33.7	4.0	0.8	1
T6	31.0	1.36	32.8	5.0	0.4	3
T7	32.0	1.83	34.2	8.0	2.8	3
T8	34.5	0.93	35.8	3.3	0.4	5
T9	33.9	1.02	35.5	4.6	1.5	3
T11	32.6	1.24	34.3	4.7	1.1	4
T16	31.1	1.48	33.3	6.7	2.1	5

Table 17: Characterization of suitable locations for core temperature monitoring attending to temperature distribution and error curves

4.4.2 Error of a single fever sensor

We study the possibility of using a single or combination of binary sensors placed over the skin for the identification of fever in children. Each binary sensor has two different states, ON and OFF, depending on whether the skin temperature is greater or lower than a chosen $T_{threshold}$. Sensor in ON will be identified with a high probability of the child having "fever" while OFF is identified with high probability of "no fever".

There is no ultimate skin temperature threshold or *limit temperature* that can guarantee 100% correct assessment, as the relation between the core and skin temperature is subject to the child and its personal conditions. Each *temperature limit* being a statistical variable has associated *alpha* and *beta* errors. An alpha type error, also named as *detected false positive*, occurs when fever is diagnosed but not the case. A beta type error, also named as *missed true positive*, would occur when fever exists but not detected (see **Table 18**). These errors depend on the selected *limit temperature* and on the location under consideration. They are "inversely" related to each other, such that a decrease in one leads to an increase in the other and vice versa. Hence, there is not a *limit temperature* which minimizes both errors at the same time. The system designer needs to identify what is more critical and choose among the following options:

1) Minimize alpha errors: More children with a fever will not be detected by the system but the number of false alarms will be reduced.
2) Minimize beta errors: Most of the children with a fever will be detected by the system although it will also diagnose many healthy children as having a fever.
3) Compromise: Choose a limit temperature which with no extreme values for both alpha and beta errors.

Alpha and beta errors are expressed in terms of percentages. However their calculation is based on different groups of children, i.e. **healthy children** and **children with a fever**. That being the case, for equal values of alpha and beta errors, alpha generates more mistakes than beta as the number of healthy children is much larger than the number of febrile children in normal circumstances. For example, an alpha error of 5% means that 5 out of 100 healthy children would be diagnosed as having a fever, while a beta error of 5% means that 5 out of 100 children with a fever will be presumed as healthy.

The four different possible cases are presented in **Table 18**, with the associated probability of occurrence. The probability of a child having fever is indicated by p_F and was taken as 0.15. Hence, the probability of no-fever is $1- p_F$ or 0.85. The total error associated to a single fever sensor is given by the alpha and beta errors, along with the probability that a random child has a fever (p_F); see equation **29**.

	Children with fever p_F	Children with no fever $1- p_F$
Sensor ON	$p_F \cdot (1 - \beta)$	$(1-p_F) \cdot \alpha$
Sensor OFF	$p_F \cdot \beta$	$(1-p_F) \cdot (1 - \alpha)$

Table 18: Possible cases of fever assessment by a single sensor

$$Total\ error = p_F.\beta + (1 - p_F).\alpha \qquad \textbf{(29)}$$

A reasonable assumption is that a fever identification device should minimize the alpha error, as if the childminders are falsely alerted many times they will stop using the device. However, if most of the times the device gives a right diagnosis of a fever, even if it overlooked it some cases, childminders would pay attention to it. For that reason, the imposition of a maximum alpha error of 10-20% is considered appropriate.

Only children with marginal fever (<38.1ºC) were present at the nurseries. This leads to an overestimation of the beta errors, which would be advantageously lower in a not biased group of children, as individuals with high fever are more likely to be detected.

4.4.3 Evaluation of possible systems for fever identification

We studied the efficiency of several configurations for the correct identification of fever in the particular case of awake children aged between 8 and 16 months and with BMI in the range of 16.53 to 19.25 kg/m^2. Identical analysis can be made for any other group of children.

4.4.3.1 Single sensor

The simplest option would be the use of a single sensor in one of the appropriate skin areas. From the ranking obtained in 4.4.1., locations *T5*, *T3*, *T6*, *T9* and *T11* were selected for evaluation. *T1* and *T7* were not selected as they are typically exposed areas. Beta error and total error ($\boldsymbol{\varepsilon_T}$) are obtained for two fixed values of alpha error, those were 10 and 20%. The probability of the sensor given the right assessment of fever (***p***) is given by $\boldsymbol{1-\varepsilon_T}$. The total error is mainly given by the alpha error, as observed in the table. The probability of a child having fever when the sensor is ON and when it is OFF is given by equation **30** and **31** respectively.

Location	α = 0.1					α = 0.2				
	β	ε_T	p(right)	p(ON+ fever)	p(OFF+ fever)	β	ε_T	p(right)	p(ON+ fever)	p(OFF+ fever)
T5	0.64	0.18	0.82	0.39	0.11	0.48	0.24	0.76	0.32	0.10
T3	0.60	0.18	0.82	0.41	0.11	0.42	0.23	0.77	0.34	0.09
T6	0.55	0.17	0.83	**0.44**	**0.10**	0.43	0.23	0.77	0.34	0.09
T9	0.71	0.19	0.81	0.34	0.11	0.62	0.26	0.74	0.25	0.12
T11	0.62	0.18	0.82	0.40	0.11	0.48	0.24	0.76	0.32	0.10

Table 19: Error estimation for single fever sensors

$$p_i(fever\,when\,sensor\,is\,ON)=\frac{p_F(1-\beta_i)}{p_F(1-\beta_i)+(1-p_F)\alpha_i} \tag{30}$$

$$p_i(fever\,when\,sensor\,is\,OFF)=\frac{p_F\beta_i}{p_F\beta_i+(1-p_F)(1-\alpha_i)} \tag{31}$$

4.4.3.2 Multiple sensors

4.4.3.2.1 Various sensors across the body surface area

The probability of successfully assessment of fever in children can be increased by using several sensors at the time. An odd number of sensors are required in order to unequivocally interpret the readings. If a set of 3 sensors is in use and at least 2 of them are ON the system indicates probable fever. No fever assessment requires at least 2 of the sensors OFF. Similarly, 3+ sensors in a set of 5 indicate fever; otherwise 3+ OFF indicate non-fever. Both, 3-sensors set and 5-sensors set are evaluated. For the 5-sensors set *T5*, *T3*, *T6*, *T9* and *T11* were selected. For the 3-sensors set *T5*, *T3* and *T11* were chosen in order to cover different both upper body and lower body. The probability that the system gives a correct assessment of fever (***p_T***) is given in **Table 20** along with the effective alpha and beta errors for the case where individual alpha errors where fixed to 10 and 20%. Equations **32** and **33** were used for the calculation of the probability of success (***p_T***) in the 3-sensors and 5-sensors set respectively based on the values for the individual sensors. Equivalent equations were used to estimate the total alpha and beta errors.

Location	**α_i = 0.1**					**α_i = 0.2**				
	p_T(right)	**α**	**β**	**p(ON+ fever)**	**p(OFF+ fever)**	**p_T(right)**	**α**	**β**	**p(ON+ fever)**	**p(OFF+ fever)**
T5-T3-T11	0.92	0.03	0.68	0.67	0.11	0.86	0.10	0.44	0.49	0.08
T5-T3-T6-T9-T11	0.96	0.01	0.72	**0.85**	**0.11**	0.90	0.06	0.47	0.62	0.08

Table 20: Error estimation for systems of several fever sensors

$$\mathrm{p}_{\text{3-sensors-set}} = \prod_{i=1}^{3} p_i + \sum_{\substack{k=1 \\ i \neq j \neq k \\ i,j \in \{1,2,3\}}}^{3} p_i p_j (1 - p_k) \qquad \textbf{(32)}$$

$$\mathrm{p}_{\text{5-sensors-set}} = \prod_{i=1}^{5} p_i + \sum_{\substack{k=5 \\ i \neq j \neq t \neq k \neq z \\ i,j,t,k,z \in \\ \{1,2,3,4,5\}}}^{1} \sum_{z=k-1}^{1} p_i p_j p_t (1 - p_k)(1 - p_z) \qquad \textbf{(33)}$$

4.4.3.2.2 Various sensors at the same location on the body surface area

The reliability of the system when indicating fever can be given by locating several sensors of different limit temperature values. This allows different levels of alert, so that the user has the option to decide when to take action.

The use of 5 sensors on the upper arm was investigated. Characteristic values for those sensors are presented in **Table 21**. Sensors are placed next to the other in a line, with the sensor of lowest temperature limit value at the bottom. There are only 6 different sensor configurations (see **Figure 35**) as in all cases when sensor *i* is ON, sensors *j* with *j*<*i* are necessarily ON as well. The probability of a child having fever when the *i-th* sensor is ON was calculated by equation **30**. A 3-set sensors could also be used by choosing 3 out of the 5 presented sensors.

Sensor	S1	S2	S3	S4	S5
$T_{threshold}$	32.6	33.7	34.4	35.1	35.3
α	0.60	0.20	0.05	0.01	0.005
β	0.14	0.48	0.75	0.91	0.94
p(ON,fever)	0.20	0.32	0.46	0.61	0.68
p display	20%	30%	45%	60%	70%

Table 21: Characterization of proposed sensors

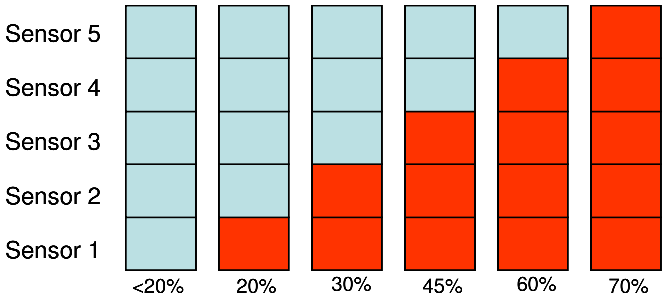


Figure 35: Possible readings

4.4.4 Implications of the use of single or multiple thresholds

Skin temperature at every location was found to be dependent on at least one parameter, leading to a separation of the babies into different cohorts and ultimately the definition of several alpha and beta error curves. Once the characteristics of the device under design such as location to be placed and constrains in the alpha error values are defined, the use of a single threshold or multiple ones needs to be selected. Each of those choices influences the design as discussed below.

The use of a single threshold simplifies the design, hence minimises cost production. Furthermore, babies do not need to be dressed in different garments depending on their age or activity, which makes it more versatile. However, the accuracy would vary for different cohorts of children.

The use of multiple thresholds allows to define a more accurate *temperature limit* for each group of children, subject to the sensor being sufficiently sensitive. When status of the baby is a relevant factor, different devices should be produced and placed either in day or night clothing, for example pyjamas. When the age is relevant, a different device needs to be produced for each of the age categories. As the growth of the children is fast at those ages, this is again feasible. Greater variety of garments increases the cost but also potentially increases the number of sales.

In any case the sensor should be embedded in the babies clothing and not in an extra band or garment, as this would change the heat transfer at that particular skin location and it would induce to error [Deng, 2008].

4.5 Conclusions

Identification of fever in young children is something that continuously worries the children carers, as it usually indicates an underlying infection, caused either by a self-limiting viral infection or a more serious bacterial infection such as meningitis or pneumonia which can be life-threatening [NICE, 2007]. Hence, a continuous core temperature monitoring system is very desirable. This system should be non-intrusive such that it can be use everyday, when children are at home, nurseries and so on. We investigated the possibility of such a system based on skin temperature measurements.

First of all, a skin temperature mapping of body in children was obtained, as it was lacking in the literature. Skin temperature at several locations was investigated, their temperature distributions characterized, correlation with the core temperature assessed and relevant factors identified (see **Figure 20** and **Figure 21**).

Skin temperatures at *T1*, *T3*, *T5*, *T6*, *T7*, *T8*, *T9*, *T11* and *T16* were found to be suitable for the core temperature monitoring, and their alpha and beta error curves obtained. Based on the strength of correlation with the core temperature and the characteristics of the alpha and beta error curves, the locations were ranked as *T5*, *T3*, <u>*T1, T6, T7, T9*</u>, *T11*, and <u>*T8, T16*</u>; the underline implies same position in the ranking.

Several system designs for the identification of fever were studied in the particular case of awake children aged between 8 and 16 months and with BMI in the range of 16.53 to 19.25 kg/m^2, although identical analysis can be made for any other group of children.

The studied systems were:

- individual sensors at either *T5*, *T3*, *T6*, *T9* or *T11* locations,
- set of 3 sensors, one at each of the locations *T5*, *T3* and *T11,*
- set of 5 sensors, one at each of the locations *T5*, *T3*, *T6*, *T9* and *T11,*
- set of 5 sensors with different thresholds at location *T5*.

The use of a single sensor has a total error of typically 18% when α = 10% and 24% when α = 20%. Hence, the probability of success is about 82 and 76% respectively. More important is the percentage of children with a fever when the sensor is ON, which averages 40% among the locations, using an α of 10%. The percentage of children with a fever when the sensor is OFF averages 10%. The use of several sensors at different locations reduces the equivalent α error to a value between 10 and 50% of the α error of a single sensor without affecting significantly the value of β error. The probability of success increases to 92% and 96% in a 3-sensors-set and 5-sensors-set respectively when α_i = 10%. In this last case, the probability of a child having fever when the system indicates so is 85%, twice the value for a single sensor. The use of several sensors of different characteristics at the same location is also beneficial. It displays different levels of probability of the child having fever. This allows the childminder to judge the need testing the child for fever with a more conventional method.

We conclude that the non-intrusive and continuous monitoring of fever in children under 2 years is possible by using the technology described in this study. This is of great importance as it would allow the detection of a greater number of feverish cases in early stages without having to measure the core temperature continuously. The fever monitoring system we propose is based on the use of 5 sensors at locations *T3*, *T5*, *T6*, *T9* and *T11* with independent α_i = 10%. In this case the child is likely to have fever in 85% of the cases in which the system alerts the childminder; and 11% of the children will have fever when the system is OFF. Missing 11% of the children with fever is reasonably taking in consideration that this is not a clinical system but an indicator. This system should not be used alone when carers suspect the child have a fever, in which case traditional core temperature measurement should be used.

5 Temperature in adults at different temperature levels

The skin temperature has been subject of a large number of studies. It is an important criterion for thermal comfort [ISO 9886, 2004] and determines the heat exchange with the environment [Sharon, 2007]. Skin temperature can be used to validate the models of the thermoregulatory response of humans when exposed to different environmental conditions [Stolwijk, 1966][Stolwijk, 1970][Tanabe, 2002][Huizenga, 2001][Salloum, 2007][Munir, 2009]. Over the years, these models have become more sophisticated.

In the literature the skin temperature was established to be dependent on the environmental temperature and to vary widely across the body surface, especially in cold conditions. However, skin temperature is usually taken as an average across the body surface. In fact, many equations for the estimation of mean skin temperature have been proposed and studied [Mitchell, 1969][Nielsen, 1984][ISO 9886, 2004]. There are not enough large studies on local skin temperatures. Most of the collected data samples are either small or were collected from manikins or nude volunteers [Burton, 1955][Werner, 1980a][Houdas, 1982][Webb, 1992][Huizenga, 2004][Munir, 2009] (**table 22**). Such approach fails to address the human body temperature response in everyday situations. Mehnert et al. [Mehnert, 2000] created a large temperature database by collating available data from several other authors. The selected data points and respective measurements are included in the ISO standards. However only 787 out of 1999 measurements were performed on clothed people, being the clothing insulation between 0.6 and 1.0 clo-units. Although the authors covered a wide range of air temperatures, radiant temperatures, humidity, air velocity and metabolic rates, they did not take any measurements for low metabolic rates. They did not provide any reflection on gender influence as female data were excluded due to the fact that less than 10% of the data were taken from female subjects.

Author	Number of sets	T_{room}	Subjects description
Burton 1955	1	25 and 30˚C	Male, resting
Werner 1980	86	10-50˚C	Males, only wearing shorts, lying and resting
Houdas 1982	---	20-40˚C	
Webb 1992	6	15, 27 and 45˚C	Males, nude and resting
Huizenga 2004	109	16-32˚C	0.32 clo (almost nude)
Munir 2009	17	19.5, 29.4 and 38.9ºC	Males, wearing only under shorts and remaining sedentary

Table 22: Summary of previous studies where local skin temperature was observed for different environmental conditions.

5.1 Study design

The present study aims to improve the understanding of how skin temperature changes with the environmental conditions at a local level and, furthermore, identify other relevant factors for each location. Skin temperature were observed at clothed and seated people at normal indoor environmental conditions i.e. mild room temperatures (18 to 30ºC), no strong radiation temperature and average humidity 20-60%. This case was chosen as people are seated at low activity level in a high percentage of normal daily life in the office, at home or when travelling. It is applicable to office workers, cinema or theatre spectators, medium and long haul travellers and so on. Such knowledge is essential for the improvement of heating/air-conditioning systems and thermal comfort monitoring systems which would ultimately lead to better energy efficiency. The experimental protocol was detailed in Chapter 2.

The aims of the study presented in this chapter were: (1) obtain a map of body temperature distribution, (2) analyze the dependency of the local skin temperatures with the room temperature, (3) identify factors affecting local skin temperature distribution, and (4) develop a predicted model for each of the local skin temperatures and validate them. This was done at normal indoor environmental conditions such that results can be used in the development of temperature control systems at a variety of indoor environments (e.g. offices, cinemas or planes).

5.1.1 Group stratification

A total of 806 measurement sessions where undertaken on 159 healthy and self-clothed adults. Participants were of diverse age and constitution in order to form a representative sample for the general population. Both genders were equally represented in the sample (48% male and 52% female). Clothing was assessed and recorded in terms of number of layers at each of the points of measurement. As the fabrics of each layer in most of the cases were typically cotton, this is a useful indicator to determine different isolation levels [Araźny, 2006]. Further description is presented in **Table 23**. Five different room temperatures were studied, as detailed in **Table 24**.

Participants were asked to remain seated for periods of 15 to 195 minutes in a room of constant temperature, keeping their metabolic rate in the range of 46 to 70 W/m^2. This range encompasses activities such as reclining, sitting relaxed, sitting upright or sedentary activity such as reading, writing, using laptop etc [ISO 7730, 1994]. They were allowed to stand up and leave the room only when physiological needs occurred.

	T_{room} (ºC)	H_{room} (%)	Age (y)	BMI (W/m2)	Tc (ºC)
Mean	24.2	39.5	29.5	24.3	36.42
Std. Dev.	3.1	10.0	10.4	4.2	0.37
Minimum	17.8	20.8	18.0	13.9	35.0
Maximum	30.9	59.5	72.0	42.5	37.3

Table 23: Description of the experimental data based on 1612 samples, 48% of them taken in male volunteers and 52% taken from female volunteers

Room temperature (ºC)			
Range	Mean	SD	N
[18.6, 20.4)	19.71	0.46	98
[20.4, 22.2)	21.36	0.48	187
[22.2, 25.5]	23.73	0.89	190
(25.5, 27.5]	23.77	0.48	200
(27.5, 30.5]	28.55	0.82	127

Table 24: Room temperature categories

In statistical terms, the acquired data can be seen as a random sampling with replacement from the population of adults. This box model allows the use of statistical analysis.

5.2 Data analysis

5.2.1 Skin temperature mapping at different room temperatures

This analysis aims to find out how the temperature at different parts of the body depend on the environmental temperature, which ones are more sensitive to changes, if they change linearly or following some other trend and if the changes are significant.

The sample data were divided into 5 cohorts attending to the room temperature, as detailed in **Table 24**. The local skin temperatures were analyzed for each group. Mean and standard deviation both of the skin and room temperatures are used to sketch the trend in each case. We assume that the curve between the core or skin temperature and environmental temperature is continuous and increasing. Two tailed Z-test with significance of 0.01 (z limit = 1.96) was used to compare the temperature distributions for each consecutive pair. Z-test was used as it takes into account not just the difference of means but the number of samples and variance of each distribution. This allows to detect ranges of room temperature where the local skin temperature remains constant.

For those locations which could either be exposed or covered with cloths, sample data were divided into two cohorts attending to this fact. Such locations were upper arm, knees and shins. The trend of skin temperature was obtained for each of the cases separately.

5.2.2 Statistical model generation: assumptions and procedure

Environmental temperature was found to influence greatly both body temperature and skin temperature. There are other factors partially accounting for the temperature variation that should be included in prediction models of such variables. In our study the effect of environmental humidity, clothing and Tc (the latest only for skin temperature) were included as proposed by Nielsen et al. [Nielsen, 1984] and furthermore some characteristics of the volunteers such as age, gender and BMI. These parameters were pointed as relevant by some authors in the literature and we want to corroborate it. Pearson correlation coefficients were used to identify possible problems due to high dependencies among the independent parameters. Ideally all the cross-correlations are null.

The relationship between local skin temperature (and core temperature) and the studied parameters (Troom, Hroom, clothing, Tc, age, gender and BMI) was assumed to be represented by an additive model. Prediction models were obtained following a multiple linear regression approach on relevant parameters, as we are looking for a simpler rather than overcomplicated description. Models were derived using the so called *bootstrap technique*, introduced in 1993 by Efron and Tibshirani [Efron, 1993] as an effective way of calculating the error of statistically-derived parameters when an analytical approach is difficult. This modern technique eliminates tedious theoretical calculations, allows the analysis of more complicated problems, reduces the assumptions of the analysis, provides a solution which is more independent on the database and overcomes possible violations of implicit statistical assumptions (like independency of the samples). Bootstrap technique only assumes that errors are independent. It does not rely entirely on the central limit theorem, hence it is more robust to violations of the normality of the error distribution or to non-constant variances. This technique has been already used by Mehnert et al. [Mehnert, 2000] for the development of a mean skin temperature prediction model, which is very similar to the problem at hand. In conclusion bootstrap technique is not just suitable but also advisable for this work.

The bootstrap is a re-sampling technique that extracts different random datasets with replacement from the original database. Each of the new datasets is used to generate a regression model, which is a relatively simple analysis of complex cases. Coefficients are obtained such that the residual square error is minimum. As all the datasets are different, the coefficients obtained are also different. The study of the distribution for each of these parameters provides the average value, which would be used in the final model, and its standard error. The number of datasets recommended by Efron and Tibshirani is in the range of 50 and 200, although the greater the number the more accurate coefficients and their errors would be.

The procedure for the generation of the models was as follow. First, factors affecting local skin temperatures needed to be defined. The re-sampling bootstrap technique was used to generate 2000 datasets. Each extracted sample was used to obtain the coefficients of a multi-linear regression (equation **35**) using all selected factors. Then, the coefficients were averaged and the initial equation for skin temperature prediction established. Predicted values for each local skin temperature on our original dataset were computed and their correlation with the independent variables was tested. Correlations where $p>0.05$ in two tailed-test pointed out the non-relevant factors, hence they were withdrawn from the analysis. Secondly, a multi-linear regression with the identified relevant factors (equation **35**) was derived for the prediction of each local skin temperature using again the bootstrap technique and 2000 new datasets. Alternatively, multiple multi-linear regression models were generated as explained later in section 5.2.4 using the same procedure.

Finally the goodness of the obtained equations was evaluated by means of residual analysis, calculated as equation **34**. The error defined in this equation is a prediction error and so its distribution should average zero. We presented observed values versus predicted values and adjusted to a linear regression, testing the linear hypothesis that the slope would be equal to one and the intercept would be zero, in which case the model would be valid. Hence, these values (slope and intercept) provided the means to assess the quality of the prediction models.

$$error_i = T_{observed,i} - T_{predicted,i} \tag{34}$$

5.2.3 Temperature prediction: simple multi-linear regression

The simple multi-linear regression used for the identification of relevant factors both core temperature and each of the skin temperatures is presented in equation **35**. A simplified version was also used for the generation of the predicting models where non-relevant parameters were withdrawn.

$$T_i = a_i + b_i.T_{room} + c_i.H_{room} + d_i.T_c + e_i.Age + f_i.BMI + g_i.Gender + h_i.N_{layers} \tag{35}$$

i accounts for location
$a_i, b_i, c_i, d_i, e_i, f_i, g_i$ *and* h_i are constants
a_i *and* g_i are in ºC
b_i *and* d_i are non dimensional but T_{room} and T_c must be given in ºC
c_i is in ºC/%
e_i is in ºC/years
f_i is in ºC/(Kg/m^2)
h_i is in ºC/(nº of layers)
Regarding the parameter *gender*, male volunteers were coded as 1 and female as 2.

5.2.4 Temperature prediction: multiple multi-linear regression

The trend of local skin temperature with the room temperature was found to be dependent on the range of room temperature under consideration. The regions per location are defined in **Appendix N Table N1**. The more significant increase of skin temperature with room temperature occurs always in region 2. Regions 1 and 3 present mild or no significant increase. Hence the use of several multilinear regressions, one per region, is recommendable. Several modifications were proposed to equation **35** for the skin temperature prediction. Coefficients for each equation were used using the same independent variables that in the equations of control and the bootstrap technique described earlier. Similarly to the simple multi-linear regression case, accuracy of the models was assessed by comparing the predicted and observed values. Linear regressions were performed and the correlation coefficients examined.

5.2.4.1 Modification 1

The equations of control were used as a base. Only the term in T_{room} was changed. This term was forced to be constant when there was not significant increase of skin temperature with room temperature. Otherwise, it was set to be linear. See equation **36**.

$$T_{i,j} = a_i + c_i.H_{room} + d_i.T_c + e_i.Age + f_i.BMI + g_i.Gender + h_i.N_{layers} + n_{i,j,1} + m_{i,j,1}.T_{room} \quad \textbf{(36)}$$

a_i, c_i, d_i, e_i, f_i *and* g_i are same constants than on the control equations

$n_{i,j,1}$ *and* $m_{i,j,1}$ are constants that define the contribution of T_{room} in each location
j = 1,2,3 in account for room temperature region

<u>Equations constrains:</u> $m_{c,1,1}, m_{0,1,1}, m_{1,1,1}, m_{3,1,1}, m_{3,3,1}, m_{5,3,1}$ *and* $m_{9,3,1} = 0$ as body temperature in those cases does not change significantly with the Troom.

5.2.4.2 Modification 2

Modification 2 is based on modification 1. It maintains the equations for regions 1 and 3. However, it forces the linear regression in *R2* such as the dependency of skin temperature with room temperature is continuous. See equation **37**.

$$T_{i,j} = a_i + c_i.H_{room} + d_i.T_c + e_i.Age + f_i.BMI + g_i.Gender + h_i.N_{layers} + n_{i,j,2} + m_{i,j,2}.T_{room} \quad \textbf{(37)}$$

$n_{i,j,2}$ *and* $m_{i,j,2}$ are constants that define the contribution of T_{room} in each location

<u>Equations constrains</u>: $m_{i,1,2} = m_{i,1,1}$, $m_{i,3,2} = m_{i,3,1}, n_{i,1,2} = n_{i,1,1}$ *and* $n_{i,3,2} = n_{i,3,1}$

$m_{i,2,2}$ *and* $m_{i,2,2}$ are such that T_i *is continuous*

5.2.4.3 Modification 3

Modification 3 is a generalization of modification 1. The equations of control were used as a base. Only the term in T_{room} was changed. This term was set to be linear in each of the room temperature regions. See equation **38**.

$$T_{i,j} = a_i + c_i.H_{room} + d_i.T_c + e_i.Age + f_i.BMI + g_i.Gender + h_i.N_{layers} + n_{i,j,3} + m_{i,j,3}.T_{room} \quad \textbf{(38)}$$

$n_{i,j,3}$ *and* $m_{i,j,3}$ are constants that define the contribution of T_{room} in each case

<u>Equations constrains:</u> no constrains

5.2.4.4 Modification 4

A different multi-linear equation is derived for each room temperature region. Only the intercept variable was forced to be the same as in the equations of control. Similarly to modification 1, the term on T_{room} was forced to be constant where there was not any significant increase of skin temperature with room temperature. Otherwise, it was set to be linear. See equation **39**.

$$T_{i,j} = a_i + c_{i,j,4}.H_{room} + d_{i,j,4}.T_c + e_{i,j,4}.Age + f_{i,j,4}.BMI + g_{i,j,4}.Gender + h_{i,j,4}.N_{layers} + n_{i,j,4} + m_{i,j,4}.T_{room} \quad \mathbf{(39)}$$

a_i is same constant than on the control equations

$c_{i,j,4}, d_{i,j,4}, e_{i,j,4}, f_{i,j,4}, g_{i,j,4}, h_{i,j,4}, n_{i,j,4}$ *and* $m_{i,j,4}$ are constants that define the contribution of each of the parameters involved for the modification 4

Equations constrains: $m_{c,1,4}, m_{0,1,4}, m_{1,1,4}, m_{3,1,4}, m_{3,3,4}, m_{5,3,4}$ *and* $m_{9,3,4} = 0$ as the body temperature in those cases does not change significantly with the room temperature.

5.2.4.5 Modification 5

Modification 5 is a generalization of 4, with removed constrains. A different multi-linear equation is derived for each room temperature region. Only the intercept variable was forced to be the same as in the equations of control. The contribution of the room temperature term was forced to be linear in each of the regions. See equation **40**. The equations obtained with modifications 4 and 5 are equivalent at locations 7 and 11.

$$T_{i,j} = a_i + c_{i,j,5}.H_{room} + d_{i,j,5}.T_c + e_{i,j,5}.Age + f_{i,j,5}.BMI + g_{i,j,5}.Gender + h_{i,j,5}.N_{layers} + n_{i,j,5} + m_{i,j,5}.T_{room} \quad \mathbf{(40)}$$

a_i is same constant than on the control equations

$c_{i,j,5}, d_{i,j,5}, e_{i,j,5}, f_{i,j,5}, g_{i,j,5}, h_{i,j,5}, n_{i,j,5}$ *and* $m_{i,j,5}$ are constants that define the contribution of each of the parameters involved for the modification 5

Equations constrains: No constrains

5.2.5 Comparison with accuracy for mean skin temperature

Mean skin temperature was determined from the observations as un-weighted average of the local skin temperatures. A multi-linear regression to predict mean skin temperature was generated following the same technique, and its accuracy assessed. The accuracy of the models predicting local and mean skin temperatures were compared to assess the goodness of the local predictions.

5.3 Results

5.3.1 Skin temperature mapping at different room temperatures

Core and local skin temperature distributions within different environmental temperature ranges and their characterization were obtained (see **Appendix M**). The distributions for forehead temperature are presented in **Figure 36** as example. The existence of significant differences among skin temperature distributions corresponding to two consecutive room temperature categories was tested. Distributions were compared using a significance level of 0.01 and 0.05 at two tailed test (**Appendix M Table M2**). **Figure 37** presents the trends of each local skin temperature with the environmental temperature. Each cohort is represented by one point. Groups with no significant difference between them are pointed out in the graphs by an underlying bracket.

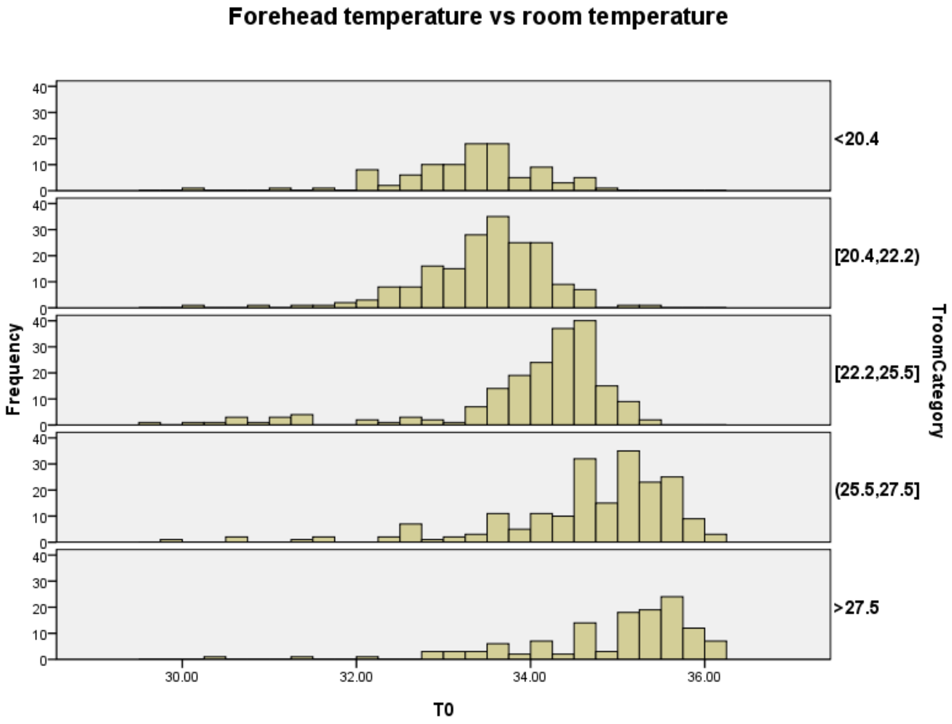
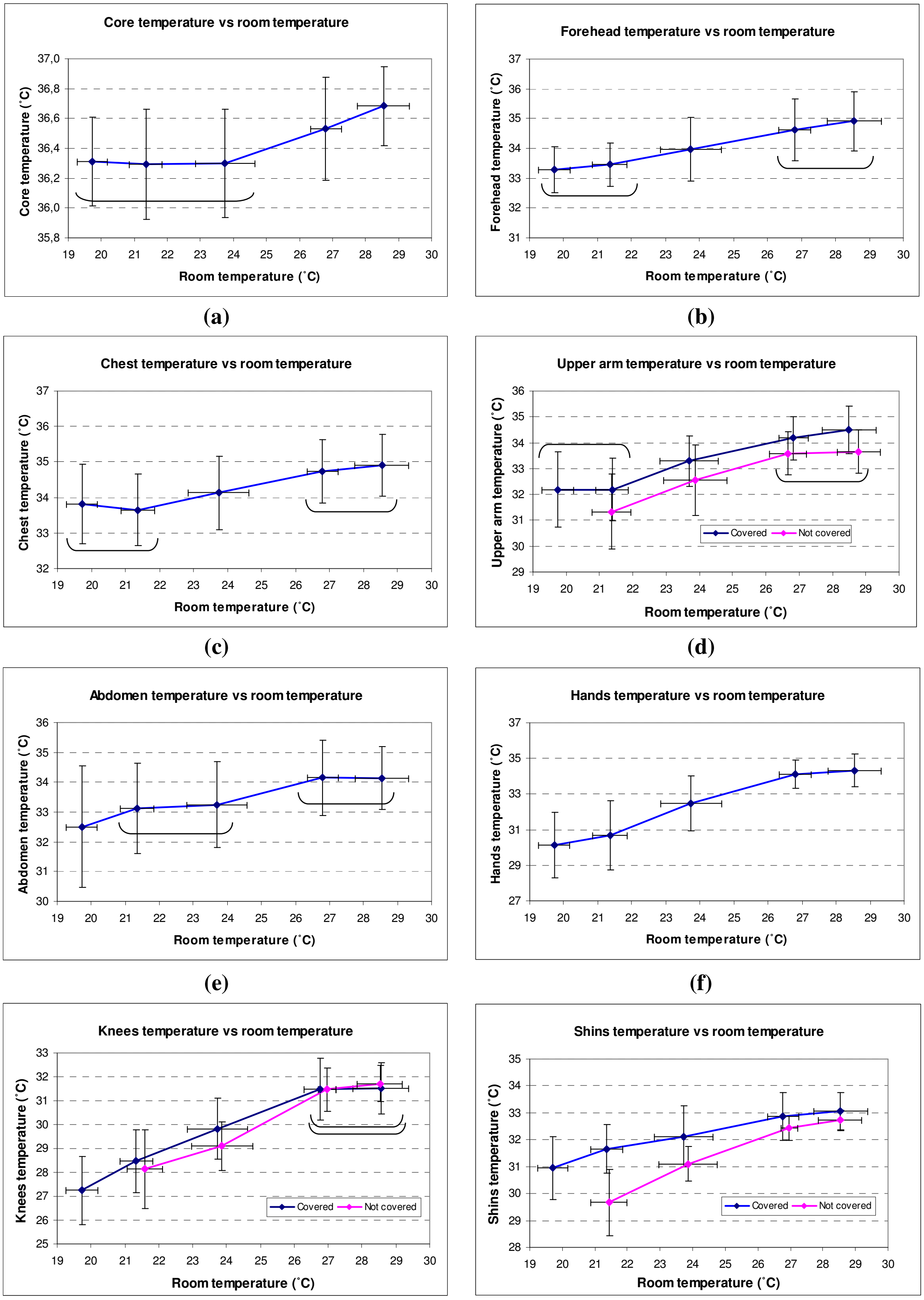


Figure 36: Local skin temperature at forehead for different environmental temperatures.



(a) **(b)**

(c) **(d)**

(e) **(f)**

(g) **(h)**

Figure 37: Skin temperature distribution in adults for different room temperature conditions

5.3.2 Identification of multicollinearity

The independence among the independent variables – T_{room}, H_{room}, *age*, *BMI*, *gender* and T_c - was studied using Pearson correlation coefficients (R). The correlations are not null but less than 0.375. That value was found for the correlation between T_{room} and T_c, which are already known to be related. The second and third highest relations are presented between H_{room} - *age* (R=0.321) and T_{room} - *gender* (R=-0.252). In general, it is still acceptable to assume there are not problems due to multicollinearity of those factors. Clothing description was also used as independent variable. The correlation values between the previously listed independent factors and the clothing are very low in general. Only the correlation between the clothing at the upper chest area and the gender stands out (R=0.514). Women were detected to wear more cloths than men at any room temperature category. We assumed that this will not present a problem although it is further studied later.

5.3.3 Prediction of local skin temperatures: single multilinear regression

An initial bootstrap analysis was performed with the total set of independent variables per location. A no significant dependency of the temperature at the upper part of the chest (*T3*) and knees (*T9*) on BMI and age respectively was detected ($p>0.05$ in two tailed-test). The other correlation values showed the rest of independent variables to be significant ($p<0.01$). The bootstrap analysis was repeated for *T3* and *T9*, withdrawing the non-significant terms from the multi-linear regression. **Appendix N Table N2** encloses the obtained coefficients of the relevant factors for each of the multi-linear regressions along with the standard errors.

Finally the validity of each of the derived equations was tested by comparing measured and predicted temperatures. A linear regression between those two temperatures was obtained for each location. The parameters of those regressions and correlation coefficients are presented in **Appendix N Table N3**. The slope in all cases is very close to the ideal value 1.0. Also the intercept values are very close to the ideal 0.0 except in the case of T5. However one can see that the error for this value is the highest and the correlation is one of the weakest.

5.3.4 Observed core and skin temperature behaviour

Core temperature does not change significantly from a mean of 36.3˚C at room temperature varying from 19.3-24.6 ºC. For higher room temperatures the mean core temperature increases linearly. Furthermore, core temperature was observed to be dependent on the gender (except at the hottest room temperatures), 0.15ºC higher for females. However humidity, age and BMI have little effect on the core temperature.

The skin temperature at each location increases with the room temperature. However the trend is not linear, as already pointed by Werner et al. [Werner, 1980a], and it is location specific. The highest rate of increase of skin temperature occurs at room temperatures around 23-26 ˚C. Skin temperature at forehead, chest and upper arm does not increase significantly ($p<0.05$) in cold environments (20-22˚C). Skin temperature at upper arm, abdomen and knees ($p<0.05$) or forehead and chest ($p<0.01$) does not increase significantly in warm environments (27-29˚C).

For the studied range of room temperature, the skin temperature changes significantly ($p>0.05$) with the room temperature. The largest variations on skin temperature were found at the limbs (7 to 13%) while temperature at trunk and forehead remains more stable (3 to 5%). The location on a human body with the most stable temperature is forehead if nude and chest if clothed. This ranking agrees in general with the literature.

In general, more compact skin temperature distributions were seen at higher room temperatures (standard deviations reduced).

Clearly skin temperature always increases when the core temperature rises. The highest correlations were found at forehead and upper arm (0.74 and 0.52ºC of skin temperature change respective 1ºC of core temperature change. Hands and shins showed the smallest change (<0.15ºC). Environmental humidity has low effect on the local skin temperature, at least at the range of humidity studied in this paper (20-60%). The most significant change occurred at hands and arms, where temperature increased/decreased around 0.25ºC for a 20% rise in the humidity. The clothing affects visibly the skin temperature. Skin temperature at upper chest and upper arm increases around 0.31 ºC per typical cotton garment worn. The effect is stronger at the shins, where the rate of increase is 0.87ºC for covered versus exposed. Abdomen and knees present the smallest variation on temperature with the clothing, 0.26 and 0.14ºC respectively. No conclusive dependency on BMI, age and gender was found at local skin temperatures.

We conclude that it is possible to predict local skin temperature with accuracy in the range of R= 0.5 and 0.8. More accurate predictions are obtained for hands and knees. It is expected that a non-linear term accounting for the T_{room} would increase R.

5.3.5 Prediction of local skin temperatures: multiple multilinear regression

Skin temperature expressions were obtained for each location, region and modification presented in section 5.2.4. Same set of independent variables as in the control case was kept. Accuracy of prediction for each of the obtained equations was tested. Correlation coefficients between observed and predicted values are presented in **Table 25**.

Dependent variable	Control	Mod 1	Mod 2	Mod 3	Mod 4	Mod 5
Tc	0.485	0.505	0.505	0.506	0.574	0.574
T0	0.640	0.641	0.632	0.645	0.669	0.671
T1	0.533	0.545	0.544	0.545	0.597	0.597
T3	0.679	0.708	0.679	0.709	0.719	0.720
T5	0.513	0.541	0.532	0.544	0.579	0.582
T7	0.765	0.781	0.778	0.781	0.797	0.797
T9	0.787	0.804	0.804	0.804	0.808	0.808
T11	0.642	0.649	0.646	0.649	0.684	0.684

Table 25: Computed R-values of the linear regression between the obtained and predicted skin temperatures at each location and for each method – control and modifications-.

5.3.6 Comparison with accuracy for mean skin temperature

A multi-linear equation for the prediction of mean skin temperature was generated. The correlation between the observed and predicted values is 0.816. This is higher than the accuracy obtained for any of the local skin temperature predictions.

5.4 Discussion

5.4.1 Relevant factors

Multi-linear regressions were derived for the prediction of core temperature and local skin temperatures (equation **35**, **Table N2**). In this section we discuss the relevance of each of the studied factors.

Regarding core temperature, room temperature appears to be an important factor, although not with linear effect. The average core temperature remains 36.3 ºC for room temperatures between 19.3 and 24.6 ºC. For higher room temperatures the core temperature rises. Core temperature was also observed to be dependent on the gender. The multi-linear regression reveals that it is 0.15ºC higher for females. This is not a result of bias in the data as females participated typically in the experiments at lower room temperatures. Furthermore, two tailed tests with significance level set at 0.05 were performed for each room temperature category. This analysis shows that core temperature distributions for female and male are significantly different except at the hottest room temperatures. The effect of gender was found to be 0.442 units of SD (**Appendix N Table N4**). Finally, humidity, age (as observed by [Sund-Levander, 2002]) and BMI have little effect on the core temperature.

Regarding skin temperature, room temperature was confirmed to be one of the most important factors, both when studying its effect alone or in conjunction with other parameters. Local skin temperature increases significantly with the room temperature, although the trend is location specific and not linear, as already pointed by Werner et al. [Werner, 1980a]. In general the larger variations were found in the limbs –hands, knees, shins and upper arms-, while skin temperature at forehead and trunk is more stable.

Secondly, the equations indicate that local skin temperatures always increase when core temperature rises. Most significant are forehead and upper arm, where the skin temperature increases 0.74 and 0.52ºC respectively for an increase on core temperature of 1ºC. Also the clothing increases the skin temperature, as they insulate the body from the environment. The more relevant cases are upper chest and upper arm, where the skin temperature increases around 0.3ºC per typical cotton garment worn. The change on skin temperature due to the environmental humidity is low, at least at the range of humidity studied in this paper.

In general, local skin temperature appears to decrease both with the age and the BMI (except at hands and knees) of the volunteers. The largest change due to the age was seen at the abdomen (-0.3ºC every 10 years), followed by upper part of the chest, upper arm and shins (about -0.11ºC every 10 years). The effect of BMI in the skin temperature is smaller, with absolute changes always under 0.07 ºC per BMI-unit. However the quantification of the dependency of skin temperature on age and BMI is not conclusive.

The correlation between age and BMI in our dataset was 0.21, hence the decrease of skin temperature could be attributed to an increase in age when it is due to an increase on BMI or vice versa. In our study we observed that the effect of the age on skin temperature was highest at locations where fat becomes more obvious with the increase of BMI and smallest at forehead, hands and knees. This led us to believe that the effect of BMI should be more pronounced than the age effect. A person with higher BMI would have the core more insulated, leading to a decrease of the skin temperature. Studies in the literature [Huizenga, 2001][Hardy, 1954] have already notice the change in skin temperature regarding the percentage of body fat.

Exploration of the obtained regressions seems to show that gender has an important effect on the local skin temperatures, which are between 0.10 and 0.75ºC lower for females (except T5). This theory is controversial and needed further analysis. First of all, correlation between room temperature and gender was found to be -0.252. A closer inspection to the data showed that the percentage of female volunteers at the coldest room temperature conditions (67 and 65%) was higher than at the hottest conditions (39 and 26%). Hence, the observed decrease on skin temperature was likely due to a mirage from the room temperature. Even the case of skin temperature at T5 could be explained by the high correlation of gender and clothing at that location. Secondly, two tailed tests with significance level set at 0.05 were performed for each location and room temperature category for the female and male cohorts. Significance difference was found in 27 out of 47 studied cases. Thirdly, the change on skin temperature due to the gender was calculated as a percentage of the averaged SD characteristic of each location. **Table N4** shows that the effect is up to 53% of the SD value at some locations, which is significant. As a summary, it seems that gender should be considered for the skin temperature estimation at forehead, hands, knees and shins. However, its effect on skin temperature at chest, upper arms and abdomen is not remarkable.

The relation of room temperature with either skin or core temperature is not linear, as seen in section 5.3.1. However, the derived regressions assume that relation to be linear as simplification. We believe that the low correlation between observed and predicted values is partially due to this simplification. Hence, further studies should use a non-linear term for the room temperature. This, we believe, will increase the agreement between observed and predicted values.

5.4.2 Thermoregulatory system

We conclude that the thermoregulatory system in clothed people is capable of maintaining core temperature around 36.3 ºC for room temperatures between 19.3 and 24.6 ºC. For higher room temperatures the core temperature rises due the increase of the stored heat on the body. In those cases, the body thermoregulation is unbalance, and a load of heat takes place.

One of the methods of the thermoregulation system to maintain stable the core temperature is by vasodilatation and vasoconstriction of the vessels that reach the surface of the skin. This controls the amount of heat that the body losses through the skin. Results of this study indicate that on room temperatures in the range of 19.3 to 23ºC the skin temperature remains fairly stable for many of the locations. Only significant change on skin temperature is seen at locations on the limbs (hands, knees and shins), so it seems that changes on skin temperature at those locations are enough to maintain the core temperature stable. Passed this threshold, for room temperatures between 23-26ºC, the skin temperature shows the most significant increase at all locations, due to an incipient need to loose heat. The change on skin temperature seems to be enough to keep the core temperature unchanged at room temperatures up to 24.6 ºC. After that, core and skin temperature would increase. However, even although the core temperature keeps on increasing, the skin temperature seems to reach a maximum at around 26ºC of room temperature. Probably at this point the onset of sweat is reached. The thermoregulatory response of sweating is a more effective and faster way to dissipate heat, keeping the skin temperature from increasing [Webb, 1992].

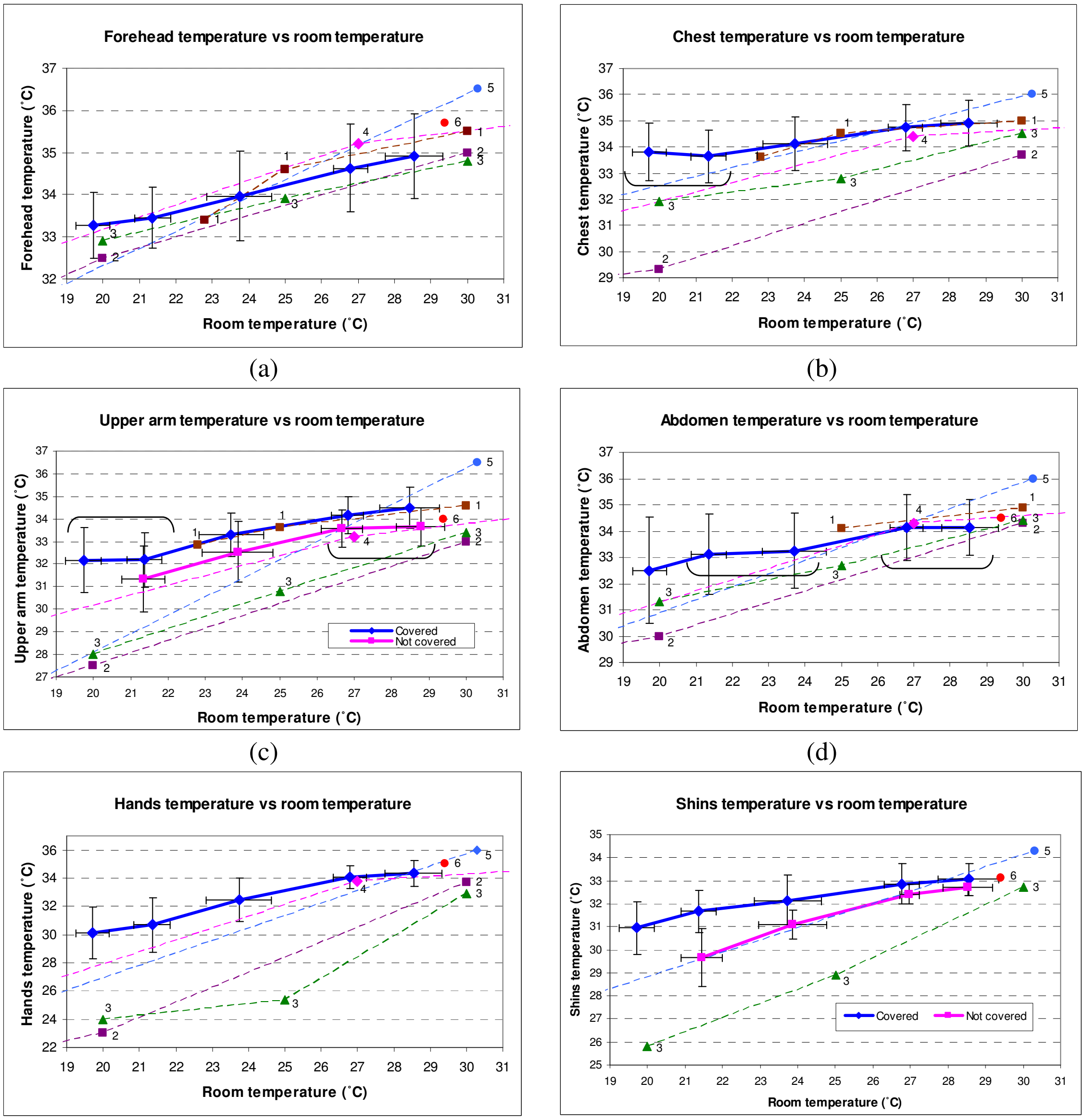
Another interesting effect of the increase of the room temperature is that, in general, the skin temperature distributions become more compact, reducing the standard deviations. This effect was also observed by Munir et al. [Munir, 2009] and Webb et al. [Webb, 1992] in their experiments under thermal-transient conditions. We believe that it reflects the variety of possibilities to control the body temperature at neutral environments. Cases such as having cold feet and hot hands are as likely as having cold hands and hot feet. The only constrain is that the net lost of heat from the body is the same. However, at warm environments the thermoregulatory system needs to force the loose of heat through all the body, hence the skin temperature is higher, and more consistently through the population.

The forehead temperature has not-surprisingly high dependency on the core temperature, as the blood from the centre of the body reaches the brain at a slightly lower temperature than at the core. This makes ear temperature very popular to estimate the core temperature. Less significant is the dependency of the skin temperature with the core temperature at the trunk, as trunk is usually well isolated. The weakest dependency was expected at the limbs. This was observed at hands, arms and shins. Surprisingly, the effect was higher at knees and similar to the one at the upper part of the chest. This could be attributed to the volunteers being in seated position. While seating, the trousers (typical garment used by the volunteers) were in touch with the knee and steady. This would increase the insulation factor and might cause an accumulation of heat.

5.4.3 Temperature mapping: comparison with previous studies

Local skin temperature was measured previously by other authors, some of which were detailed in **Table 22.** The values they reported were compared with our observations in **Figure 38**.

Werner et al. [Werner, 1980a] and Houdas et al. [Houdas, 1982] observed notably lower skin temperatures than what we measured at forehead, abdomen, chest, upper arm, hands and shins, especially Werner. The difference is greater at lower room temperatures, and differs with the location. Maximum difference (about 7ºC) was found at hands in low room temperature, while minimum (about 0.3ºC) is observed at forehead and abdomen in high room temperatures. Webb et al. [Webb, 1992] also observed lower skin temperatures than us in most of the cases, mainly at low room temperatures. However the differences are much smaller, about 2.5 ºC at the worst of the cases which corresponds again to the hands. At mild and warmer environmental conditions, the skin temperature difference reduces considerably; it even becomes positive at forehead and abdomen. The skin temperature observations made by Huizenga et al. [Huizenga, 2004] are lower/higher than ours, at low/high room temperatures. The trends cross at room temperature around 27-28ºC for most of the cases, while at forehead the cross occurs at 24.5ºC approximately. Munir et al. [Munir, 2009] performed measurements mainly at higher room temperatures than the scope of our study. However, the skin temperatures they observed at 29.4 ºC are typically a bit higher than our measurements. Finally, the curves obtained by Burton et al. [Burton, 1955] are very similar to ours.


Forehead temperature vs room temperature

Chest temperature vs room temperature

Upper arm temperature vs room temperature

Abdomen temperature vs room temperature

Hands temperature vs room temperature

Shins temperature vs room temperature

(a) (b)

(c) (d)

(e) (f)

Figure 38: Comparison of present and previous studies of local skin temperature. (Full lines) observed values in the present study. (Broken lines) observations of other authors: (1) Burton 1955, (2) Werner 1980, (3) Houdas 1982, (4) Webb 1992, (5) Huizenga 2004 and (6) Munir 2009.

In general we observed higher skin temperature at all locations than the values retrieved from other studies in the literature. This is partially due to their volunteers being naked –males wearing only shorts- while in our experiments the volunteers were self clothed. This reasoning also applies at forehead and hands. Being the body more insulated from the environment, the load of heat in the body kept in hot environments would be less, hence the skin temperature remains lower. The other reason is the different activity the volunteers were performing. While the other authors´ volunteers were typically resting, our volunteers were seating and either quiet or performing low level activity. Although there is not large difference, the extra muscular activity increase the heat production hence the skin temperature. Huizenga et al. [Huizenga, 2004] detected a difference of maximum 3 ºC between skin temperatures at the fingers while using a computer mouse. Opposite cooling has been observed by Nielsen [Nielsen, 1984] with the movement of the limbs. It is known that layers of dead air increase greatly the insulation [ISO 9920, 1995] while the movement decrease it (pumping effect), specially when their cloths have openings [ISO 11079, 1993]. In any case, the difference on the measured temperatures is smaller for higher room temperatures.

Another effect of the clothing on the subjects is the lost of skin temperature sensitivity to room temperature. The differences we observe on local skin temperature between cold and hot environments are not as high as other authors observed in nude or semi-nude volunteers. The clothing acts as a protection of the body from the environment. It increases the insulation, maintains the skin warmer in low room temperatures and cooler in high room temperatures. Among all the mentioned studies, Huizenga observed the largest variations on skin temperature with the room temperature. Furthermore, there is a general agreement in the rank of locations where skin temperature is more sensitive. Locations at limbs (hands, shins and upper arms) present in order of highest change on skin temperature for the same change on room temperature. Skin temperature of locations at the trunk (abdomen and chest) and forehead are less sensitive, as forehead and chest show least change.

Beside this difference in the absolute values, the ranks of locations by their skin temperature are similar in all the studies. The only difference is that the location on a human body with the most stable temperature is forehead if nude and chest if clothed. Abdomen is next in the ranking, followed by the limbs, i.e. upper arm, shins and hands. For high room temperatures skin temperature of hands might exceed temperature of shins and upper arms.

Interestingly all the values of forehead skin temperature, except at the lowest of the studied room temperatures, are within a margin of one SD, even though the forehead temperature distribution has smallest standard deviation. This effect is not seen in the rest of the locations.

Temperature sensors attached to the body might cause an increase on the insulation at the locations of interest. We believe that IR measuring techniques are advisable as the temperature measurements can be performed without touching the body.

5.4.4 Single versus multiple multilinear regressions

Compared to the single multilinear regressions or control for the prediction of core and local skin temperature, all the proposed modifications improve the goodness of the regressions. Modifications 4 and 5 present similar results, highest among the studied modifications. Modification 4 was chosen as the optimal one, as it yields almost identical results as modification 5 but is simpler.

Modification 4 improves the prediction of body temperatures between 3 and 9.5%, with respect to the control. The most marked improvement is observed on the prediction of core temperature. Similarly the prediction based on several parameters – T_{room}, H_{room}, T_c, *clothing*, *age*, *BMI* and *gender*- is between 2.7 and 11.7% better than taking into account only T_{room} (**Table 26**). Hence, although the modification 4 of the equations causes relatively small improvement at each body location, its use is justifiable.

Improvement (%)	Tc	T0	T1	T3	T5	T7	T9	T11
Control vs. Single factor	9.7	11.4	7.5	7.2	11.7	3.9	2.7	7.5
Mod 4 vs. control	9.5	4.0	7.6	5.9	7.7	5.5	3.1	5.8

Table 26: Comparison on the efficiency of core and skin temperatures prediction. Cases under consideration are: (Single factor) Equations where only T_{room} is used as independent parameter. (Control) equations used as control –equation **35**-, where up to 7 independent variables are taken into account. (Mod 4) Equations obtained with modification 4 –equation **39** -.

Confidence intervals have also improved with the modifications. **Table 27** presents the values for an 80% confidence of the predictions, for the cases described in **Table 26**. We observe that the confidence interval for modification 4 ranges 1.06 - 1.70 ˚C for skin temperature and it is 0.39 ˚C for core temperature.

80% confidence interval (˚C)	Tc	T0	T1	T3	T5	T7	T9	T11
Case 1	0.44	1.20	1.25	1.46	1.86	1.92	1.62	1.31
Control	0.42	1.10	1.20	1.35	1.70	1.80	1.57	1.22
Mod 4	0.39	1.06	1.13	1.27	1.64	1.70	1.51	1.16

Table 27: 80% confidence intervals of the predicted core and skin temperatures in three different cases, described in**Table 26**.

It seems that it is not possible to predict local skin temperatures with higher accuracy than the one obtained here. This is due to the large variability of local skin temperature even when the same individual characteristics and environmental conditions apply.

We observe higher accuracy of the prediction of mean skin temperature than local skin temperatures, even though the same basic average formula was used. It seems that the response of the body as a whole is more predictable and replicable than a prediction per parts of it. The thermoregulatory system forces the needed exchange of heat in slightly different ways, depending on the person and occasion, but the average response is the same. The mapping of the exchange of heat between body and environment seems dependent on the individual characteristics.

As summary, the use of equation **39** for the prediction of core and skin temperature is proposed. The coefficients are enclosed in table **Appendix N Table N5**.

5.5 Conclusions

Core and local skin temperatures were observed to depend non-linearly on the ambient temperature. The non-linear effect on skin temperature was also pointed by Werner et al. [Werner, 1980a], and further investigated here. Larger skin temperature variations with T_{room} were found in the limbs (hands, knees, shins and upper arms) while forehead and trunk were more stable. The increase of skin temperature occurs progressively with the room temperature, starting at the limbs (hands, knees and shins). Greater variability of skin temperature is observed at cold environments, and reduces significantly with the room temperature as observed in the literature [Munir, 2009][Webb, 1992]. The ranking of temperatures observed in our study are in agreement with previously reported works [Burton, 1955][Werner, 1980a][Houdas, 1982][Webb, 1992][Huizenga, 2004][Munir, 2009]. The increase of skin temperature helps to maintain the core temperature stable for room temperatures between 19.3 and 24.6ºC. From this point onwards, core temperature increases due to an accumulation of stored heat.

Core temperature was also observed to be dependent on the gender. Local skin temperature increases with the core temperature, most significantly at forehead and upper arm (0.74 and 0.52ºC per 1ºC increase on T_c). Also the clothing increases the skin temperature. Skin temperature appears to decrease with BMI, except at hands and knees. Dependency on the percentage of body fat was noticed by Hardy [Hardy, 1954] and Huizenga [Huizenga, 2001], which agrees with our results. It seems gender should be considered for skin temperature estimation at forehead, hands, knees and shins.

Several multilinear regressions were derived for the prediction of core and local skin temperatures, and compared. The model given in equation **39** (coefficients enclosed in **Appendix N Table N5**) was chosen as the optimal, as it balances the number of parameters with the accuracy and confidence intervals. The accuracy is limited due to the large variability of local skin temperature even when the same individual characteristics and environmental conditions apply.

Typically in the literature, volunteers for thermal studies are resting and/or nude. For that reason the models developed in this study are of great importance as they predict temperatures for self clothed people seating and performing light activity or resting. Hence, these models apply to a great part of everyday life of people working in offices, and furthermore to those travelling, going to cinema, and so on.

6 Alternative non-intrusive methods for core temperature estimation in adults

The core temperature is the most meaningful parameter for human temperature assessment. It is one of the main parameters in the evaluation of the thermal sensation and thermal comfort of a person within a given environment. Additionally, it provides information about the general health of the person. A high core temperature, known as fever, is indicative of a health problem like infection, cold, flu and so on.

There are plenty of scenarios where the identification of the core temperature of a person is beneficial. The identification of infected people before entering public places, such airports or theatres, is desirable and the best option for that is the measurement of the core temperature of each of the potential passengers or audience. Another interesting field where the monitoring of the core temperature is needed is the thermal comfort control. Nobody wishes to feel uncomfortable due to environmental conditions; even less if one needs to remain in the same place for a considerable period of time. It is frequently the case on a plane where certain passengers are too hot while others complain of cold. Hence, there is a need for a system that adjusts to the individual requirements. However, one of the main parameters for the estimation of the thermal comfort level is the core temperature and it should be measured frequently. This is neither practical nor comfortable for those who would get the benefit of more appropriated room temperature.

A central piece in the development of climate control system is a method for measuring the core temperature in a non-contact and non-intrusive way. Of course, by definition, core temperature can not be measured in such a way. However, a reliable approximation value is sufficient. The aim of this chapter is to describe the development of alternative methods for the estimation of core temperature in a non-intrusive way. Two methods are proposed, based on skin temperature and inner ear temperature measurements.

6.1 Core temperature estimation using local skin temperature measurements

6.1.1 Study design

Skin temperature was observed to depend on core temperature [Mairiaux, 1987] [Houdas, 1972] and furthermore in our chapters 2 and 3. The possibility of core temperature estimation based on skin temperature measurements is being investigated in the literature [Togawa, 1985][Ng, 2005] [Ng 2, 2005], but is still in a very early stage. This study looked for a relation between the core temperature and different local skin temperatures in adults at several environmental and individual conditions using the experimental setup detailed in **Chapter 3**. The objectives were to:

- Identify the core temperature distribution at different skin temperature ranges for each studied location.
- Obtain the average values of core temperature for different skin temperature levels at several locations.
- Obtain the individual correlations between core temperature and skin temperature at each location.
- Derive a new equation for the estimation of core temperature based on one or several skin temperature measurements and/or environmental conditions and assess its accuracy.

6.1.2 Data analysis

6.1.2.1 Core temperature at different skin temperatures

This section aims to identify relationships between core temperature and skin temperature at different parts of the body, determine which parts are sensitive to changes, and establish whether a sub-set of those measurements could be used as a reliable estimation of the core temperature.

Several skin temperature categories were defined (**Appendix O Table O1**). The cohorts were selected such that they include from 0 to 20th percentile, 20th to 40th, 40th to 60th, 60th to 80th and 80th to 100th percentile. The core temperature values were selected as the maximum value of the measurements taken in left and right ear. The core temperature was analyzed for each group. Mean and standard deviation of both skin and core temperatures were used to derive the trend for each location. Two tailed Z-test with significance of 0.01 and 0.05 was used to compare the skin temperature distributions in each case. This test does not assume equal means or variances between the groups. The room temperature ranges where the local skin temperature remains constant were identified. For those locations that could either be exposed or covered (upper arm, knees and shins), sample data were divided into two cohorts and the trend of skin temperature was obtained for each of the cases separately.

6.1.2.2 Prediction of core temperatures: multi-linear regression

An accurate and effective prediction of core temperature using potential factors such as skin temperature values at each location – T_i -, environmental conditions – T_{room} and H_{room} - and individual conditions – *weight*, *height*, *BMI*, *gender*, *age* and clothing on upper arm, knees and shins – was sought. Several models were built using multilinear regressions.

In first instance correlation between the core temperature and each individual factor was obtained; non significant factors at the 0.05 level (2-tailed Student test) were withdrawn. Then the maximum predictive capability of a model with the relevant factors was tested. A multilinear regression including all those parameters was derived by using bootstrap technique and 2000 samples out of the original dataset. This technique was previously described in section 5.2.2. The values predicted by this model were compared with the observed. The correlation value obtained establishes the maximum R-value that a multilinear model could achieve based on our data when using all studied parameters.

Simpler models, i.e. with reduced number of parameters, were also studied and their efficiency assessed. The parameters included in those models range from 15 to 1. Parameters with higher correlation with the core temperature were prioritised.

6.1.2.3 Variations to the model

The accuracy of the multi-linear models built as just described in the previous section is not as high as desirable, mainly due to inherent problem of high variability of the skin temperature even among humans of similar anthropometric characteristics and under the same environmental conditions. This low accuracy is also due to the non-linear relation between the core and each of the local skin temperatures. For most of the local skin temperatures, the core temperature remains constant up to a threshold point beyond which it rises linearly. For example, core temperature only holds a relevant correlation with forehead temperature when $T0 \geq 33.4$ºC and with chest temperature when $T1 \geq 34.2$ºC. These ranges establish different constrains on when the model is applicable.

New models were derived for the ranges of skin temperature at which a statistically significant increase of core temperature occurs. Furthermore, the effects of relaxing the constraints were studied. A new parameter, ***relax factor***, is proposed and defined as the number of local skin temperature measurements allowed to be out of range. For instance, when the relax factor is equal to 2, measurements that are taken into account are those where a maximum of 2 local skin temperatures out of the seven locations are not within the desirable temperature ranges. This is a novel technique we developed during this thesis and which we believe appropriate for data of this nature. Several levels of relaxation of those constrains were investigated.

Finally, additional models were built as a combination of several parameters based on their practicability and accessibility.

6.1.2.4 Model selection

Different models were derived for the estimation of core temperature, each of them having a different number of parameters, R-value and relax factor value. These models were compared the R-values, effectiveness defined as $R^2 * N_{cases}$, and the Akaike's Information Criteria (AIC) such that the best model can be identified.

The Akaike's Information Criteria (AIC) identifies the best model regarding the likelihood and number of parameters [Akaike, 1974]**.** The adjusted formula of AIC for small samples (n/K<40) is given in equation **41**, where n is the number of samples, K is the number of parameters including intercept and error, and ***RSS*** is the residual sum of squares (equation **42**). The last term is the adjustment, becoming very small as the sample size increases. The relative distance to the "truth" is then calculated (equation **43**) and the ***relative likelihood*** of the model obtained (equation **44**). The relative likelihood values are then normalized to the total value among the models under study and the ***Akaike weights*** obtained (equation **45**). The maximum value of $\boldsymbol{w_i}$ points out the best model. Candidate models with w_i smaller than the 10% of the maximum are withdrawn from the ***confidence set***. When there are several models within the confidence set, the Akaike technique allows their combination by means of a weighted average (equation **46**). The coefficient for each parameter is obtained by an average with normalized weights, obtained by equation **47**. j and k represent model and parameter respectively. R_k represents the set of models where a parameter k is used. The standard error (SE) for each of the new coefficients is then calculated (equation **48**). Finally, the effect of the relax factor is then studied and optimum model selected based on the overall information.

$$AIC = n \times \ln\left(\frac{RSS}{n}\right) + 2K + \frac{2K(K+1)}{n-K-1} \qquad \textbf{(41)}$$

$$RSS = \sum_{i=1}^{n} (Tc_{predicted} - Tc_{observed})^2 \qquad \textbf{(42)}$$

$$\Delta_j = AIC_j - \min AIC \qquad \textbf{(43)}$$

$$relative\ likelihood_j = \exp(-0.5 \times \Delta_j) \qquad \textbf{(44)}$$

$$w_j = \frac{\exp(-0.5 \times \Delta_j)}{\sum_{j=1}^{J} \exp(-0.5 \times \Delta_j)} \qquad \textbf{(45)}$$

$$coeff_{k,averaged} = \sum_{j}^{R_k} coeff_{j,k} \times w_{j,k,normalized} \qquad \textbf{(46)}$$

$$w_{j.k,normalized} = \frac{\exp(-0.5 \times \Delta_j)}{\sum_{j}^{R_k} \exp(-0.5 \times \Delta_j)} \qquad \textbf{(47)}$$

$$SE_{k,averaged} = \sum_{j=1}^{R_k} \sqrt{\left(coeff_{k,average} - coeff_{j,k}\right)^2 + SE_{j,k}^2} \times w_{j,k,normalized} \qquad \textbf{(48)}$$

6.1.3 Results

6.1.3.1 Core temperature distributions at different local skin temperatures

The trend for core temperature distributions within different ranges of local skin temperature was observed. The trend in terms of forehead temperature is presented in **Figure**; trends respect the other locations are given in **Appendix O Figure O1**. Characteristics of core and local skin temperature distributions in each of the defined cohorts are enclosed in **Table O2**. The existence of significant differences among core temperature distributions corresponding to two consecutive local skin temperature categories was tested. Distributions were compared using a significance level of 0.01 and 0.05 at two-tailed Student test (**Table O3**). **Figure 40** presents the trends of mean core temperature with each local skin temperature. Each cohort is represented by one point. Groups with no significant difference between them are marked in the graphs by an underlying bracket.

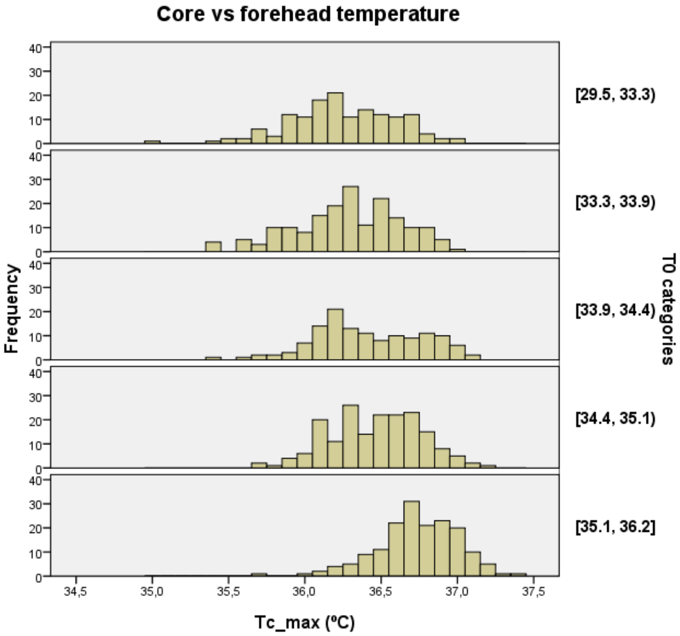
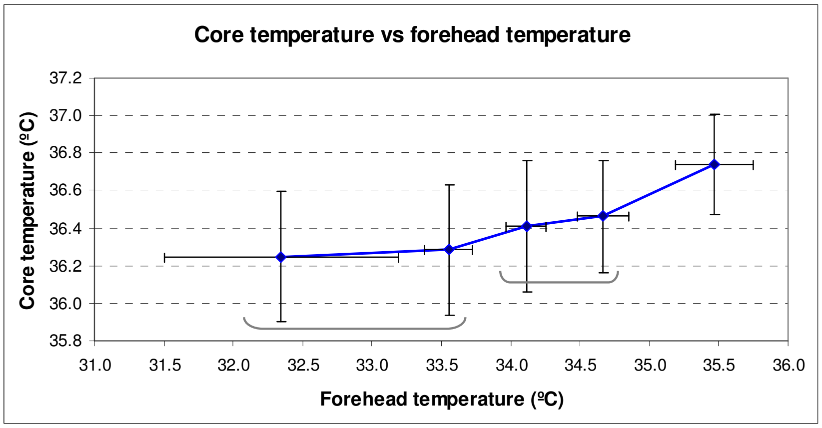
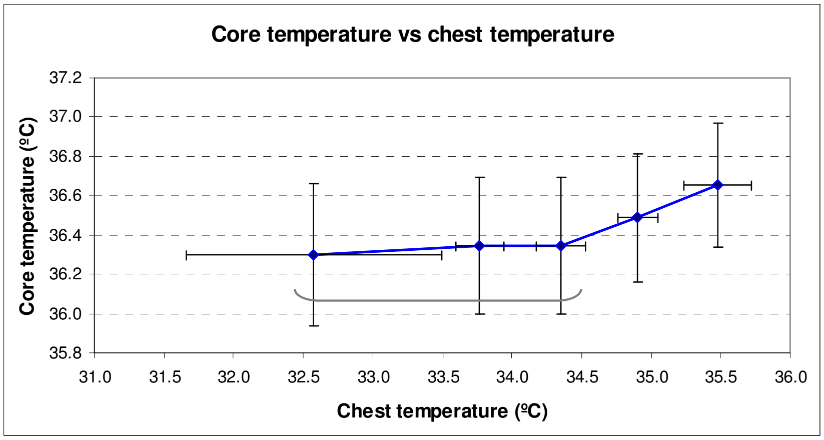


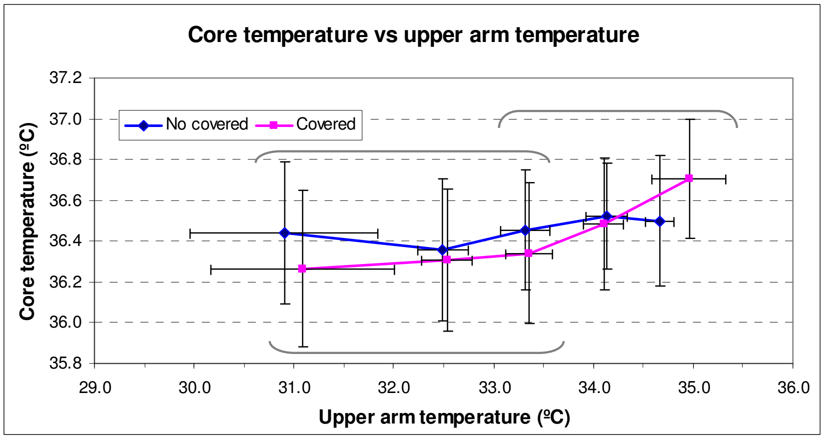
Figure 39: Core temperature distributions at different local skin temperatures ranges


Core temperature vs forehead temperature
Core temperature (ºC)
37.2
37.0
36.8
36.6
36.4
36.2
36.0
35.8
31.0
31.5
32.0
32.5
33.0
33.5
34.0
34.5
35.0
35.5
36.0
Forehead temperature (ºC)

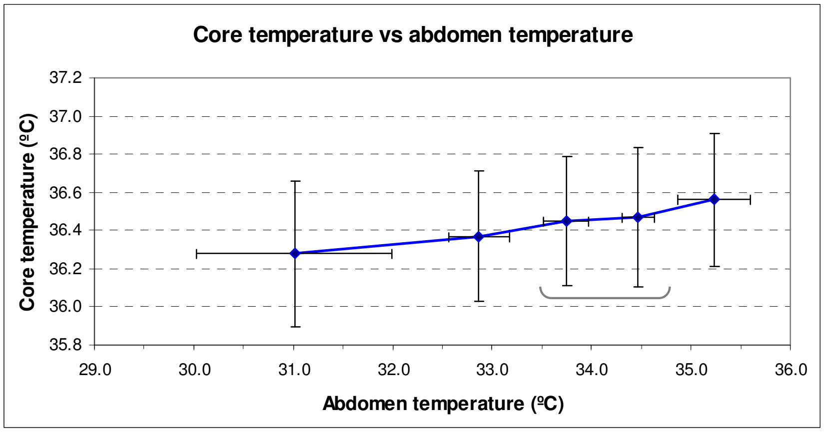
(a)


Core temperature vs chest temperature
Core temperature (ºC)
37.2
37.0
36.8
36.6
36.4
36.2
36.0
35.8
31.0
31.5
32.0
32.5
33.0
33.5
34.0
34.5
35.0
35.5
36.0
Chest temperature (ºC)

(b)


Core temperature vs upper arm temperature
No covered
Covered
Core temperature (ºC)
37.2
37.0
36.8
36.6
36.4
36.2
36.0
35.8
29.0
30.0
31.0
32.0
33.0
34.0
35.0
36.0
Upper arm temperature (ºC)

(c)


Core temperature vs abdomen temperature
Core temperature (ºC)
37.2
37.0
36.8
36.6
36.4
36.2
36.0
35.8
29.0
30.0
31.0
32.0
33.0
34.0
35.0
36.0
Abdomen temperature (ºC)

(d)

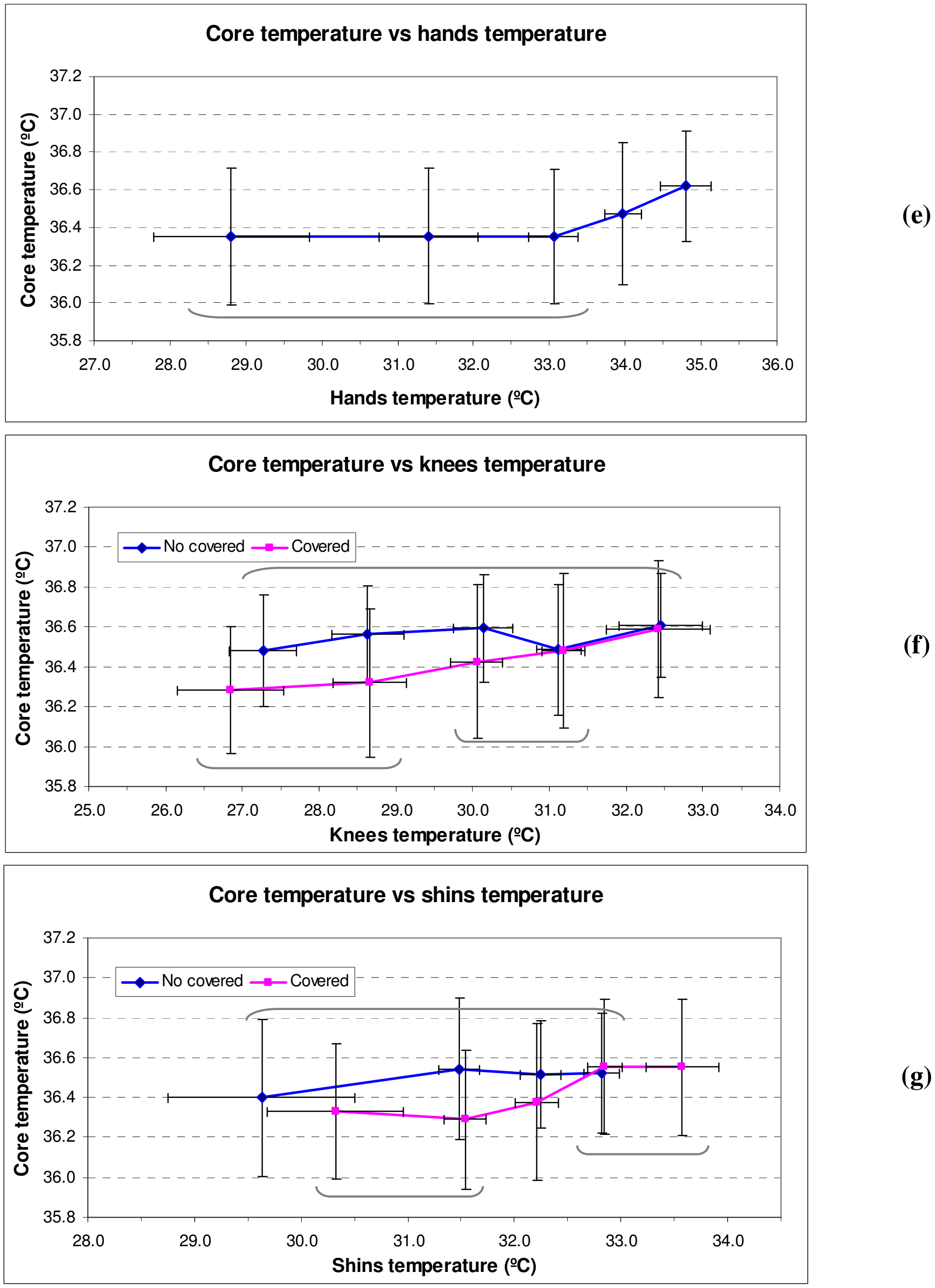


Figure 40: Core temperature versus skin temperature at several locations

6.1.3.2 Prediction of core temperature: multi-linear regression

Correlation of core temperature with each of the 17 observed parameters - local skin temperatures, environmental characteristics and anthropometric and clothing description of the subjects - was determined (**Appendix O Table O4**). The parameter describing clothing on the upper arms was withdrawn as it is not significant at 0.05 level (2-tailed Student test).

An initial multilinear regression for the prediction of core temperature was derived using the remaining 16 parameters listed. A linear regression between predicted and observed values was obtained. Parameters of that regression and correlation coefficient are presented in the first row of **Table O5**. The slope and the intercept are the ideal values, 1.0 and 0.0 respectively.

The same procedure was followed to derive simpler models by varying the number of parameters from 15 to 1, prioritizing those with higher correlation to the observed core temperature. A summary of the models is presented in **Table O5**. The R-value indicates the agreement between observed values and those given by the multilinear model. Maximum 0.561 is reached when all 16 parameters are used.

The statistical significance of individual variables within the models was found to be dependent on the selection of model parameters. The example in **Table O6** corresponds to the core temperature model when using parameters 1 to 9.

6.1.3.3 Variations to the full model

Figure 40 shows the relation between the core and local skin temperatures. In most cases, core temperature remains constant up to a threshold point of skin temperature beyond which it rises linearly. The ranges of local skin temperature that correspond to a significant increase in the core temperature were identified (**Appendix O Table O7**) and are summarized in **Table 28**. They were determined by subtracting from the mean value the standard deviation corresponding to the cohort where the trend changes (see **Figure 40**). These ranges were used to filter the data before deriving new models, and so they represent the constrains of applicability of those models.

Location	Valid range of skin temperature
T0	>= 33.4
T1	>= 34.2
T3	>= 32.3 and location covered
T5	>= 30.0
T7	>= 32.7
T9	>= 28.2 and location covered
T11	[31.3, 33.0] and location covered

Table 28: Constrains to the model: local skin temperatures for which the new model applies. Values have been chosen to provide higher correlation.

The effects of relaxing the constraints were studied. A new parameter, ***relax factor***, is proposed and defined as the number of local skin temperature measurements allowed to be out of the ranges defined in **Table 28**. A 16-parameters model and its agreement with the observed data – maximum due to the use of all parameters - was obtained for relax factors from 0 to 6 (**Table O8**).

The addition of constraints improves the accuracy of the model, which had a maximum of 0.561 when not applied. However it is not recommended to enforce all the constraints at the same time, but instead to use a relax factor of 1 or 2, as otherwise the model will not be applicable the majority of cases. We decided to work with a relax factor of 2, which covers almost 60% of the cases without compromising the accuracy of the model (R=0.641) when using the measurements from the 7 skin locations. The percentage of cases for which it applies would increase when using simpler models (less number of local skin temperature measurements), hence lower values of relax factor were also tested in those cases.

The correlation between each parameter and the observed core temperature was also studied by applying the constraints individually for each of the local skin temperatures and with a relax factor of two for the rest of the parameters. The relevant values are presented in **Table O9**. According to the new significance ranking of the factors, new models were developed with 14 to 1 parameters. Description and results are presented in **Table O10**. Simplest models with less parameters (1 to 6 in total) are presented for relax factors of 1 and 0.

Finally some extra models were derived attending to the practicability of the parameters involved, and not necessarily the ranking of correlation values with the core temperature. Results are presented in **Table O11**.

6.1.3.4 Identification of the optimal model

On one hand, the derived equations for the prediction of core temperature were assessed in terms of accuracy and applicability, that is, the percentage of cases for which the equation applies. This effectiveness was determined as $R^2 * N_{cases}$. Results are shown in **Figure 41**. The effectiveness is dependent on the application of constrains, the relax factor and the number of parameters involved in the model. The greater values are found at 22%. They correspond to some of the so-called extra models, having between 3 and 5 parameters and no constraints. Also the models with constraints and relax factor of 2 perform similarly with the use of 6 or 7 parameters. As the efficiency of the mentioned models is more or less equivalent, the optimal model would be the simplest or least computationally demanding. In this case one could opt for any of the first 3 or 4 models tagged in **Figure 41**, which are fully described in **Table 29.** Those models do not hold the highest R-values among the studied models, but they apply to almost 99% of the cases. The standard estimated error of those models is about 0.32 °C. This is the expected difference between the predicted value and the actual core temperature. It is a noticeable fact that models with higher number of parameters are not necessarily better.

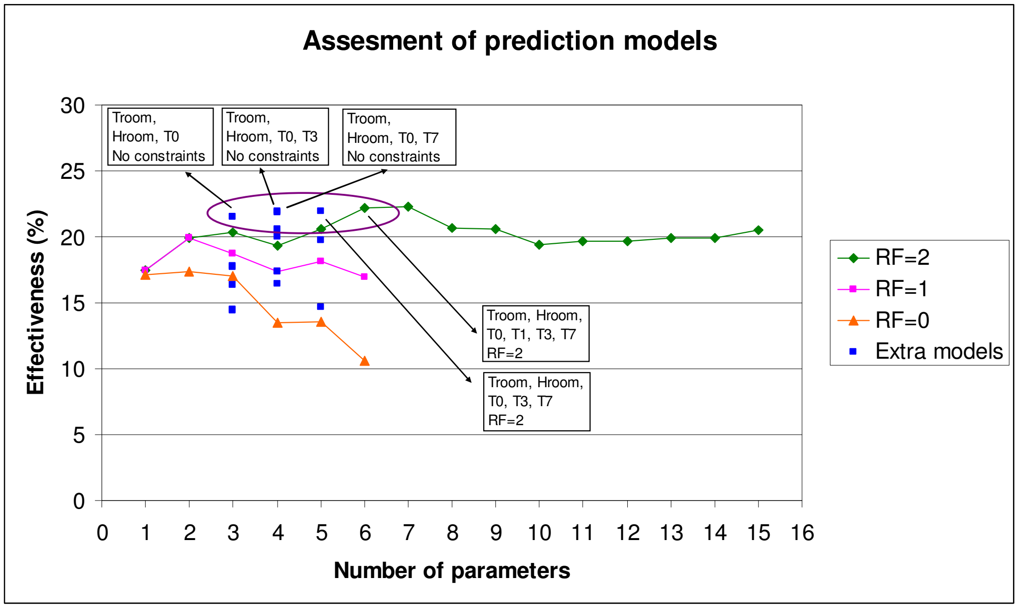


Figure 41: Assessment of core temperature models regarding their effectiveness, number of parameters involved and level of relaxation of the constraints. *Effectiveness* = $R^2 * N_{cases}$

Model parameters	Constant	T_{room}	H_{room}	T0	T3	T7	Std. error estimate
T_{room}, H_{room}, T0	32.97 (0.44)	0.021 (0.004)	-0.005 (0.001)	0.093 (0.012)	---	---	0.321
T_{room}, H_{room}, T0, T3	32.56 (0.34)	0.015 (0.004)	-0.005 (0.001)	0.085 (0.010)	0.024 (0.00	---	0.316
T_{room}, H_{room}, T0, T7	33.16 (0.32)	0.030 (0.004)	-0.004 (0.001)	0.097 (0.010)	---	-0.018	0.313

Table 29: Optimal models under assessment method 1 for the prediction of core temperature of an adult based on environmental and skin temperature measurements. No skin temperature constraints apply.

On the other hand, the models were assessed exclusively regarding the R-values that characterise them, the number of factors involved and the level of relaxation of the constraints (see **Figure 42**). Under this method of assessment, the performance of the models is better when including strict constraints (low relax factor). The optimal models, both in terms of performance and computational cost, would be the first 4 models tagged in **Figure 42**, which are described in **Table 30**. They have 4, 5 or 6 parameters and they work under constrains and relax factor of 0. Similar or greater performance was achieved by the 10- to 15-parameters models with relax factor of 2. However the increase on the computational demand does not compensate for the increase in performance, hence they were not selected. The standard estimated error of selected models is about 0.28 ˚C, obtained from the difference between the predicted values and the actual core temperatures. Among the models proposed in **Table 30**, the first and third models (4 and 5 parameters respectively) apply to the highest percentage of cases, just over 38%. Mainly cases with low room temperatures are filtered out. It is estimated that the models should apply at room temperatures over 24ºC, as they would lead to higher skin temperatures.

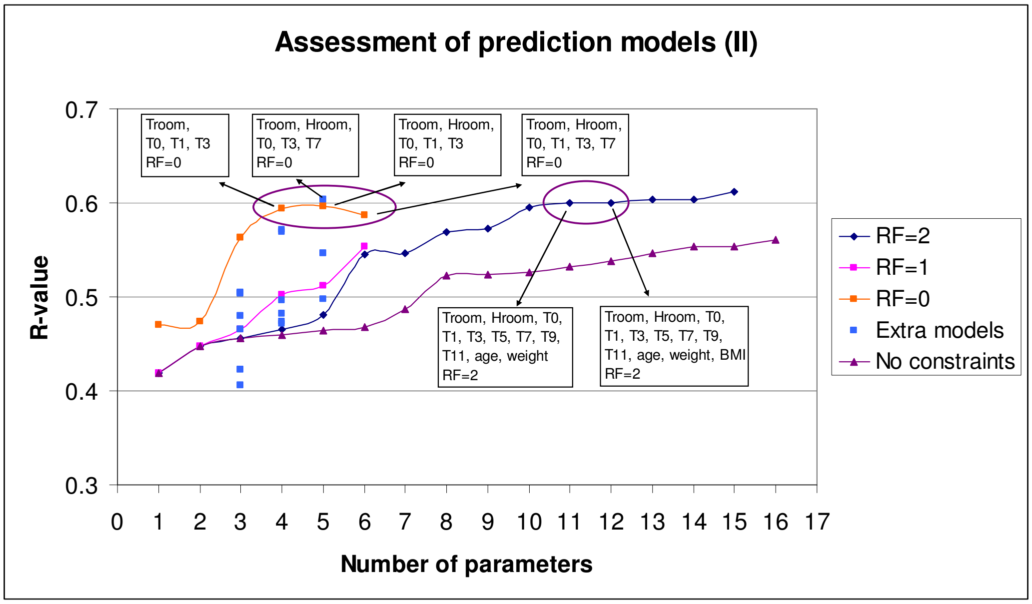


Figure 42: Assessment of core temperature models regarding the number of parameters involved, the R-value they achieve and the level of relaxation of the constraints.

Model parameters	Constant	T_{room}	H_{room}	T0	T1	T3	T7	SError Estim.
T_{room}, T0, T1, T3	24.80 (0.96)	0.010 (0.006)	---	0.207 (0.026)	0.089 (0.031)	0.035 (0.019)	---	0.286
T_{room}, H_{room}, T0, T3, T7	27.97 (0.78)	0.037 (0.007)	-0.002 (0.001)	0.182 (0.021)	---	0.049 (0.018)	-0.010 (0.018)	0.274
T_{room}, H_{room}, T0, T1, T3	25.34 (0.97)	0.011 (0.006)	-0.002 (0.001)	0.199 (0.025)	0.088 (0.031)	0.029 (0.019)	---	0.286
T_{room}, H_{room}, T0, T1, T3, T7	25.7 (1.1)	0.033 (0.009)	-0.001 (0.001)	0.183 (0.028)	0.082 (0.034)	0.043 (0.022)	-0.020 (0.019)	0.267

Table 30: Optimal models under assessment method 2 for the prediction of core temperature of an adult based on environmental measurements and skin temperature measurements. Strict skin temperature constraints apply (0 relax factor)

Finally the models were compared using the Akaike's Information Criteria. All models derived were compared at once. The RSS values are quite large (in part because of the large number of samples) and so the relative likelihood is equals to zero in all models but one. This is the model with no constrains and parameters T_{room}, H_{room}, T0 and T7, previously described in the last row of **Table 29**.

6.1.3.5 Discussion of core temperature distribution and local skin temperatures

The relationship between core and each local skin temperatures was established. For most locations, core temperature does not change significantly for low skin temperatures (*range of no-change*) while it increases beyond a threshold point (*range of change*). This shows that the thermoregulatory system is able to maintain constant core temperature within a given range of skin temperatures. However, once this threshold is exceeded, the body is not able to increase sufficiently the rate of expelled heat and the core temperature rises. The ranges where change is significant, presented in **Table 28**, are different for each location. Chest, upper arm and hands present the widest ranges of skin temperature corresponding to constant core temperature.

Core temperature increases slower with the skin temperature when location is exposed rather than covered for upper arm, knees and shins where this was investigated. This could potentially be explained by the extra insulation that clothing provides to the body. When the skin is exposed, the heat transfer is greater, facilitating the core temperature to be kept more stable. However, when the skin is covered, the heat load increases and leads to an increase of core temperature.

The influence of a given parameter in the core temperature models was found to vary with the number and selection of the other parameters included in the model. As an example, **Table O6** shows significance values of each factor in several core temperature models when 1 to 9 parameters were used. It can be observed for instance that *T5* was relevant when included in the 6-parameters model until weight of the subject was included. They correlate at p=-0.244, the strongest relation of weight with any of the skin temperatures. Also *T1* and *T3* lost relevance when *T5* was included. Hence, when developing the models we tried to optimize the number of parameters, such that they all contribute to the final accuracy. When two or more of the parameters are highly correlated among themselves, the inclusion of all of them became useless for the model as they do not provide any extra information. In the given example the combination of *T0*, T_{room} and *T3* either by themselves or along with *T1* or *T5* appears to be suitable for estimating of core temperature, although further statistical analysis is needed to prove it.

The standard deviation of the core temperature distribution does not show a very clear tendency for the skin temperature, although it remains within 0.30 and 0.40ºC in the majority of the cases. Only *T0*, *T1*, *T3* and *T7* could be said to present an equivalent trend, with constant core temperature standard deviation at low skin temperatures and a decrease at high skin temperatures.

Correlation between the core temperature and the selected factors was investigated. **Table O4** presents the correlations when all the data were taken into account (range of change and no-change), while **Table O9** shows the correlation values at the range of change only. In both the cases the three highest values were for T_{room}, *T0* and *T3*. For the complete set of data, parameters *T9*, *T1*, *T5* and H_{room} follow in relevance in that order; while in the case of the filtered data, the ranking follows with *T1*, H_{room} and *T7*. Comparing the two rankings a promotion of *T1* and *T7* can be observed, while *T5* and *weight* fall to lower positions. In general, a high dependency of the core temperature on the environmental conditions – T_{room} and H_{room} - can be observed. Also important are the skin temperature at forehead and upper arm, followed by chest, knees and hands. Those rankings were used to select factors included in the core temperature models. However, as discussed before, this does not guarantee that the best set of parameters will be used to derive the prediction models.

The forehead temperature was found to be a good indicator of the fever in children under two (chapter 4), presenting a strong relation with core temperature. Here forehead appears again to be one of the best options for core temperature prediction. This is a typically exposed skin area, possible to be measured in a non-contact way by using thermal cameras or IR devices. However, unobstructed view of the forehead is needed. The presence of hair in front of the forehead leads to inaccurate readings of skin temperature due to its insulating properties, as explained in section 2.5.3.2.

Following the same procedure as with the correlation, several core temperature models were derived in the first instance while taking into account both the range of change and no-change of core temperature with skin temperature. Results are presented in **Table O5**. However, after confirming the bilinearity of the trend, and in order to increase the efficiency of the models, data within the no-change range was filtered out. Different levels of constraint relaxation were studied, and finally set at a maximum of 2. New models were derived and improvement can be observed (see **Table O10**). Some other extra models were derived attending to the practicability of the parameters involved, and not to the ranking of correlation values (**Table O11**). In general, the evaluation of the models indicates that, beside the linear regression between observed and estimated values fit the perfect line, the R-values are low. This is due to the great variability in human thermoregulatory response even under the same environmental and personal conditions. It is also observable that the accuracy of the models increases with the addition of new parameters, although that is not necessarily the optimal solution.

Several methods were used to compare the derived equations for the prediction of core temperature. On one hand, they were assessed in terms of effectiveness, which we defined as $R^2 * N_{cases}$. This is dependent on the application of constrains, the relax factor and the number of parameters involved in the model. The greater values are found at 22%. For equivalent efficiency the optimal model are those least computationally demanding. In this case any of the first 3 models tagged in **Figure 41**, which are fully described in **Table 29.** Their standard estimated error is about 0.32 ˚C. On the other hand, the models were assessed exclusively regarding the R-values. Better performance was observed when including strict constraints (low relax factor). Again for similar performance the simpler models are selected. Optimal models in this case are the first 4 models tagged in **Figure 42**, which are described in **Table 30**. The standard estimated error of selected models is about 0.28 ˚C. Finally the models were compared using the Akaike's Information Criteria. The RSS values were quite large and different, leading to a relative likelihood equals to zero in all models but one. This is the model with no constrains and parameters T_{room}, H_{room}, T0 and T7, previously described in the last row of **Table 29**. This model was also found optimal when assessing in terms of effectiveness, hence it is the one recommended.

The error of the proposed model was estimated to be about 0.3 ˚C. This represents a significant difference in terms of core temperature; hence they are clearly not suitable for medical diagnosis. However it provides a feasible non-obtrusive way for long term core temperature monitoring in a great variety of circumstances.

6.2 Core temperature estimation using IR images of ears

Ear temperature is said to be one of the best approximations of the core temperature within the non-intrusive methods. However, there is no non-contact method which one could use to measure it. In search for a continuous and stress-free monitoring system, this section studies the possibility of measuring core temperature by using an IR camera, as it does not require contact with the person and it can be placed at a significant distance from the target.

6.2.1 Study design

We proposed a non-contact measurement method consisting of the identification and measurement of the auditory channel temperature by using an IR thermal camera. This temperature can be detected in thermal images by using simple inspection or recognition programs due to the particular characteristics of the ear channel exit: it is small, rounded and with a high temperature, higher than the temperature at the forehead. Examples of images taken for this purpose are shown in **Figure 43** and **Figure 44**.

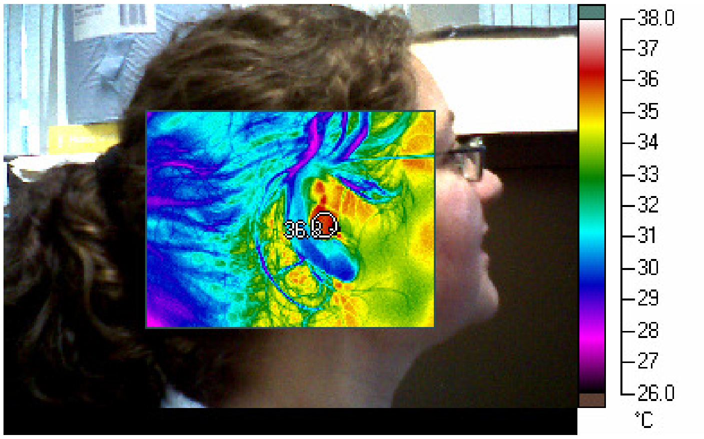


Figure 43: Thermal image taken with a camera Fluke TiR1

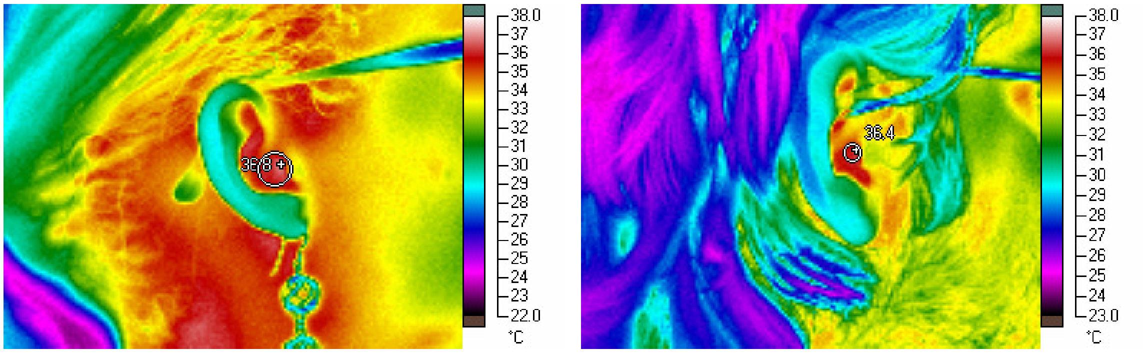


Figure 44: Examples of thermal images of ears

In this study, core temperature measurements were taken by using the classical auditory channel temperature and our novel non-intrusive method for correlations and comparisons. The objective was to prove that core temperature could be estimated by using non-intrusive methods such as the one proposed.

6.2.1.1 Scope

A total of 134 measurement sessions where undertaken on 25 healthy and self-clothed adults, at room temperatures ranged between 19.5ºC and 29.3ºC. All the volunteers were adapted to the room temperature and performing sedentary activities, keeping their metabolic rate low. Test protocol indicated in Chapter 2 was followed.

6.2.2 Data analysis

Each of the ear thermal images was individually processed to identify the exit of the ear channel and its temperature. Two descriptors were used to characterize this temperature, (i) the maximum temperature value in the ear area – T_{max} – and, (ii) the average temperature in a small circular area around the maximum value – $T_{average}$ –.

Correlation values between the core temperature measured by the classical method –T_c– and the extracted temperatures – T_{max} and $T_{average}$ – were obtained. The deviation of both T_{max} and $T_{average}$ with respect to T_c is studied. Linear regressions are derived and its accuracy studied for the estimation of core temperature based on the values extracted from the IR images and the room temperature. These multilinear regressions are obtained using a bootstrap technique, detailed in section 5.2.2, and later compared using the Akaike's Information Criteria, previously reported in section 6.1.2.4, in order to identify the optimal model.

6.2.3 Results

Correlation between T_c, T_{max}, $T_{average}$ and T_{room} and other derived parameters was obtained (**Appendix P Table P1**). The correlation of T_c and T_{room} with T_{max} and $T_{average}$ is observed to be significantly higher than the correlation between T_{room} and T_c. The two extracted temperatures from the IR images – $T_{average}$ and T_{max} – are highly related, although with a $R^2 = 0.82$. However, the dispersion from T_{room} of those two parameters correlate almost perfectly, with a $R^2 = 0.99$. No statistically significant correlation is observed between T_c and either "T_{max} - T_{room}" or "$T_{average}$ - T_{room}". A comparison with previous results of our research shows that the correlation values of T_c with T_{max} and $T_{average}$ are similar to the correlation with forehead temperature. The distribution of deviation values between the T_c and both $T_{average}$ and T_{max} are presented in **Figure 45** and **Figure 46** respectively.

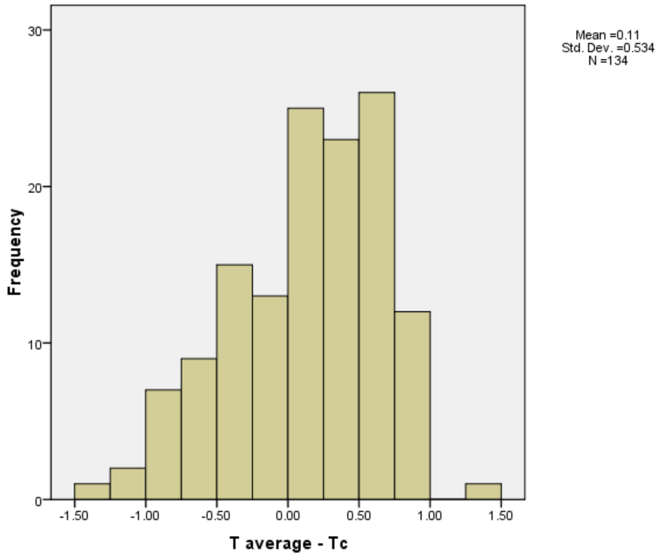


Figure 45: Frequencies of deviation between T_c and $T_{average}$

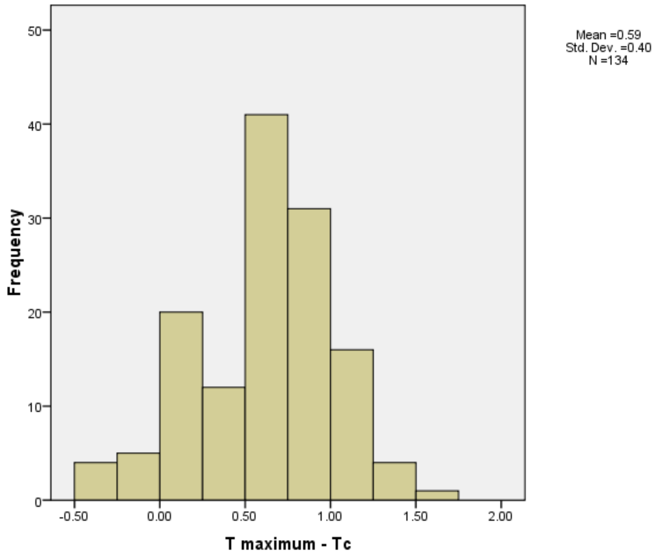


Figure 46: Frequencies of deviation between T_c and T_{max}

The nature of the relationship between T_c and both $T_{average}$ and T_{max} was studied. Scatter diagrams are presented as *graph of averages*. Several levels were identified and characterized as shown in **Figure 47** and **Figure 48**. Linear regressions are included in the figures.

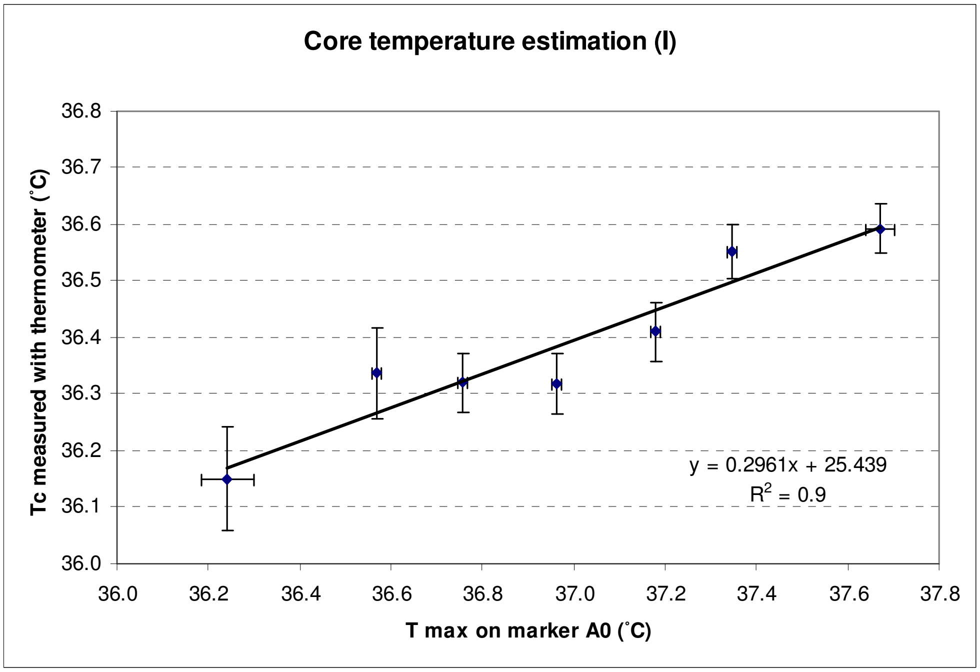


Figure 47: Relation between core temperature and ear channel temperature for adults (maximum temperature detected by the IR imager).

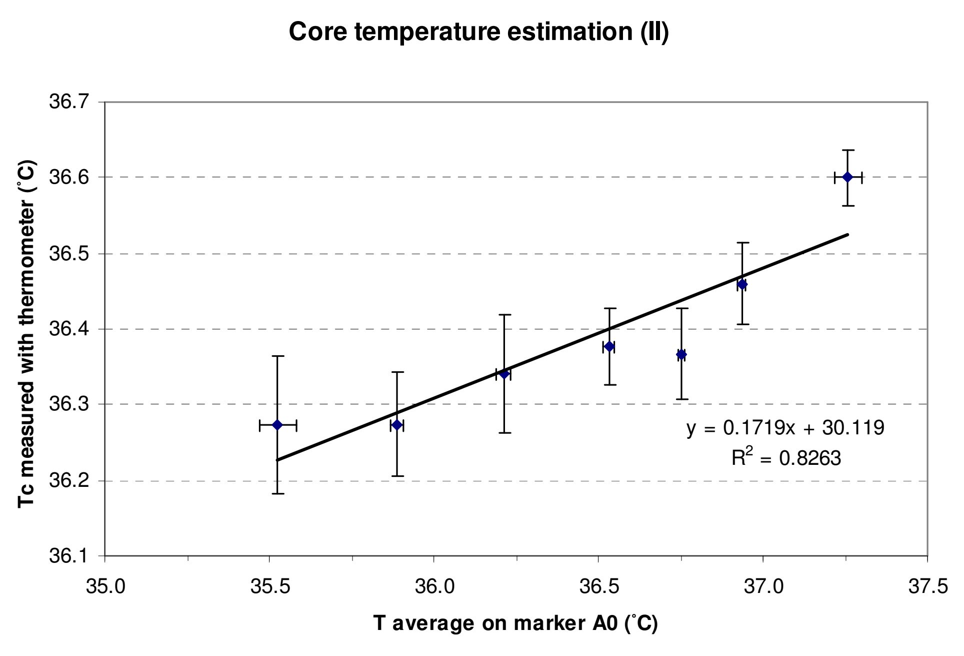


Figure 48: Relation between core temperature and ear channel temperature for adults (average temperature detected by the IR imager in a circular area around the ear).

The parameters that correlate better with the T_c are, in order, T_{max}, $T_{average}$ and T_{room} (**Table P1**). According to that, several multi-linear regressions were derived using the bootstrap technique introduced in 5.2.2. All combinations of 1, 2 and 3 of these parameters were used. Results are presented in **Appendix P Table P2**. Models where parameters are only $T_{average}$, T_{room} and the combination of both were withdrawn as they are not within the confidence set. The rest of the models were combined into the form of equation **49** using the Akaike's technique such that the new weight averaged coefficients and standard errors were obtained. Results are enclosed in **Table 31** along with confidence intervals.

$$T_c = b_0 + b_1.T_{\max} + b_2.T_{avg} + b_3.T_{room} \qquad \textbf{(49)}$$

Model coefficients	Estimate	SE	Lower CI	Upper CI
b_0	25.68	2.13	22.18	29.18
b_1	0.354	0.122	0.154	0.554
b_2	-0.127	0.116	-0.317	0.063
b_3	0.0091	0.0119	-0.0105	0.0286

Table 31: Coefficients for the core temperature predictive model based on IR images of ears.

6.2.4 Discussion

Extracted parameters from infrared images – $T_{average}$ and T_{max} – appear to correlate with the core temperature to a similar extent as the forehead temperature, as shown in **Table P1**. Their deviation from the core temperature, that is "$T_{average}$-Tc" and "T_{max}-Tc", were studied and presented in **Figure 45** and **Figure 46** respectively. Mean values happen to be positive, which indicates that in most of the cases the value of Tc is under the temperature observed by the IR camera. This might be related with the T_{room} values, which correlates significantly with both $T_{average}$ and T_{max}.

Individual linear regressions of T_c with $T_{average}$ and T_{max} were derived through *graphs of averages* (see **Figure 47** and **Figure 48**). However, the inclusion in the model of several parameters is more effective as seen in **Table P2**. Regarding the R-values the model with better performance seems to be the one including $T_{average}$, T_{max} and T_{room}. Regarding the Akaike weights, which takes into account not just the standard error estimate but also the number of parameters, the model with only T_{max} has the better performance, closely followed by the model with $T_{average}$ and T_{max} and the model with $T_{average}$, T_{max} and T_{room}. The models within the confidence set were combined by weighted averaged and the optimal model derived (equation **49**). The corresponding coefficients are presented in **Table 31**. The use of the three parameters could be argued, as the R-value is similar than when using T_{max} only, and AIC-values are worst.

However, the use of three parameters was selected as their measurement does not require more equipment or time, and provides a more stable model.

The estimation of core temperature based in any of the models studied in this section has limitations. Direct observation of the ear channel is needed. The existence of hair in front of the ear channel results in wrong readings of temperature due to its insulative properties, as was explained in section 2.5.3.2.

6.3 Conclusion

The core temperature is the most meaningful parameter for human temperature assessment. It provides information both about the general health and thermal comfort of the person. The occurrence of fever is likely to indicate infection and so its detection could spare other people from getting infected. Hence, the identification of the core temperature of any person, no just during their visits to the doctor but in the everyday life, at any time and place, is of great interest.

Ideally core temperature should be estimated in a non-intrusive way in non-clinical applications, especially in mass fever screen systems. A system of a kind should assess the core temperature without either disturb the subject or made him aware-of during the temperature monitoring. This chapter presented two novel non-intrusive methods for the estimation of core temperature, based on skin temperature and inner ear temperature measurements. A system based in any of those methods could be used in public places (e.g. cinemas, theatres, planes, buses, cars or offices) provided that the measurement device can be placed facing the side or front of the head of the person to be monitored. Furthermore, with some techniques of face or body recognition, these methods could be also suitable for standing people.

The first system is based on the relation between core and local skin temperature. Unfortunately this relation is limited to a certain range of local skin temperatures while null otherwise, showing a bilinear trend, and so several constrains on the T_{skin} values apply. Several degrees of relaxation of these constrains were studied, for what we introduced a parameter denoted *relax factor*. This factor indicates how many exceptions to these local skin temperature constrains can be permitted such that the core temperature model is still applicable. Several models were obtained with different combinations of locations and *relax factors*. Akaike's weights, accuracy and efficiency (defined as R^2 times the percentage of cases to which the model applies) were assessed. Finally a prediction model based on T_{room}, H_{room}, *T0* and *T7* and with null relax factor was recommended. Among the studied locations forehead (*T0*) was observed to be a good option. Its temperature can be measured in a non intrusive way, provided the area is exposed, and proved to be one of the best indicators of core temperature. *T7* represents hands temperature and could be obtained by placing a temperature sensor in the hand rest.

The second system is based on the relation between core temperature and that measured at the ear aperture with an infrared camera, reflecting the inner ear temperature. T_{max} and $T_{average}$ were extracted from the images and related with core temperature. A multilinear regression using T_{max}, $T_{average}$ and T_{room} was proposed for the prediction of core temperature. This was obtained by combining the models, generated by bootstrap technique that fall within the model confidence set, using the Akaike's weighted average. Among these parameters, T_{max} was observed to be the best indicator for core temperature.

The characteristic standard estimated error is about 0.3°C for each of the proposed models. This is due to the great variability in human thermoregulatory response even under the same environmental and personal conditions. Hence, these methods are not recommended for medical assessments but are still valid in everyday body temperature monitoring and mass fever screen.

As a further step in the non-intrusive monitoring of body temperature, both systems could be combined to obtain a more accurate prediction of core temperature. This would be a possibility to overcome their individual limitations. No figures of the increase in the performance are presented in this study, as unfortunately both experiments were run independently. A very interesting combination of factors would be T_{room}, H_{room}, T_{max}, $T_{average}$ and *T0*. The demanding physical system is not excessive as only monitoring of the temperature at the head are would be necessary.

7 Effect of long periods of inactivity on temperature, thermal sensation and comfort level in adults

The temperature of the body – skin and core - is known to get adapted to the environmental conditions at all times by the means of *thermoregulation*. Psychological parameters, such as thermal sensation and comfort level, also respond to the environment. This chapter investigates the evolution of both physiological and psychological parameters on a sedentary person while subjected to the same environmental conditions for long periods of time.

7.1 Study design

Core and local skin temperatures were studied in sedentary adults at several room temperatures following the protocol described in Chapter 2. The main aims were:

- To identify and model the change (if any) of core and local skin temperature with time for any given room temperature.
- To identify and model the change (if any) of comfort level and thermal sensation during long periods of inactivity for any given room temperature.

7.1.1 Scope

Data from a subgroup of the volunteers reported in Chapter 5 was selected for this study. The group consisted of a total of 106 healthy adults (52 male and 54 female) in their choice of clothing, who remained seated for periods of 165 to 195 minutes in a room of constant temperature (ranging from 20 to 30 ºC) and performed sedentary activities, keeping their metabolic rate in the range of 46 to 70 W/m^2. Volunteers were between 19 and 72 years old and had a BMI in the range of 14 to 43 kg/m^2. Group stratification is further described in **Appendix Q Table Q1**. Studied skin locations were given in **Figure 12.**

7.2 Data analysis

7.2.1 Evolution of temperature in time

Volunteers were divided into 9 cohorts in terms of the room temperature they were subjected to (see **Table Q2**). There were a minimum of 10 subjects per cohort. Averages of core and local skin temperature were obtained for each T_{room} category and time. The evolution in time of the averages (average temperature versus time) was observed.

7.2.2 Temperature change in time: effect of room temperature

Changes in the core temperature and skin temperature (*ΔTc* and *ΔTskin*) were obtained at each location with respect to their initial values (after 15 minutes, within the studied environmental conditions) (equation **50**). The time needed for that change is given by *Δt* (equation **51**). *s*, *i* and *j* indicate subject, location and time in minutes respectively.

$$\begin{aligned} \Delta Tc_{s,j} &= Tc_{s,j} - Tc_{s,15} \\ \Delta Tskin_{s,i,j} &= Tskin_{s,i,j} - Tskin_{s,i,15} \end{aligned} \qquad \textbf{(50)}$$

$$\Delta t_j = j - 15 \qquad \textbf{(51)}$$

Linear regressions for *ΔTc* and *ΔTskin$_i$* (left and right separately) versus Δt were derived for each subject as indicated in equation **52**. Intercept was assumed to be zero as the change in temperature is considered zero at the starting point, minute 15. Hence, a characteristic $m_{s,j}$ is obtained for each subject and location, representing the rate of temperature change in time.

$$\begin{aligned} \Delta Tc_{s,j} &= m_s.\Delta t_j \\ \Delta Tskin_{s,i,j} &= m_{s,i}.\Delta t_j \end{aligned} \qquad \textbf{(52)}$$

Correlations between $m_{s,j}$ values obtained for same location at left and right sides of the body were observed to decide if the body response was symmetrical. Dependency of those slopes on environmental temperature (T_{room}) was investigated: correlation values obtained, graph of averages vs. T_{room} given; and significance test performed. The test used in each case was chosen according to the characteristics of the distributions (normality and homogeneity of variances) as detailed in section 4.2.1.

7.2.3 Evolution of thermal sensation and comfort level in time

The evolution in time of both thermal sensation (*TS*) and comfort level (*CL*) were studied in a parallel analysis with the core and local skin temperatures. Volunteers were divided into the 9 cohorts defined earlier (see **Table Q2**). Changes in the thermal sensation and comfort level were computed with respect to their initial values as indicated in equations **53**. *s* and *j* indicate subject and time in minutes respectively.

$$\begin{aligned} \Delta TS_{s,j} &= TS_{s,j} - TS_{s,15} \\ \Delta CL_{s,j} &= CL_{s,j} - CL_{s,15} \end{aligned} \qquad \textbf{(53)}$$

Linear regressions were derived for ΔTS and ΔCL versus Δt (see equation **54**), and their rate of change for each given volunteer was characterized by the slope values (m_{TS} and m_{CL}). The correlation of these slopes with environmental conditions, individual factors, and the rates of change of core and local skin temperature were found. Statistical tests were used to corroborate dependency of m_{TS} and m_{CL} on room temperature.

$$\begin{aligned} \Delta TS_{s,j} &= m_{TS,s}.dt_j \\ \Delta CL_{s,i} &= m_{CL,s}.dt_j \end{aligned} \qquad \textbf{(54)}$$

7.2.4 Time correction factor

A time-factor needs to be added for the prediction of those parameters which vary with time, potentially core and local temperature, thermal sensation and comfort level. This time-factor might be dependent on environmental conditions (T_{room} and H_{room}) or individual characteristics (*age*, *BMI*, *gender* and *clothing*). Relevant factors are identified and an equation for each time-dependent parameter derived using the re-sampling bootstrap technique described in 5.2.2.

7.3 Results

7.3.1 Evolution of temperature in time

The time evolution of the average core and local skin temperatures were observed. Trend for the specific cases of abdomen and knees are presented for each T_{room} cohort in **Figure 49** as example. Trend for each location are presented in **Appendix Q Figure Q1**.

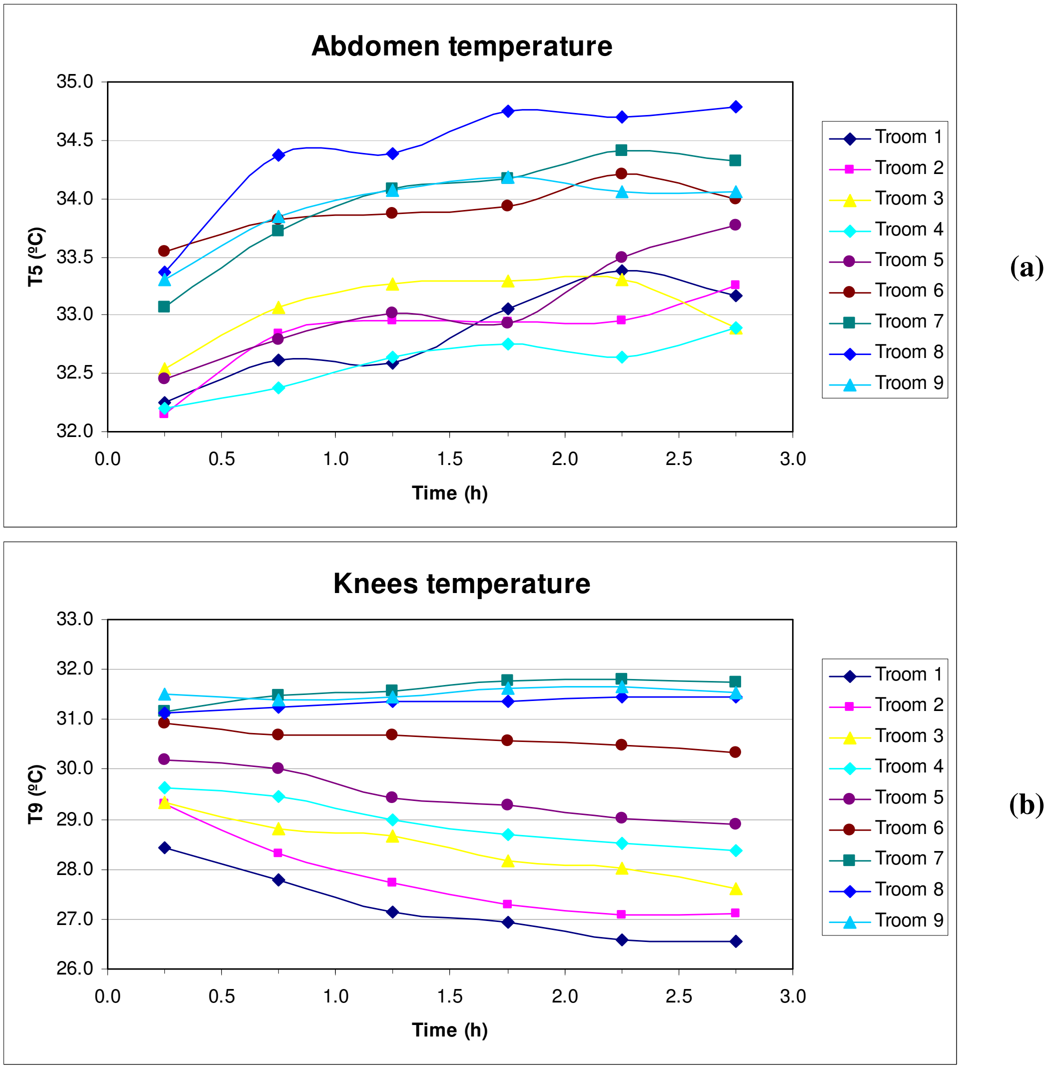


Figure 49: Core and local skin temperatures versus time in prolonged periods of inactivity for different T_{room} categories, defined according to **Table Q2**.

7.3.2 Temperature change in time: effect of room temperature

Average change of core and skin temperature (ΔT) were derived for each location, time and T_{room} category (defined in **Table Q2**) and represented versus Δt. **Figure 50** presents the cases of T_{room} *1* (mean = 19.9ºC, SD=0.2ºC) and T_{room} *8* (mean= 27.2ºC, SD=0.3ºC).

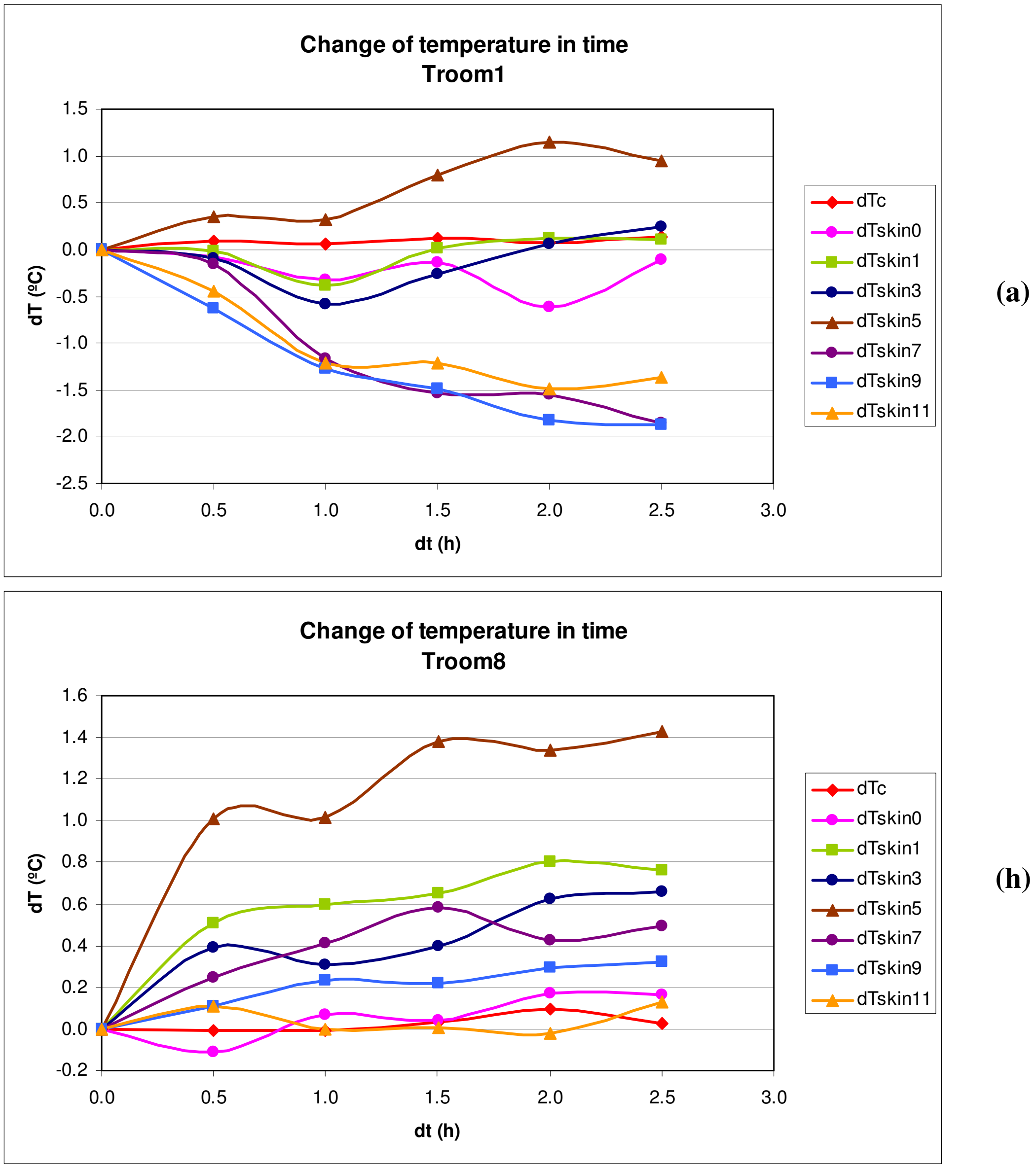
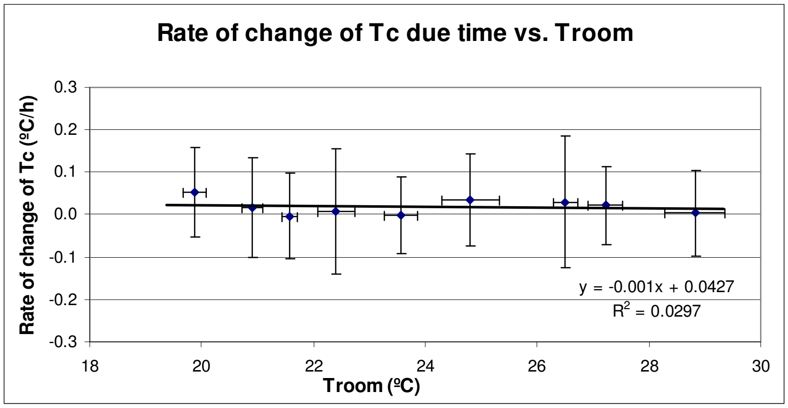


Figure 50: Variation of core temperature and local skin temperatures in prolonged periods of inactivity. Same graphs but presented by location are given in **appendix Q3**. Indices for skin temperature in the legend stand for forehead (0), upper chest (1), upper arm (3), abdomen (5), hand (7), knee (9) and shin (11).

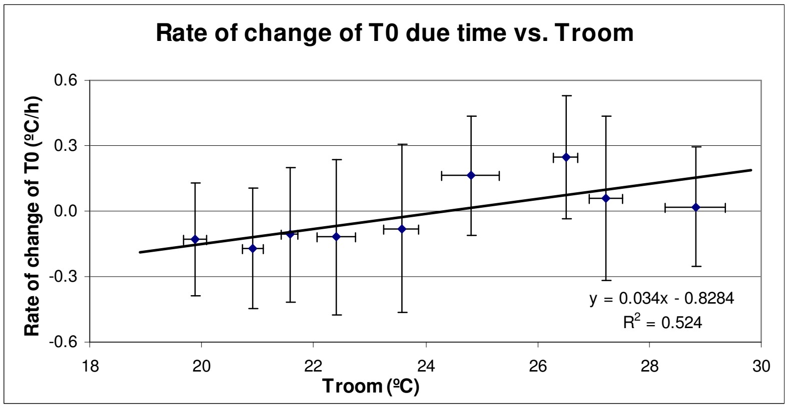
For each subject ΔTc and $\Delta Tskin$ were derived and their relation with Δt assumed to be approximately linear. Characteristic slopes m_i – rate of temperature change in time – were computed for each person and location. High correlation between measurements at left and right side of the same location was found as expected. Hence, measurements at left and right side were grouped and analyzed together from here onwards.

Correlations between environmental conditions (T_{room} and H_{room}) and each of the slopes ($m_{s,i}$ and m_s) were obtained (**Table Q3**). The distributions for the slope values were observed to be normal in the majority of the cases. Equal variances were found in all cases but m_5, m_7 and m_9 according to the Levene test. In case of equal variance distributions were compared using ANOVA and robust tests of equality of means (Welch and Brown-Forsythe) otherwise. T_{room} proved to correlate significantly with each of the temperatures' slopes except for core temperature and abdomen temperature. Average m_i for each T_{room} category was obtained and presented versus the average environmental temperature (see **Figure 51**). Linear regressions and R-values are included in the graphs.

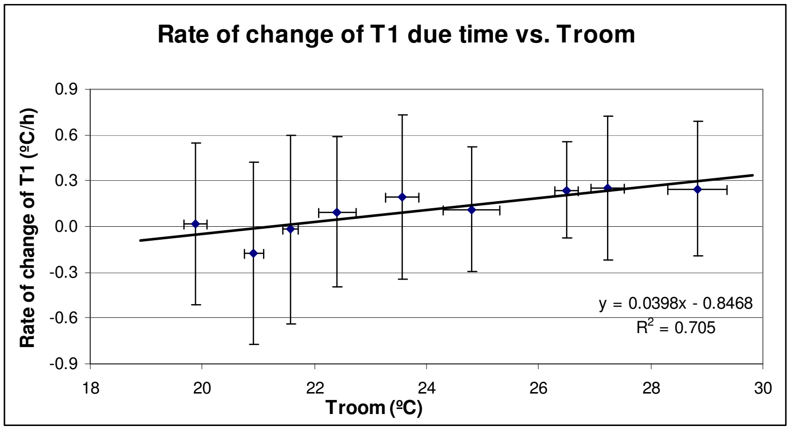
It is concluded that temperature at upper arm (*ΔT5*) and core temperature (*ΔTc*) does not change significantly with the room temperature. Parameters *ΔT0* and *ΔT3* show only a significant difference when the room temperature changes greatly. However, at similar room temperatures, especially between 20 and 25ºC, they seem to remain the same. The change in the local skin temperature varies significantly with the room temperature at locations *T1*, *T7*, *T9* and *T11*. Especially significant is the change on the hands and legs. Locations at the limbs, being further away from the core of the body, are more sensitive to the room temperature, holding the greatest exchange of heat with the environment.



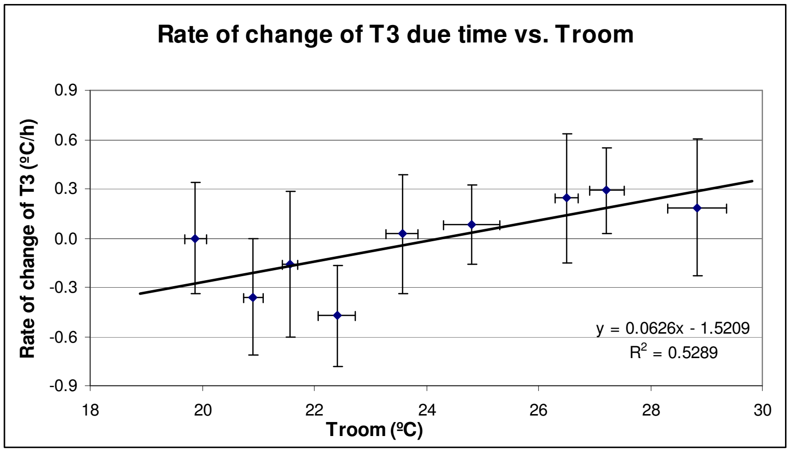
(a)



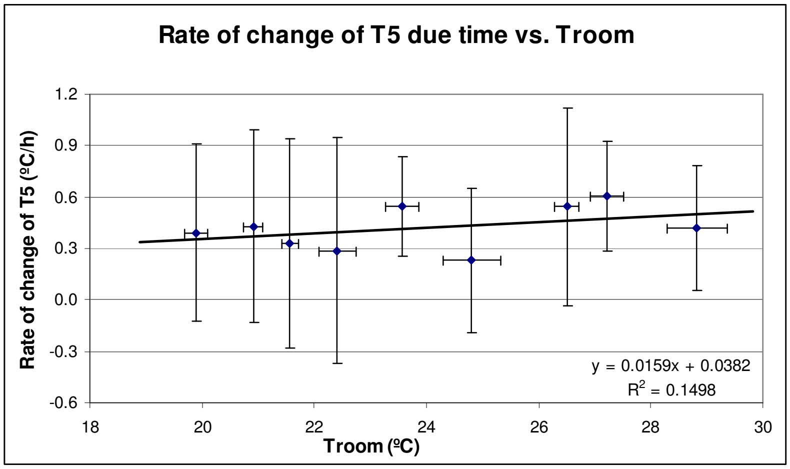
(b)


Rate of change of T1 due time vs. Troom
Rate of change of T1 (ºC/h)
0.9
0.6
0.3
0.0
-0.3
-0.6
-0.9
18
20
22
24
26
28
30
Troom (ºC)
y = 0.0398x - 0.8468
R² = 0.705

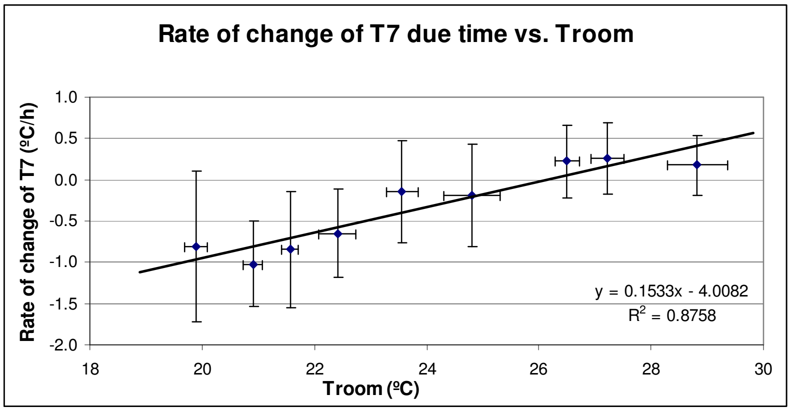
(c)


Rate of change of T3 due time vs. Troom
Rate of change of T3 (ºC/h)
0.9
0.6
0.3
0.0
-0.3
-0.6
-0.9
18
20
22
24
26
28
30
Troom (ºC)
y = 0.0626x - 1.5209
R² = 0.5289

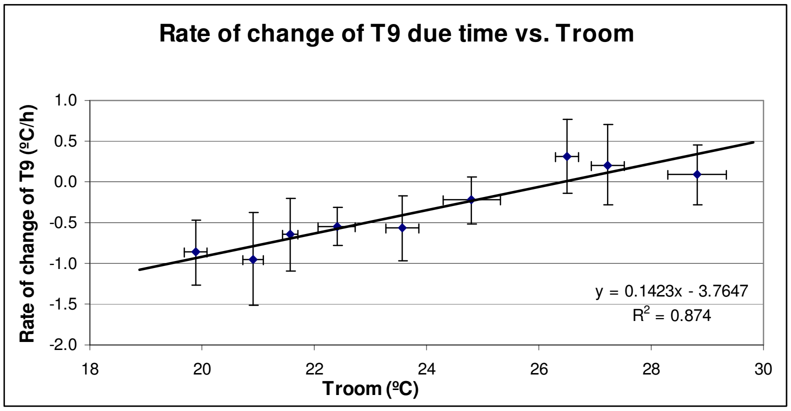
(d)


Rate of change of T5 due time vs. Troom
Rate of change of T5 (ºC/h)
1.2
0.9
0.6
0.3
0.0
-0.3
-0.6
18
20
22
24
26
28
30
Troom (ºC)
y = 0.0159x + 0.0382
R² = 0.1498

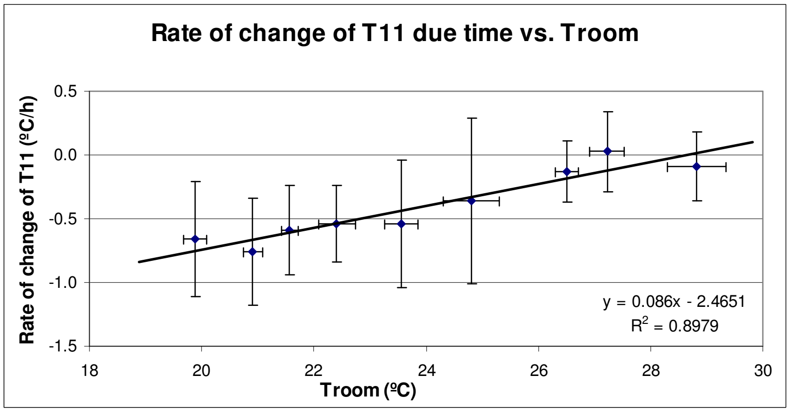
(e)


Rate of change of T7 due time vs. Troom
Rate of change of T7 (ºC/h)
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
18
20
22
24
26
28
30
Troom (ºC)
y = 0.1533x - 4.0082
R² = 0.8758

(f)



(g)

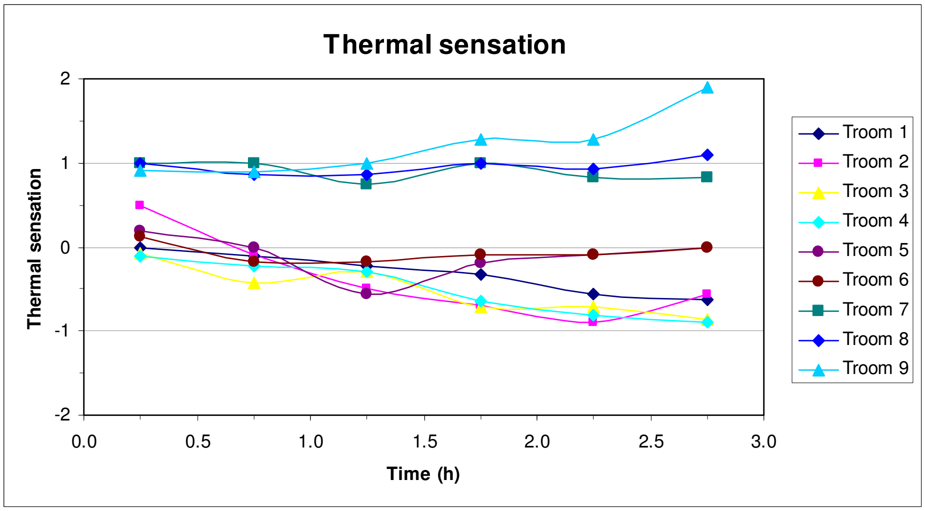


(h)

Figure 51: Change in time of core and local skin temperatures versus room temperature during prolonged periods of inactivity. Skin temperature indices stand for forehead (0), upper chest (1), upper arm (3), abdomen (5), hand (7), knee (9) and shin (11).

7.3.3 Evolution of thermal sensation and comfort level in time

The evolution in time of the average thermal sensation (*TS*) and comfort level (*CL*) are presented for each T_{room} cohort in **Figure 52**. Average change was derived for each of these parameters, *time* and T_{room} category and represented versus Δt (**Figure 53**).



(a)

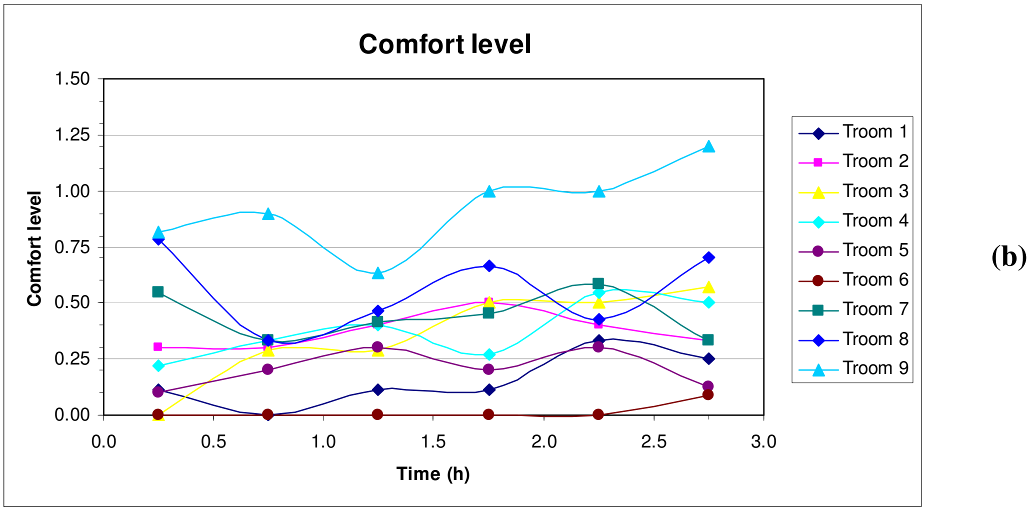


Figure 52: Thermal sensation and comfort level versus time during prolonged periods of inactivity at different T_{room} categories, defined according to **Table Q2**

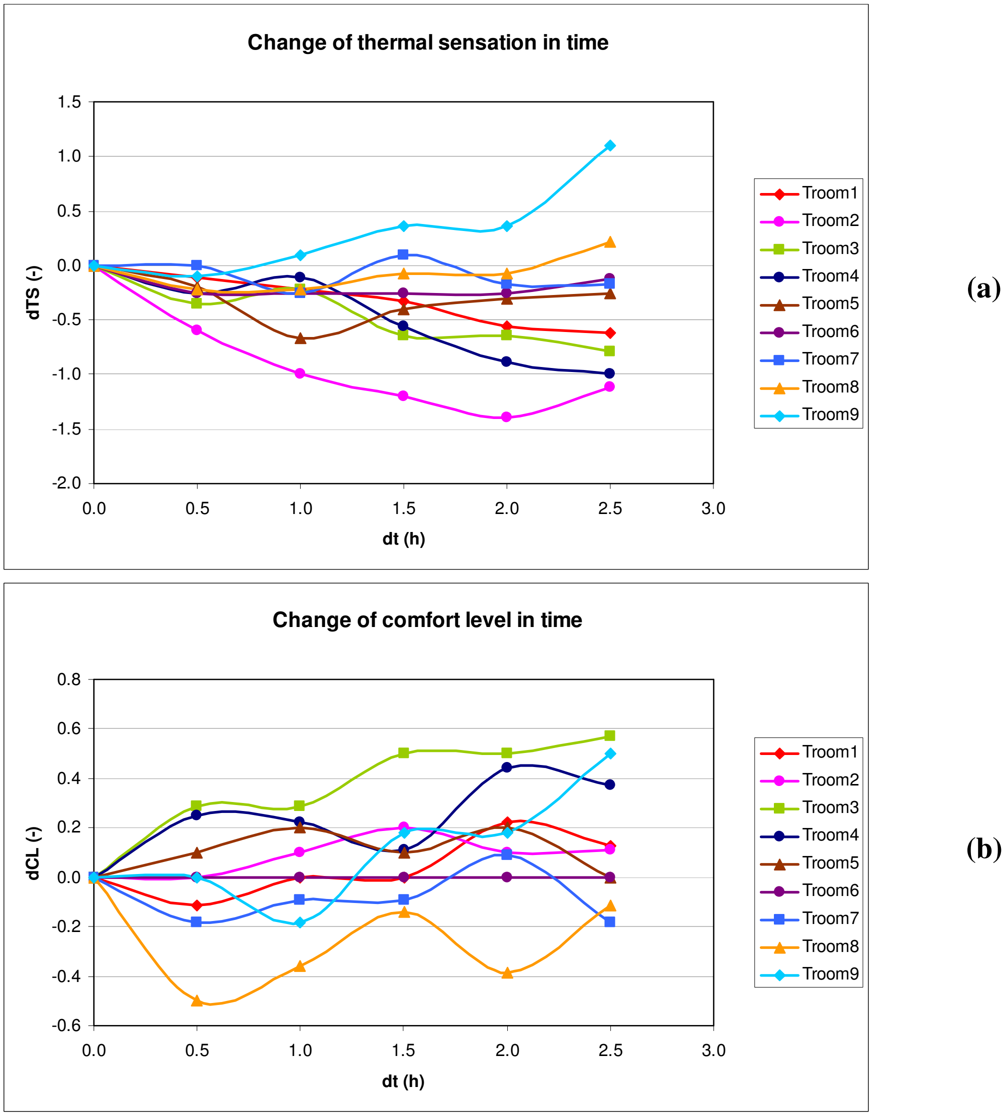


Figure 53: Thermal sensation and comfort level vs. time during prolonged periods of inactivity

Furthermore, *TS* and *CL* curves with respect to T_{room} were observed at the beginning (*t=15* and *t=45 min*) and at the end (*t=135* and *t=165 min*) of the session (see **Figure 54**). Z-test indicates that *TS* presents significant differences at low (*G1-G4*) and high (*G9*) room temperatures. *CL* was observed to be significantly different only at *G3*.

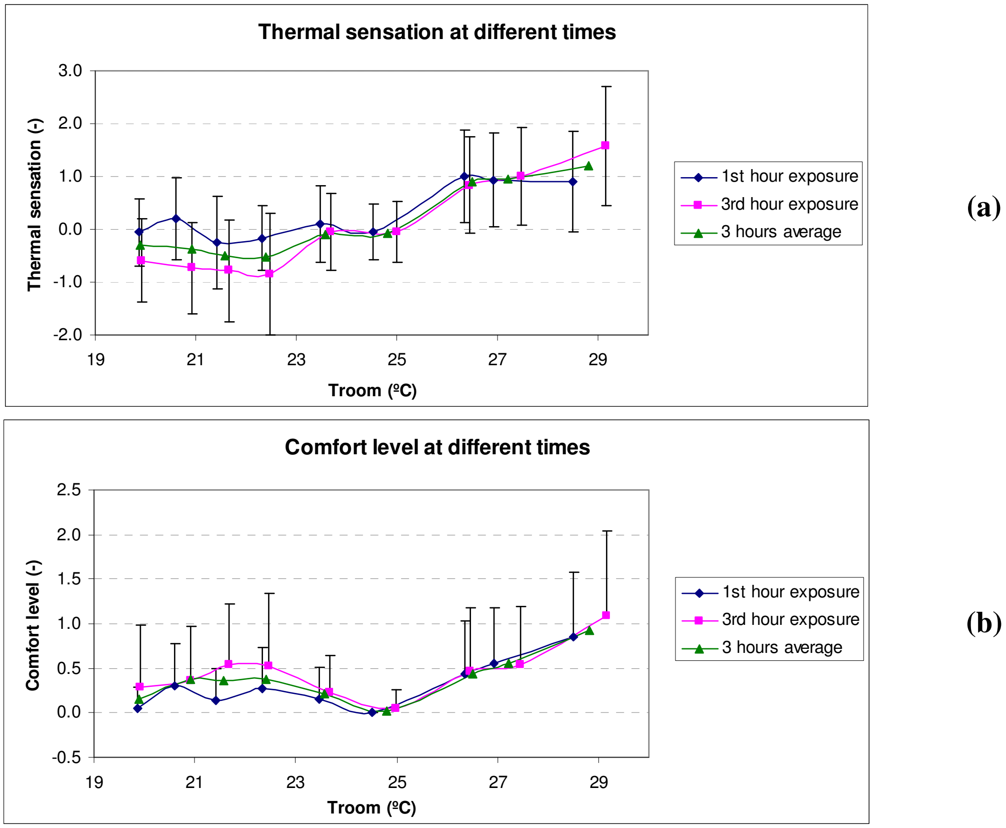


Figure 54: Thermal sensation and comfort level curves at the beginning and end of a prolonged period of inactivity; and average

Following the same procedure than with core and skin temperature, linear regressions of ΔTS and ΔCL versus Δt were derived for each volunteer (see equation **54**) and slopes m_{TS} and m_{CL} obtained. The correlations of those slopes with environmental conditions and individual factors were found (**Table Q3**).

Rate of change of thermal sensation (m_{TS}) seems to correlate with the room temperature (see **Figure 55**). Also, the rate of change of comfort level (m_{CL}) appears to be highly correlated with the room temperature, but not linearly. Statistical tests were used to investigate dependency of m_{TS} and m_{CL} in room temperature. m_{TS} was found to be dependent on T_{room} within the studied range. m_{CL} appears to be independent on T_{room}, but this is perhaps due to its sinusoidal shape. When investigated at each of the cohorts, it seems to be dependent on T_{room} at high room temperatures.

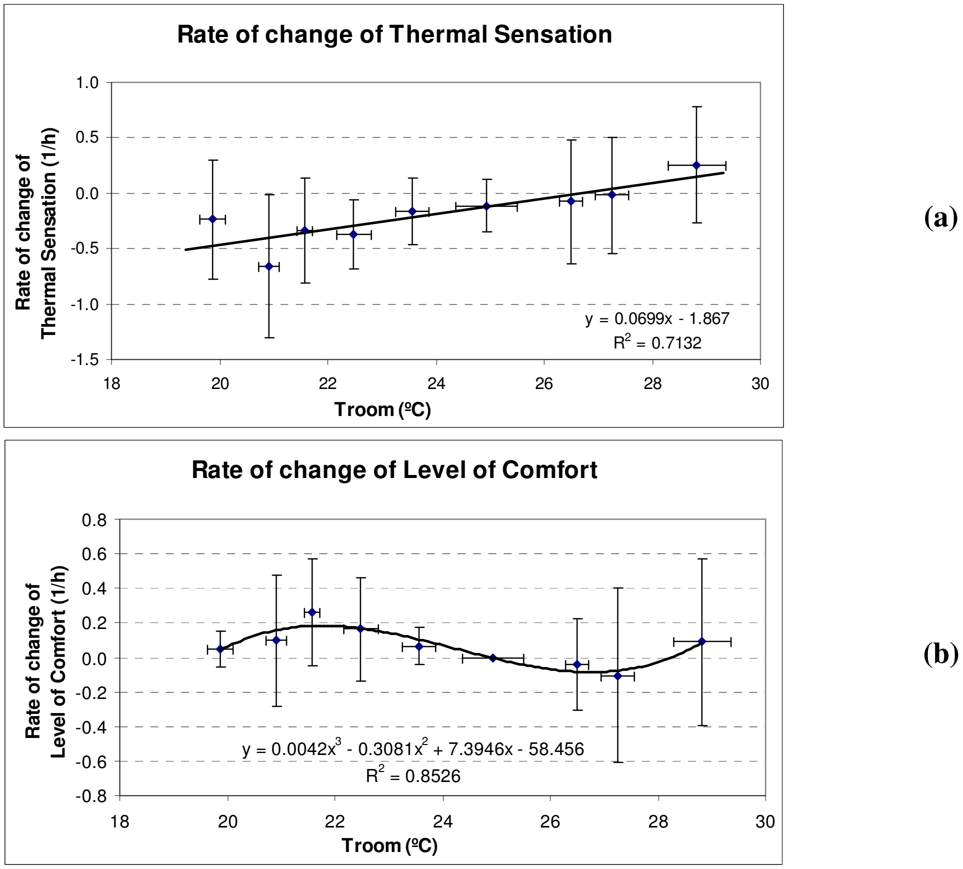


Figure 55: Change in time of thermal sensation and comfort level versus room temperature during prolonged periods of inactivity

7.3.4 Time correction factor

Core and skin temperature proved to vary with the time a person remains in a seated position. Dependences of *ΔTskin/Δt* and *ΔTc/Δt* on environmental conditions (T_{room} and H_{room}), *age*, *BMI*, *gender* and clothing (*Loc3C*, *Loc9C* and *Loc11C*) were studied. Parameters for clothing indicate weather the respectively locations 3, 9 and 11 are covered rather than exposed. Correlation values are given in **Table Q3**. Significant parameters were identified using 0.01 level in a two-tailed test, and marked in bold letters. The apparent correlation between *ΔT1/Δt* and *Loc9C* was discarded, as they refer to different skin locations. Multi-linear equations for the prediction of the correction factor of each temperature were derived including only the relevant parameters found earlier (equation **55**). Coefficients for the obtained equations are given in **Table 32**.

$$\Delta T_i / \Delta t = a_i + b_i.T_{room} + c_i.H_{room} + d_i.T_c + e_i.Age + f_i.BMI + g_i.Gender + h_i.N_{layers} \qquad \textbf{(55)}$$

$a_i, b_i, c_i, d_i, e_i, f_i, g_i$ *and* h_i are constants and their value depends on the location

i accounts for location.

a_i *and* g_i are in ºC/h

b_i *and* d_i are in h^{-1} and T_{room} and T_c must be given in ºC

c_i is in ºC/%.h

e_i is in ºC/years.h

f_i is in ºC/(h.Kg/m^2)

h_i is in ºC/h.(nº of layers)

gender was coded as 1 and 2 for male and female volunteers respectively

	a	b	c	d	f	g	R
m_c	0.018 (0.011)	-	-	-	-	-	0.000
m_0	-0.482 (0.311)	0.028 (0.011)	-	-	-	-0.133 (0.067)	0.352
m_1	-1.162 (0.248)	0.034 (0.090)	-	-	0.018 (0.007)	-	0.377
m_3	-1.806 (0.343)	0.056 (0.012)	-	-	0.019 (0.008)	-	0.356
m_5	-0.301 (0.221)	-	-	-	0.038 (0.007)	-0.147 (0.066)	0.387
m_7	-2.176 (5.880)	0.157 (0.016)	-	-0.053 (0.164)	-	-	0.606
m_9	-7.732 (3.261)	0.134 (0.011)	-0.008 (0.003)	0.124 (0.090)	-	-	0.701
m_{11}	-2.107 (0.300)	0.074 (0.009)	-	-	0.010 (0.007)	-0.201 (0.060)	0.572

Table 32: Coefficients for the multi-linear regressions computing the time-factors (m_i) of core and local skin temperatures, which is *ΔTskin/Δt* and *ΔTc/Δt*.

Following the same procedure, relevant factors for the correction factor of thermal sensation and comfort level (m_{TS} and m_{CL}) were obtained (see **Table Q3**) and multi-linear regressions derived in the form of equations **56**. Alternatively, a second model for m_{CL} was derived using 3rd order dependency on T_{room} (equation **57**), based in the earlier found regression in **Figure 55-b**. Obtained models are reported in **Table 33**.

$$\Delta i / \Delta t = a_i + b_i.T_{room} + c_i.H_{room} + d_i.T_c + e_i.Age + f_i.BMI + g_i.Gender + h_i.N_{layers} + k_i.Weight \tag{56}$$

$a_i, b_i, c_i, d_i, e_i, f_i, g_i$ *and* h_i are constants, being *i = TS* or *i = CL*

a_i *and* g_i are in h^{-1}

b_i *and* d_i are in (h.ºC)$^{-1}$ and T_{room} and T_c must be given in ºC

c_i is in (%.h)$^{-1}$

e_i is in (years.h)$^{-1}$

f_i is in (h.Kg/m^2)$^{-1}$

h_i is in (h.(nº of layers))$^{-1}$

gender was coded as 1 and 2 for male and female volunteers respectively

$$\Delta i / \Delta t = a_i + b_{i,3}.T_{room}{}^3 + b_{i,2}.T_{room}{}^2 + b_{i,1}.T_{room} + c_i.H_{room} + d_i.T_c + e_i.Age + f_i.BMI + g_i.Gender + h_i.N_{layers} \tag{57}$$

being *j=1, 2* and *3* depending of the order of the T_{room} factor.

	a	b	c	d	f	g	h	k	R
m_{TS} (eq 56)	-1.85 (0.45)	0.069 (0.018)	-	-	-	-	-	-	0.393
m_{CL} (eq 56)	0.14 (0.16)	-	-0.008 (0.003)	-	-	0.184 (0.064)	-		0.377
m_{CL} (eq 57)	-19.7 (8.4)	j=1) 2.5 (1.0) j=2) -0.106(0.043) j=3) 1.44E-3 (5.9E-4)	-0.010 (0.003)	-	-	0.141 (0.058)	-	-	0.473

Table 33: Coefficients for the multi-linear regressions computing the time-factors (m_i) of thermal sensation and comfort level.

7.4 Discussion

7.4.1 Temperature evolution in time

The evolution curves of core and skin temperature in time were characterized. The width of the possible range of temperatures at the initial and final part of the measurement session - *minute 15* and *165* – along with the variation of the minimum and maximum values were extracted (see **Table 34**). Correlations of the m_i values with environmental temperature were classified as low for *Tc* and *T5*; medium for *T0*, *T1* and *T3*; and highly relevant for *T7*, *T9* and *T11*.

Variable	Range width (t=15) (ºC)	Range width (t=165) (ºC)	$\frac{Range(t=165)}{Range(t=15)}$	Δmin (ºC)	Δmax (ºC)
Tc	0.45	0.47	1.05	0.051	0.073
T0	1.40	1.68	1.20	-0.109	0.173
T1	0.92	1.85	2.01	-0.400	0.530
T3	1.91	2.91	1.52	-0.489	0.511
T5	1.40	1.90	1.36	0.744	1.246
T7	2.46	4.81	1.95	-2.081	0.264
T9	3.09	5.18	1.68	-1.868	0.229
T11	0.98	2.42	2.48	-1.368	0.078

Table 34: Characterization of the core and skin temperature vs. time curves

Core temperature (T_c) oscillated while increasing slightly with time for any given T_{room} category (see **Figure Q1-a** and **Q2**). Only at the highest room temperature studied - T_{room} = *28.82 (0.53)ºC* – the core temperature decreases for about 1.5 hours and then it increases. Similar results were obtained by Huizenga et al. [Huizenga, 2004]. Under neutral conditions, subjects' core temperature was very stable, fluctuating within 0.1 ºC. They observed that in warm conditions (31.5ºC) T_c slightly decreases (>0.1 ºC), while in cold conditions (15.6 ºC) it slightly increases (0.15 ºC). **Table 34** showed that although the possible range width of T_c appears to be independent of the exposure time, with a rate between final and initial values of 1.05, both minimum and maximum values increase slightly in time. The rate of change of T_c (m_c) was obtained and presented versus T_{room} (**Figure 51-a**). Statistical analysis showed that it has no significant dependency on environmental conditions – T_{room} and H_{room} – (although T_c does), any of the skin temperature rates of change (m_i) or any of the characteristics of the volunteers – *age*, *BMI*, *gender*, and so on – (see **Table Q3**). The non dependency of m_c in T_{room} was further corroborated with the statistical tests. For room temperatures raging 20-30ºC, **Figure 51-a** shows that m_c ranges between 0.00 and 0.05ºC/h on average. Multi-linear regression established that m_c should be accounted as shown below (see **Table 32**).

$$m_c = 0.018\ (0.011) \quad (ºC/h) \tag{58}$$

Skin temperature at the forehead (*T0*) is one of the most stable temperatures with respect to time, along with *T1* and *T3* with regards to the absolute temperature change (see **Figure Q1-b** and **Q2**). **Table 34** showed that the range width of temperature values increases only slightly, with a decrease of 0.1ºC of the minimum and an increase of 0.2ºC of the maximum, being the rate between final and initial width of ranges about 1.2. Still, this local skin temperature oscillates for most of the T_{room} categories. Interesting behaviour occurs at T_{room} *categories 3 and 6*. At T_{room} *3* - 21.57(0.14)ºC -, the skin temperature remains constant throughout the 3 hours, indicating that it is at equilibrium. At T_{room} *6* - 28.81(0.51)ºC -, skin temperature increases reaching a stable value, indicating that heat dissipation is being forced without reaching the onset of sweating, which would lower the skin temperature. The rate of change of *T0* (*m0*) was obtained and presented versus T_{room} (**Figure 51-b**). Statistical analysis showed that it has a significant dependency on environmental temperature – T_{room} – but not the humidity - H_{room} –; it correlates mildly with *m1*, *m3*, *m7*, *m9* and *m11* - p-values between 0.243 and 0.326 – but not m_5 or m_c; and it depends on the gender of the volunteers (see **Table Q3**). The dependency of m_0 on T_{room} was corroborated with statistical tests, although it changes slowly with the T_{room}. For room temperatures between 20 and 30ºC, **Figure 51-b** shows that m_0 ranges between -0.2 and 0.2ºC/h, crossing zero at about T_{room}= *24.4ºC*. Multi-linear regression established that m_0 should be accounted as equation **59** (see **Table 32**), that is, in the range of -0.05 and 0.23ºC/h for males and -0.19 and 0.09ºC/h for females.

$$m_0 = \Delta T0/\Delta t = -0.482 + 0.028.T_{room} - 0.133.Gender \quad (ºC/h) \tag{59}$$

Skin temperature at the upper chest (*T1*) oscillates for all T_{room} categories but is still, along with *T0* and *T3*, one of the most stable temperature with respect to time when the absolute temperature change is considered (see **Figure Q1-c** and **Q2**). The change in time of *T1* appears to be negative only at T_{room}*<21.2ºC*. T1 increases by up to 0.5ºC during the exposure, if $21.2ºC<T_{room}<26.9ºC$. The increase is greater (0.7-0.8ºC) for warmer environments. However, in relative terms, **Table 34** showed that the range width of temperature values increases significantly, with the final range width being double the initial ones. The minimum decreased by 0.4ºC and the maximum increased by 0.5ºC. The rate of change of *T1* (m_1) was obtained and presented versus T_{room} (**Figure 51-c**). Statistical analysis showed that it has significant dependency on environmental temperature – T_{room} – but not on the humidity - H_{room} –; it correlates with all the m_i, especially with m_3 - p=0.491 -; and it depends on the *BMI* (see **Table Q3**). It also depends on the volunteers clothing on their knees; this was neglected as probably due to the cross correlation of both parameters with T_{room}. The dependency of m_0 on T_{room} was corroborated with statistical tests. For room temperatures between 20 and 30ºC, **Figure 51-c** shows that m_1 ranges between -0.18 and 0.25ºC/h, crossing zero at about $T_{room}= 21.3ºC$. Multi-linear regression established that m_1 should be accounted as equation **60** (see **Table 32**), that is, in the range of -0.04 and 0.30ºC/h for a normal person of $BMI= 24.5\ W/m^2$.

$$m_1 = \Delta T1/\Delta t = -1.162 + 0.034.T_{room} + 0.018.BMI \quad (ºC/h) \qquad \textbf{(60)}$$

Skin temperature at the upper arm (*T3*) oscillates for all T_{room} categories but still is, along with *T0* and *T3*, one of the most stable temperature with respect to time when regarding the absolute temperature change (see **Figure Q1-d** and **Q2**). Upper arm appears to have three ranges in which the temperatures could oscillate. At low room temperatures ($T_{room}<23.0ºC$), *T5* oscillates between 31.5 and 32.5ºC and with a net change always negative and up to 1ºC. At medium T_{room} ($23.0<T_{room}<26.0ºC$) the values oscillate between 33.2ºC and 33.8ºC, with alternatively positive and negative net change up to 0.3ºC difference from the initial value. At higher T_{room} ($T_{room}>26.0ºC$), *T3* increases slowly without much oscillation from 33.7 to 34.4ºC. In relative terms, **Table 34** showed that the range width of temperature values increases, the rate between final and initial width of ranges is about 1.5. The minimum decreased by 0.5ºC and the maximum increased by 0.5ºC. The rate of change of *T3* (m_3) was obtained and presented versus T_{room} (**Figure 51-d**). Statistical analysis showed that it has significant dependency on environmental temperature but not on the humidity; it correlates with all the m_i, especially with m_1 and m_7 - p=0.491 and 0.402 respectively -; and it depends on the *BMI* (see **Table Q3**). The dependency of m_3 on T_{room} was corroborated with statistical tests, although the change with T_{room} is slow. For room temperatures between 20 and 30ºC, **Figure 51-d** shows that m_3 ranges between -0.47 and 0.29ºC/h, crossing zero at about $T_{room}= 24.4ºC$. Multi-linear regression established that m_3 should be accounted as equation **61** (see **Table 32**), that is, in the range of -0.22 and 0.34ºC/h for a normal person of $BMI= 24.5\ W/m^2$.

$$m_3 = \Delta T3/\Delta t = -1.806 + 0.056.T_{room} + 0.019.BMI \quad (ºC/h) \tag{61}$$

Skin temperature at the abdomen ($T5$) increased for all T_{room} *categories*, although more significantly at higher T_{room} (see **Figure Q1-e** and **Q2**). **Table 34** showed that minimum and maximum values increased by about 0.7 and 1.2ºC respectively, with a rate of 1.36 between final and initial width of ranges. $T_{room}4$ showed the lowest values for skin temperature at the abdomen. This happens as a consequence of the subjects wearing less clothing than at colder T_{room} categories. Hence, besides the subjects feeling warmer, and so willing to wear less clothing, their abdomen temperature is lower. On the other hand, $T_{room}9$ does not present the largest $T5$, even although the clothing is similar to the one at $T_{room}8$. This might be due to the onset of sweating, by means of the thermoregulatory system to lower the temperature. The rate of change of $T5$ (m_5) was obtained and presented versus T_{room} (**Figure 51-e**). Statistical analysis showed that it has no significant dependency on the environmental conditions – T_{room} and H_{room} –, it correlates mildly with m_1, m_3 and m_{11} - p-values between 0.230 and 0.259 -; and it depends on the *BMI* and *gender* of the volunteers (see **Table Q3**). The non dependency of m_5 on T_{room} was corroborated with statistical tests. For room temperatures ranging 20-30ºC, **Figure 51-e** shows m_5 to be between 0.2 and 0.6ºC/h, hence always positive. Multi-linear regression established that m_5 should be accounted as equation **62** (see **Table 32**), that is about 0.48ºC/h for males and 0.34ºC/h for females of normal complexion -$BMI=24.5\ W/m^2$ -.

$$m_5 = \Delta T5/\Delta t = -0.301 + 0.038.BMI - 0.147.Gender \quad (ºC/h) \tag{62}$$

Temperature at the limbs, which is hands (T7), knees (T9) and shins (T11), are the ones that in general change the most during long periods of inactivity. In relative terms, **Table 34** showed that the range width of temperature increases, with the rate between final and initial width of ranges being about 2.0, 1.7 and 2.5 respectively. The minimum decreased by 2.1, 1.9 and 1.4ºC and the maximum increased by 0.3, 0.2 and 0.1ºC respectively. Hence, the temperature of the limbs is affected greatly at cold room temperatures, dropping by up to 2ºC while they increase slightly, if at all, at hot room temperatures. Furthermore, the rate of temperature change at each of those locations –

m_7, m_9 and m_{11} – highly correlates with each other showing that they have similar behaviour.

More specifically, hand temperature presented three typical and well defined patterns (see **Figure Q1-f** and **Q2**). At low room temperatures – $T_{room}<23.0ºC$ - $T7$ decreases in the first hour and a half ($\Delta T7=-1.6ºC$ on average at $\Delta t=90min$) and then it oscillates with a final $\Delta T7$ in the range (-1.3, -2.1)ºC. At warmer environments, $23.0ºC<T_{room}<26.0ºC$, the $T7$ steadily decreases mildly ($\Delta T7=-0.45$ on average). Instead, at the hotter environments – $26.0ºC<T_{room}<29.8ºC$ -, $T7$ increases steadily for one and a half hours ($\Delta T7=0.46ºC$) and then it remains constant. The separation between those 3 cases is very sharp, which indicates that the temperature at hands is controlled by the thermoregulatory system in a discrete way, having specific thresholds. It seems like there is no intermediate case: either it loses/gains that amount of heat or remains constant. The rate of change of $T7$ (m_7) was obtained and presented versus T_{room} (**Figure 51-f**). Statistical analysis showed that it has significant dependency on environmental temperature – T_{room} – but not on the humidity - H_{room} –, it correlates with all the m_i but m_5, especially with m_9 and m_{11} - p=0.577 and 0.402 respectively -; and it depends on the T_c and BMI of the volunteers (see **Table Q3**). The dependency of m_7 on T_{room} was corroborated with statistical tests. For room temperatures between 20 and 30ºC, **Figure 51-f** shows that m_7 ranges between -1.0 and 0.3ºC/h, crossing zero at about $T_{room}= 26.1ºC$. Multi-linear regression established that m_7 should be accounted as equation **63** (see **Table 32**). Under normal circumstances T_c increases with T_{room}. Hence, the equation for $\Delta T7/\Delta t$ indicates that the change of temperature seen at hands is a compromise between the increase due to the room temperature and the decrease due to the increase of the core temperature. Based on that equation, and on T_c data retrieved from **Figure 37-a**, m_7 is in the range of -0.96 and 0.59ºC/h on average.

$$m_7 = \Delta T7/\Delta t = -2.176 + 0.157.T_{room} - 0.053.T_c \quad (ºC/h) \tag{63}$$

Temperature at knees presented a monotonous change without noticeable oscillation, with the change being more rapid in the first 1.5 hours (see **Figure Q1-h** and **Q2**). At low/medium room temperatures ($19.8<T_{room}<26.0ºC$) $T9$ decreases. After 150 min, $\Delta T9$ is in the range -2.2 and -0.6ºC, having a larger change for the colder rooms. At warm environments ($26.9ºC<T_{room}<29.8ºC$), $T9$ increases with a $\Delta T9$ in the range of 0.3 and 0.6ºC. $T9$ oscillates with a net change of zero for $26.0ºC<T_{room}<26.9ºC$, hence this room temperature can be identified with the threshold at which the thermoregulatory system switches ON the heat dissipation through the knees. Although the clothing is similar for all T_{room} categories (nº of layers between 0.73 and 1), slightly lighter clothes were observed for the hotter rooms, so the clothing does not interfere with the results. The rate of change of $T9$ (m_9) was obtained and presented versus T_{room} (**Figure 51-g**). Statistical analysis showed that it has significant dependency on environmental temperature – T_{room} and H_{room} –, it correlates with m_0, m_1, m_3, m_7 and m_{11}, especially with the last two, being p=0.577 and 0.570 respectively; and it depends on the core temperature of the volunteers (see **Table Q3**). The dependency of m_9 on T_{room} was corroborated with statistical tests. For room temperatures between 20 and 30ºC, **Figure 51-g** shows that m_9 ranges between -0.95 and 0.31ºC/h, crossing zero at about T_{room}= *26.5ºC*. Multi-linear regression established that m_9 should be accounted as equation **64** (see **Table 32**). Opposite of what happens for *T7*, $\Delta T9/\Delta t$ increases both due to the increase of T_{room} and the T_c. Based on the given equation, and on T_c data retrieved from **Figure 37-a**, m_9 is in the range of -0.87 and 0.52ºC/h on average.

$$m_9 = \Delta T9/\Delta t = -7.732 + 0.134.T_{room} - 0.008.H_{room} + 0.124.T_c \quad (ºC/h) \qquad \textbf{(64)}$$

Temperature at shins presented two typical and well defined patterns (see **Figure Q1-h** and **Q2**). At low/medium room temperatures – $19.8<T_{room}<26.0ºC$ – *T11* decreases continuously. After 150 min, $\Delta T11$ is in the range -1.6 and -0.7ºC, having larger change for the colder rooms. At warm environments, $26.0ºC<T_{room}<29.8ºC$, *T11* remains virtually constant, with a maximum $\Delta T11$ of 0.2ºC. It seems that the thermoregulatory system sacrifices the temperature at the shins in order to reduce the loss of heat. However, at greater room temperatures it identifies that the heat load is increasing and so same mechanism discussed for hands temperature applies. The rate of change of *T11* (m_{11}) was obtained and presented versus T_{room} (**Figure 51-h**). Statistical analysis showed that it has significant dependency on environmental temperature – T_{room} – but not on the humidity - H_{room} –, it correlates with all the m_i, especially with m_7 and m_9 - p=0.402 and 0.570 respectively -; and it depends on the *BMI* and gender of the volunteers (see **Table Q3**). The dependency of m_{11} on T_{room} was corroborated with statistical tests. For room temperatures between 20 and 30ºC, **Figure 51-h** shows that m_{11} ranges between -0.76 and 0.03ºC/h, crossing zero at about T_{room}= *28.7ºC*. Multi-linear regression established that m_{11} should be accounted as equation **64** (see **Table 32**). Based on this equation, m_{11} is in the range of -0.59 and 0.15ºC/h for males and -0.80 and -0.06ºC/h for females of normal composition - $BMI= 24.5\ W/m^2$ -. However, the use of this equation is recommended only T_{room} in the range (19.8, 26.0)ºC, as beyond this point and up to 29.8ºC, $T11$ is constant at a 0.05 level on 2-tailed-test, hence m_{11} follows a bi-linear dependency on T_{room}.

$$m_{11} = \Delta T11/\Delta t = -2.107 + 0.074.T_{room} + 0.010.BMI - 0.210.Gender \quad (^{o}C/h) \qquad \textbf{(65)}$$

In summary, the present study found that local skin temperature changes significantly during long periods of inactivity. For most locations, except T_c and $T5$, the rate of temperature change depends on T_{room}, such that it is negative for low room temperatures and positive for high room temperatures. On the one hand, at low/medium room temperatures, local skin temperature decreases fastest at the limbs (hands, knees and shins), with maximum rate change of -1.0, -0.95 and -0.75ºC/h respectively. The range of temperature decrease was (-1.3, -2.1), (-0.6, -2.2) and (-0.7, -1.6)ºC respectively, with an interesting non-zero minimum decay. Milder negative temperature change rate of -0.47ºC/h was observed at upper arm, again located at the limbs. Temperature at forehead and chest remained the most stable at low/medium room temperatures with a change no greater than -0.2ºC/h. On the other hand, at high room temperatures (value depending on the location), most of the locations present an increase of temperature by about 0.2-0.3ºC/h. Exceptions are shins, whose temperature remains practically constant. No dependency with T_{room} was found for T_c and $T5$, which increase regardless of the room temperature, 0.02 and 0.4ºC/h in average (based on the multi-linear regression equations), and an increase in temperature at $\Delta t=150min$ in the range of (0.00, 0.14) and (0.45, 1.43)ºC respectively. Also Huizenga et al. [Huizenga, 2004] observed that in general skin temperatures at limbs decreased significantly while forehead and trunk remained reasonably constant. They observed that under neutral conditions the hand and finger skin temperatures fluctuated considerably, up to 1ºC and 2 ºC respectively. They believe that hand vasodilatation and constriction takes place to regulate heat loss around the neutral set point, without the person to perceive these variations. These fluctuations do not appear in warm or cold conditions, when the hands were well-dilated or constricted, respectively.

The preferences and ways in which the thermoregulatory system tries to maintain constant heat load on the body were investigated in this study. Initially, for low room temperatures ($T_{room}<21.3^{o}C$), all the locations (except $T5$) get their temperature reduced in an attempt to preserve the heat load by decreasing the heat loss. As the room temperature increases, the decrease of skin temperature becomes milder in most locations. At $T_{room}=21.3ºC$, the chest temperature change rate (m_1) changes to positive and $T1$ starts to increase up to 0.5ºC. At $T_{room}=23.0ºC$ m_7 changes abruptly from -1.6 ºC/h to 0.45ºC/h. It is clear that the thermoregulation system has "switched ON" a mechanism to avoid the reduction of the hand temperature so quickly. At $T_{room}=24.4ºC$, both m_0 and m_3 (forehead and upper arm) became positive. The temperature at those locations did not increase straight away but oscillated, showing that the heat loss was being adjusted. At $T_{room}=26.1ºC$ m_7 (hands) becomes positive and $\Delta T7$ increases up to 0.46ºC. At $T_{room}=26.5ºC$, m_9 (knees) becomes positive. Soon after, at $T_{room}=26.9ºC$, m_1 changes abruptly to a more positive value, generating a $\Delta T1$ of 0.7-0.8ºC. Between T_{room} =26.9 and 28.0ºC, m_5 decreases unexpectedly, leading to the conclusion that abdomen reached the onset of sweating. Finally, at $T_{room}=28.7ºC$, m_{11} (shins) becomes positive.

It is clear that when a person is exposed to cold the thermoregulatory system reduces first the temperature at the limbs, i.e. shins, knees and hands in that order. Temperature at forehead and upper arm are used to adjust the heat load at lower room temperatures, with a typical oscillation between positive and negative changes. Only at the lowest room temperatures is the thermoregulatory system forced to decrease the temperature at the upper chest, while temperature at the abdomen is always preserved, if not increased.

There are also abrupt changes of the m_i's values at hands (3 stages) and shins (2 stages). They seem to indicate that the thermoregulatory system has only discrete control over the conditions for heat dissipation at those locations, meaning that either the mechanism(s) for heat dissipation are either ON of OFF.

Room temperature was observed to be an important factor for the temperature evolution in most cases; exceptions are core and abdomen temperature. However environmental humidity was only relevant for m_9. The average core temperature of the volunteers during the experiment only presents significant correlation with the room temperature and the change of skin temperature at hands and knees. However, m_c appears to be completely independent of all m_i and even the environmental conditions. Gender significantly correlated with m_0, m_5 and m_{11}. *BMI* significantly correlated with m_1, m_3, m_5 and m_{11}. Multi-linear regressions of the form of equation **55** were derived for each of the m_i's, including only the significant parameters. Coefficients are given in **Table 32**.

7.4.2 Thermal sensation and comfort level evolution in time.

The evolution curves of thermal sensation and comfort level on time were also characterized (**Table 35**).

Variable	Range width (t=15) (-)	Range width (t=165) (-)	$\frac{Range(t=165)}{Range(t=15)}$	Δmin (ºC)	Δmax (ºC)
Thermal sensation	1.11	2.80	2.52	-0.789	0.900
Comfort level	0.82	1.11	1.36	0.091	0.382

Table 35: Characterization of the thermal sensation and comfort level vs. time curves

Thermal sensation oscillated while changing slightly with time, especially when T_{room} was low or high (see **Figure 52**, **53** and **54**). **Table 35** showed that the possible range width of thermal sensation votes increases with the exposure time, with a rate between final and initial values of 2.52; both minimum and maximum become more extreme in time. In general, greater change in the thermal sensation is seen after one hour of exposure. The rate of change of *TS* (m_{TS}) was obtained and presented versus T_{room} (see **Figure 55-a**). Statistical analysis showed it has a significant dependency on T_{room} and correlates with all skin temperature rates of change (m_i) except forehead and abdomen. It does not correlate with H_{room} or any of the characteristics of the volunteers – *age*, *BMI*, *gender*– (see **Table Q3**). Statistical tests further corroborated the dependency of m_{TS} on T_{room}. For room temperatures between 20 and 30ºC, **Figure 55-a** shows that m_{TS} ranges between -0.7 and 0.3 h^{-1} on average, crossing at T_{room} of 26.5ºC. A multi-linear regression was derived for the estimation of m_{TS}, based on equation **56**, and reported in **Table 33**. The model established that m_{TS} should be accounted as equation **66**, that is in the range of -0.47 and 0.22 h^{-1}, which is conservative.

$$m_{TS} = -1.85 + 0.069.T_{room} \qquad (h^{-1}) \qquad \textbf{(66)}$$

Comfort level oscillated throughout the experimental sessions, especially for the cases where the room temperature was low or high (see **Figure 52**, **53** and **54**). **Table 35** showed that the possible range width of comfort level increased only slightly with the exposure time, with a rate between final and initial values of 1.36. The comfort level of a person both at cold or hot environments is the same, which masks the fact that how a person feels in a given environment has more dispersion after a long period of time. The rate of change of *CL* (m_{CL}) was obtained and presented versus T_{room} (**Figure 55-b**). The curve is a third order polynomial. However, statistical analysis appears to indicate that it has no significant dependency on T_{room} or the skin temperature rates of change (m_i)

except for chest and shins, but it seems to depend on the environmental humidity and the gender of the volunteers (see **Table Q3**). Statistical tests showed lack of correlation between CL and T_{room}, although it might be due to the non-linear relation between them (**Figure 55-b**). Further analysis proves the dependency of m_{TS} on T_{room}, but only at high room temperatures. For room temperatures between 20 and 30ºC, **Figure 55-b** shows that m_c ranges between -0.1 and 0.3 h^{-1} on average, crossing at T_{room} of 24.9ºC. Two different multi-linear regressions were derived for the estimation of m_{CL}, based on equations **56** and **57,** and reported in **Table 33**. The best model established that m_{CL} should be accounted equation **67.** Based on this equation, m_{CL} is in the range of 0.08 and -0.02 h^{-1} for males and 0.22 and 0.12º h^{-1} for females at 40% humidity. Note that an increase in the comfort level value is not desirable as it implies an increase in on the discomfort; the optimal situation is when comfort level is zero.

$$m_{CL} = -19.7 + 2.5T_{room} - 0.106T_{room}^{2} + 1.44E\text{-}3T_{room}^{3} - 0.010H_{room} + 0.141Gender\ (h^{-1}) \qquad \textbf{(67)}$$

In summary, thermal sensation and level of comfort voted by people varies in time. Rate of change of thermal sensation is related to T_{room} and furthermore correlates with the rate of change of skin temperature at several locations, particularly the limbs. The awareness of the change of the temperature on the skin leads to the corresponding thermal sensation. If we feel that our skin temperature has dropped we identify that as cold/cool, while a rise in the skin temperature leads us to classify the room as warm/hot. m_{CL} seems to dependent only on H_{room} and gender. The lack of correlation with other parameters is due to its V-shape. It seems that the thermoregulatory system is capable of maintaining the heat load stable for a while, and so the thermal sensation and comfort level, even in cold and hot room temperatures. Afterwards, the heat load is greatly unbalanced and so the thermal sensation changes more abruptly. It is also observed that volunteers are in general not aware of their thermal sensation until some time has elapsed. That might be partially the reason why the votes do not change drastically in the first hour. However, during the procedure of this experiment, as we were enquiring about the thermal sensation and comfort level every half an hour, we might have accelerated the awareness of the subjects.

7.5 Conclusions

The present study found that local skin temperature, thermal sensation and comfort level change significantly during long periods of inactivity under same environmental conditions. T_{room} in this study ranged from 19.5 to 29.8ºC.

The rate of temperature change depends on the T_{room}. It is negative for low room temperatures and positive for high room temperatures, except for T_c and $T5$ which always increase. At low/medium T_{room}, local skin temperature decreases fastest at the limbs (hands, knees and shins), with maximum rate change of -1.0, -0.95 and -0.75ºC/h respectively, with an interesting non-zero minimum decay. Upper arm presents a milder decrease of temperature ($m=-0.47ºC/h$), while temperature forehead and chest remained the most stable ($m<-0.2ºC/h$). At high T_{room} temperature increases at all locations by about 0.2-0.3ºC/h but shins which remain practically constant.

The ways in which the thermoregulatory system tries to maintain a constant heat load on the body were investigated. For T_{room} below 21.3ºC temperature at all locations (except $T5$) decrease in an attempt to preserve the heat load by decreasing the heat loss by radiation. As T_{room} increases, the local skin temperatures evolution changes: first their decrease gradually becomes milder; later on m_i becomes positive for $T1$ (at $T_{room}=21.3ºC$), $T7$ (at $T_{room}=23.0ºC$), $T0$ and $T3$ (at $T_{room}=24.4ºC$), a further abrupt increase for $T7$ (at $T_{room}=26.1ºC$), $T9$ (at $T_{room}=26.5ºC$), further abrupt increase in $T1$ (at $T_{room}=26.9ºC$), and finally $T11$ (at $T_{room}=28.7ºC$). Hence, in case of exposure to cold, temperature at the limbs decreases first – shins, knees and hands in that order -, followed by forehead, upper arm and finally upper chest. Temperature at the abdomen did not decrease for the studied room temperatures.

Both, m_{TS} and m_{CL} depend on T_{room}. m_{TS} also correlates with the rate of change of skin temperature at several locations, and in particular the limbs. Hence the awareness of cold or hot is related with the change on skin temperature. *TS* and *CL* votes did not change drastically in the first hour, showing that thermoregulatory system is capable of maintaining the heat load stable for a while, beyond this point the heat load is greatly unbalanced and so *TS* and *CL* changes more abruptly.

In summary, this chapter provides the means to account for the change of core and skin temperatures and also thermal sensation and comfort level of an average person who remains seated for long periods of time (equations **58**-**67**). This is of great significance for the development of an automatic monitoring system which aims to control the indoor environmental temperature according to the needs of a person.

8 Thermal comfort model

The effect of the indoor environmental conditions such as temperature, humidity, velocity of the air supplied is something that millions of people face every day during their working time at offices, schools, universities; while travelling in aeroplanes, trains, buses, cars or in their leisure time at cinemas, theatres, and so on. There is little one can do about the environmental conditions in the open air; however one expects to be offered a pleasant temperature in confined spaces where one spends a significant period of time.

Standards exist which indicate the range of temperature values that should be maintained indoors, like the ones given by ASHRAE (Refrigeration and Air Conditioning Engineers). However, this range of temperatures is mainly addressed to guarantee healthy and minimum comfort conditions. The range of temperatures which keeps a person comfortable –neither slightly cold not slightly warm- is narrower.

Many indoor environments offer the possibility of temperature control as desired by the occupants. Also available are automatic conditioning systems which can maintain the environmental temperature to a selected value. However, the use of those systems is always an issue of discussion as the ideal room temperature is something very subjective and multi-factor dependent. The same person's opinion on comfort may change during the day, depending in their activity, clothing, etc.

A system that automatically detects the thermal comfort of a person and adapts the environment to personal needs is highly desirable. Once a person starts feeling uncomfortable it is too late for a smooth transition to neutral environment. The ideal system would recognize that the comfort level of a person is decreasing and would act on the environmental factors/conditions before the person realizes, avoiding him/her getting uncomfortable. Such system offers economic benefits as it can minimize the use of heaters and coolers in an inefficient way.

Despite the interesting advantages and numerous fields where it could be used, nowadays there are no automatic systems that monitor the individual thermal comfort and automatically adjust the environmental conditions to achieve comfort status as close as neutrality as possible.

Hence, the final and most important aim of this work is to propose a novel system which by continuous monitoring of the occupant could

a) assess the level of comfort and thermal sensation of that individual person
b) identify the environmental conditions required for that person to achieve a pleasant sensation

8.1 Proposed thermal comfort model

The thermal comfort model presented in this chapter was developed within the international FP6 project SEAT (**Figure 56**), sponsored by the European Commission DG H.3 Research (Aeronautics Unit). Hence, this model was specifically tailored for the use in airplanes, but it could be used for majority of sedate activities.

The thermal comfort model is composed of 3 independent modules for estimation of comfort level and thermal sensation: a “basic thermal comfort module”, “personal temperature module” and “behavioural adaptation module”. They are based on previous statistical studies and individual observations of physiological signals and behaviour of the person being monitored. Predictions done by each of them are compared and weighted in the “decision module” to obtain a more reliable indication of the person’s thermal sensation. A diagram of the model is presented in **Figure 57**.

Figure 56: Logo of the international SEAT project.

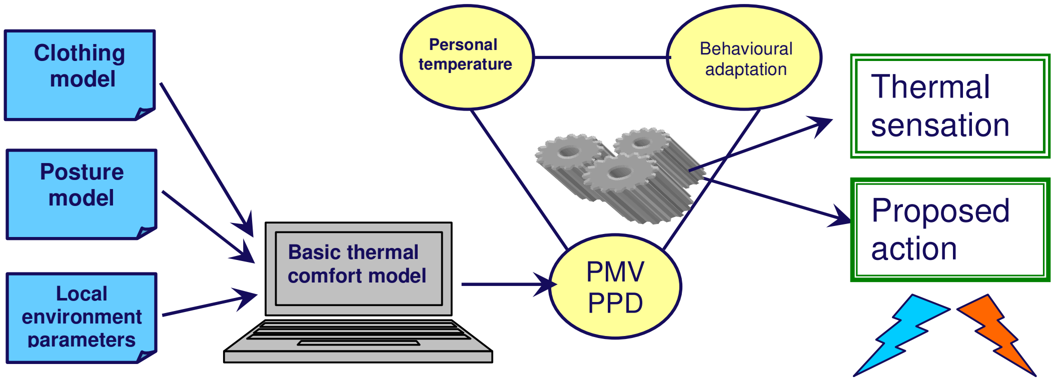


Figure 57: Sketch of thermal comfort model

The required inputs of the proposed thermal comfort model are:

- Environmental temperature and humidity
- Face temperature
- Back and thigh temperature
- Personal air nozzle state (level of aperture)
- Use of the cabin air supply system by passenger
- Standards (ISO 7726, 7730, 8996, 9920 and 11079)
- Activity, provided by a posture model

The corresponding outputs are:

- Individual adjustments
  - Personalized thermal sensation
  - Proposed action
    - Increase temperature
    - Maintain temperature
    - Reduce temperature
  - Personalized optimal cabin temperature

- Global adjustments
    - Optimal welcome cabin temperature
    - Adjustment based on individual observations to optimize PMV and minimise PPD

8.1.1 Basic thermal comfort model

The basic thermal comfort module uses the standard definition of *PMV* – Predicted Mean Vote - and *PPD* – Predicted Percentage of Dissatisfied - for the determination of the comfort level of the passenger in a given environment and at a certain individual circumstances. Hence, the output is valid for an average person in a large group of people with those characteristics. It is a good start for thermal comfort monitoring. It also provides an output without advance knowledge of the characteristics of the passenger such as clothing or metabolic rate. The standard value of metabolic rate of a walking person is initially used in this module, simulating a person entering the airplane. In a similar way, the clothing insulation is estimated based on the environmental conditions and the metabolic rate of the person, as detailed in section 2.9.3. Once a more accurate and personalised value is obtained for each passenger by the corresponding module, it will be made used of. In this way this module, besides giving a statistical value, provides a more personal answer for each passenger according to his/her characteristics.

The second task of this module is to obtain the optimal environmental temperature for each of the passengers, that is, the environmental temperature that makes the person feel the most comfortable. Those values can be obtained by inspecting graphs such as the ones presented in **Figure 58** and **Figure 59**. These graphs show that there is a change of 4 ºC in the optimal temperature of the environment between a person wearing 0.4 clo units and another wearing 1.4 clo units. Also the optimal temperature varies by 5ºC for the same person when his/her metabolic rate goes from 0.8 to 1.2 met units.

This module feeds from 3 sub-modules, as indicated in **Figure 57**, i.e. “clothing model”, “posture model” and “local environment parameters”.

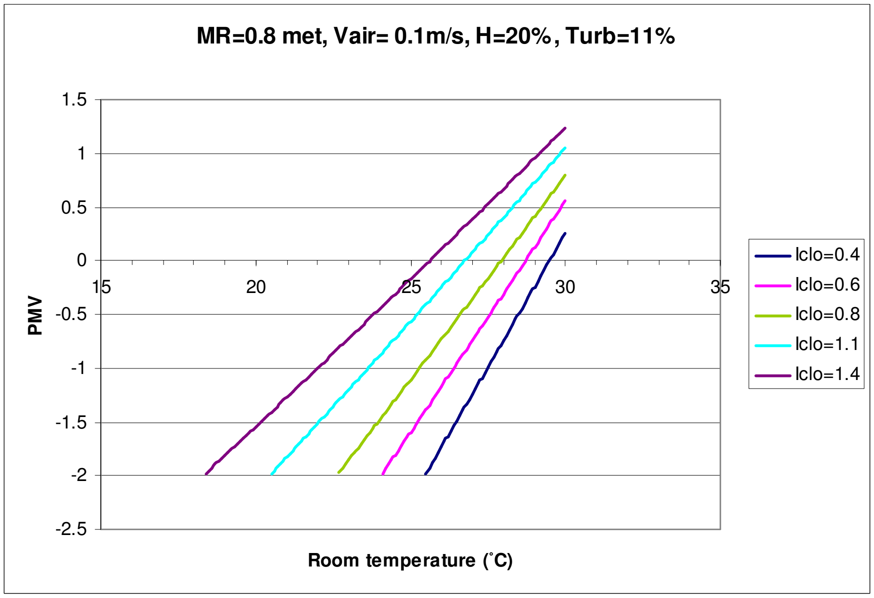


Figure 58: PMV values versus room temperature for different values of clothing insulation (in clo units)

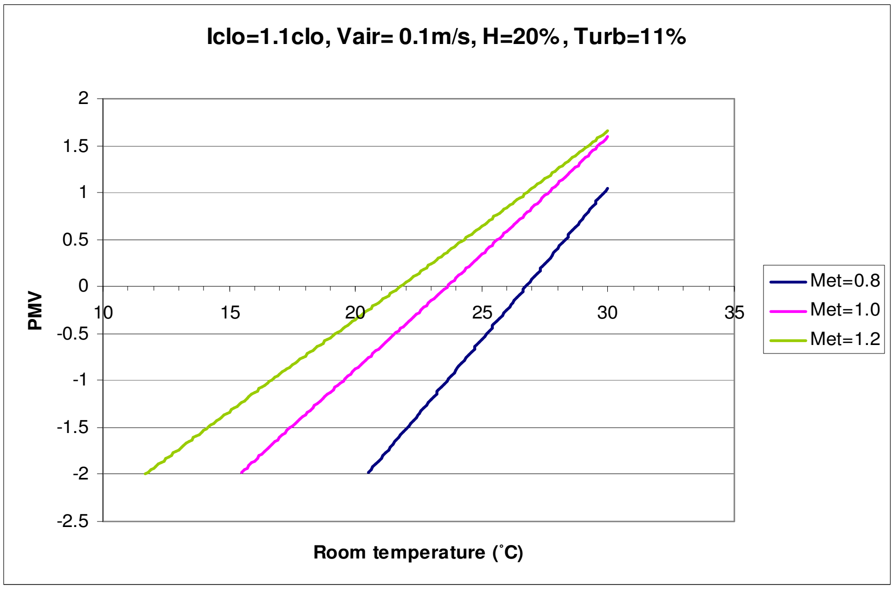


Figure 59: PMV values versus room temperature for different values of metabolic rate (in met units)

The clothing model estimates the insulation factor of the clothing of each passenger, based on direct measurements taken from each person. Hence it allows a more personalized assessment of the thermal comfort. Details can not be discussed here as this unit is in consideration to be patented.

The posture model indicates the level of activity of each passenger. It is based on pressure readings at the bottom of the seat. The level of activity is within a small range, as all the passengers remain seated. However, the passenger can be sleeping, just sitting and relaxing or working with a computer or similar device. Such information is considered whenever available and improves the reliability of the predictions.

The local environmental parameters, that is, temperature and humidity, are measured at a certain frequency, for instance 1 Hz. However not every individual sample will be input into the model. Instead, the input samples are averaged for 15 seconds and this is seen to decrease the possibility of having sampling errors due to noise.

8.1.2 Personal temperature module

Every person reacts physiologically in a different way when subjected to certain environmental conditions, neither is their thermal sensation or comfort level equivalent. Statistical models such PMV represent the thermal comfort level of majority of the people. However, the thermal comfort of a small percentage of the group (minority) is miscalculated as their appreciation of the environment differs from the majority. This module monitors and evaluates the temperature of each passenger individually. Its main purpose is the personalization of the basic statistical model such that individuals belonging to the aforementioned minorities are identified and their thermal sensation estimated more accurately.

Several models were studied (see section 8.3.1) for the prediction of thermal sensation and comfort level based on environmental conditions and skin temperatures. The skin temperatures selected to be monitored were the face and hands temperature. Forehead temperature holds one of the strongest relations with the core temperature among the local skin temperatures, both for babies (see 4.3.3) and for adults (see 6.1). Face temperature was identified with a 16-sensor-array pointed to the area where the passenger's face should be located. Temperature at hands holds the strongest relation with thermal sensation and comfort level (see 8.3.1). This temperature can be monitored by placing IR temperature sensors or placing a temperature sensor in the armrest. Selected models for thermal sensation and comfort level are given in equations **70** and **71**. These values are combined into the thermal sensation suggested by this module and its reliability obtained according to **table 38**.

Furthermore the temperature at the back and thigh of the person is monitored such that abnormal temperature values are detected.

The main tasks of this module are:

- Estimation of the core temperature of the passenger, which can indicate potential health problems.
- Personalized estimation of the thermal sensation based on a combination of environmental conditions and skin temperature measurements.

8.1.3 Behavioural adaptation module

The air velocity is an important factor when calculating thermal comfort, as it significantly changes the thermal sensation of a person even though the environmental temperature and humidity remain the same. Hence, the model needs to know whether the air supply is on or off.

Furthermore, valuable information about the thermal sensation of a passenger can be obtained by monitoring the use that this person makes of his/her personal air conditioning system, which is a behavioural adaptation to the environment. This information is especially accurate when a change is detected, that is, when the fresh air is turned on or off, when the air supply is reduced or increased and so on, as it reflects that the passenger wills to change its thermal sensation. On the contrary, long periods of inactivity can be due to the person being asleep or unaware of the possibility of changing the configuration (see **Figure 60**). Hence, this module provides not just an estimation of the thermal sensation of the passenger at any given time based on the state of the air conditioning system but also an estimation of the reliability of this value. Reliability is computed based on the existence of a net change from one window of time to the next, the possible change within this window and the coherence of the change compared with the history for a particular passenger (see **Table 36**).

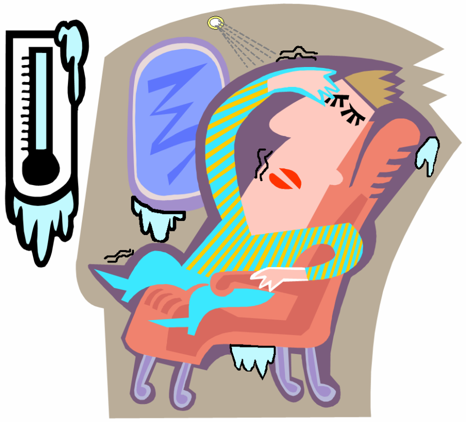


Figure 60: Example of bad use of the air conditioning system by the passenger where the passenger falls asleep with the air supply on and eventually feels very cold.

Net change	Erratic change	Reliability
0	False	Low
0	True	Medium
≠ 0	False	High
≠ 0	True	Medium

Table 36: Basic scheme of decisions for the estimation of the reliability of the thermal sensation obtained by the *Behavioural adaptation model*. Furthermore the history for the particular person is taken into account as a correction factor.

Finally, the use that each passenger makes of the air conditioning system is used to assess the global model, particularly when the action taken by the person is contrary to the actions taken by the thermal comfort system.

In summary, the main aims of this module are:

- Make an estimation of the subject's thermal sensation.
- Obtain the person's feedback regarding the environmental conditions selected by the thermal comfort system as the desirable ones.

8.1.4 Decision module

This module combines the predictions of thermal sensation of a person made by each of the three independent modules to generate a final output. It regards the reliability of each of the estimations, as they vary from one case to another. Part of the decision process is detailed in **Table 37**. Outputs from the *basic thermal model* and *behavioural-adaptation module* are prioritised as their reliability is higher.

Case	Condition 1	Condition 2	Suggestion	Reliability
A	sugg1=sugg2		sugg2	High
B	|sugg1-sugg2|<=1	reliab2= 1 or 2	sugg2	High
		reliab2=3	sugg1	High
C	sugg1*sugg2>0 & |sugg1-sugg2|>1	reliab2=1	sugg2	High
		reliab2=2	(sugg1,sugg2)	High
		reliab2=3	(sugg1,sugg2)	High
D_1	sugg1*sugg2 ≤ 0 & reliab2=1	|sugg1-sugg2|<=2	sugg2	High
		|sugg1-sugg2|>2	sugg2	Medium
D_2	sugg1*sugg2 ≤ 0 & reliab2=2	|sugg1-sugg2|<=2	(sugg1,sugg2)	Medium
		|sugg1-sugg2|>2	(sugg1,sugg2)	Low
D_3	sugg1*sugg2 ≤ 0 & reliab2=3	sugg1=1 & |sugg1-sugg2|=3		Low
		sugg1=1 & |sugg1-sugg2|<3		Medium
		sugg2*sugg3>0	(sugg1,sugg2)	
		sugg2*sugg3≤0	(sugg1,sugg2)	
…	…	…		

Table 37: Example of decision process done in the *decision module*. The outputs of the *basic thermal model* are tagged with 1, the outputs of the *behavioural-adaptation module* with a 2 and finally with a 3 the outputs of *personal temperature module*.

This module also assesses the performance of the general model by (a) comparing passenger's temperature with the predicted one; (b) adapting based on actions taken against the model. The thermal comfort model automatically modifies the environmental conditions to those preferred by the person. If that works perfectly, the passenger would not need to manually change the settings of the air conditioning system. When the passenger changes the settings, the model obtains a personal feedback with regards to the actual climate-control made by the comfort system, which can in turn adjust to the particular preferences. This learning process ultimately leads to a more personalized monitoring system, which becomes more efficient with time.

Hence, the main tasks of the decision module are:

- Identification of the most likely thermal sensation of a person based on the estimations made by the independent modules.
- Decide which action to take (e.g. increase or decrease the environmental temperature) in order to improve the comfort level of the person, if necessary.
- Assess the actions taken by the thermal comfort system regarding the environmental conditions and readjust if passenger's behaviour indicates otherwise.

8.1.5 Application of the system to a group of people

The description of the thermal comfort model, given above, assumes the particular case of a single person being monitored. However, more commonly there would be a group of people within a confined space, such a room or an airplane cabin. So the system needs to provide the best comfort to the majority of the occupants within that confined space. This requires the monitoring of each individual person in within this space, the identification of their preferred environmental conditions and the selection of compromising conditions to minimize the percentage of people dissatisfied (PPD).

The thermal comfort model flow chart (**Figure 61**) follows several key steps:

1) Assure safe temperature range.
2) Establish a welcome cabin temperature.
3) Determine PMV and TS for each person, by applying the thermal comfort model individually. That includes estimation of clothing factor and activity level.
4) Decide required action for each person.
5) Obtain PPD and check if a change in the general environment would reduce it.

6) Change the personal and/or general environmental conditions as required.
7) Proceed with step 3.

Furthermore, in those cases where actuators per individual person are not available, this system could adapt the general environmental conditions of the room to allow the best comfort to all or the majority of the occupants.

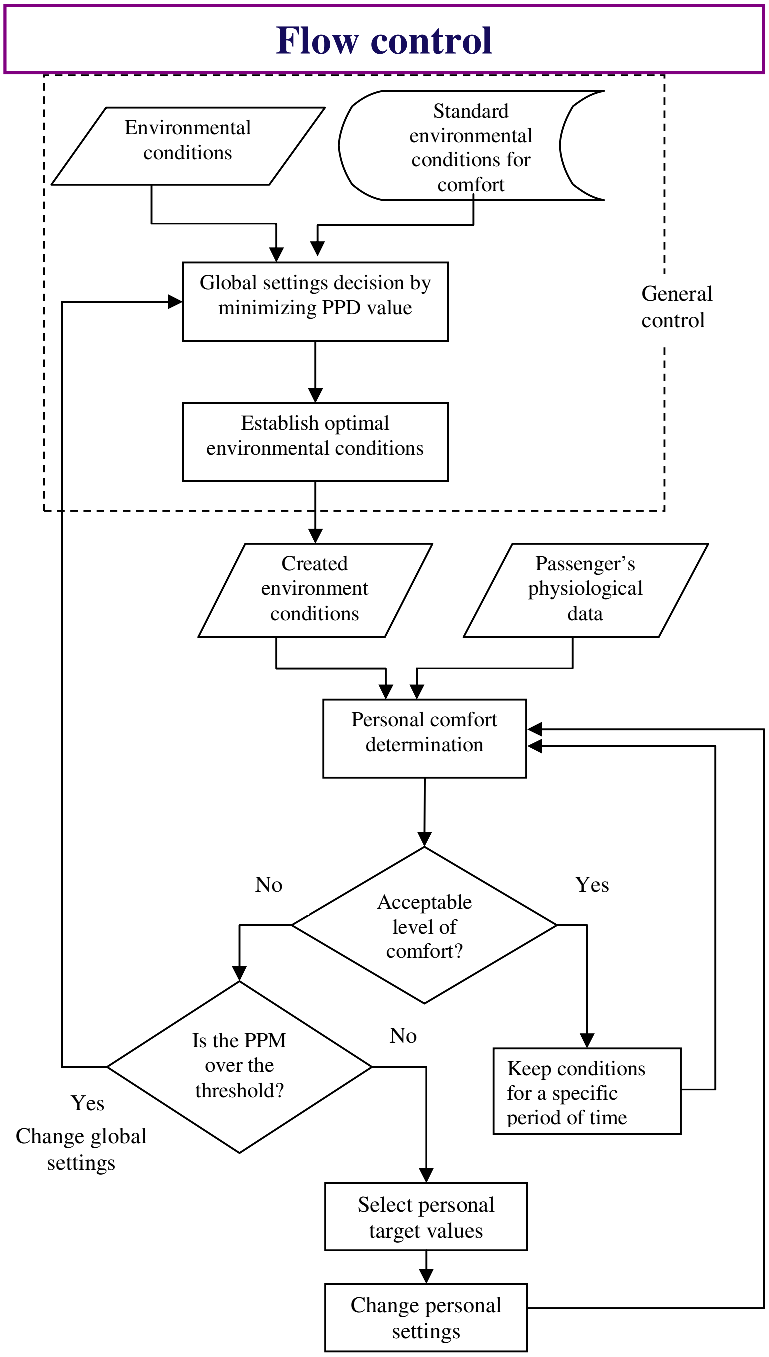


Figure 61: Flow chart of the thermal comfort model

8.2 Physical monitoring system

The prototype of the system used for tests and experiments is presented in **Figure 62**. Sensors were provided by INESCOP and integrated by AITEX in the seat prototype. It was tested and demonstrated in an aircraft cabin mock-up at Thales premises in Toulouse (see **Figure 63**) to industry representatives.

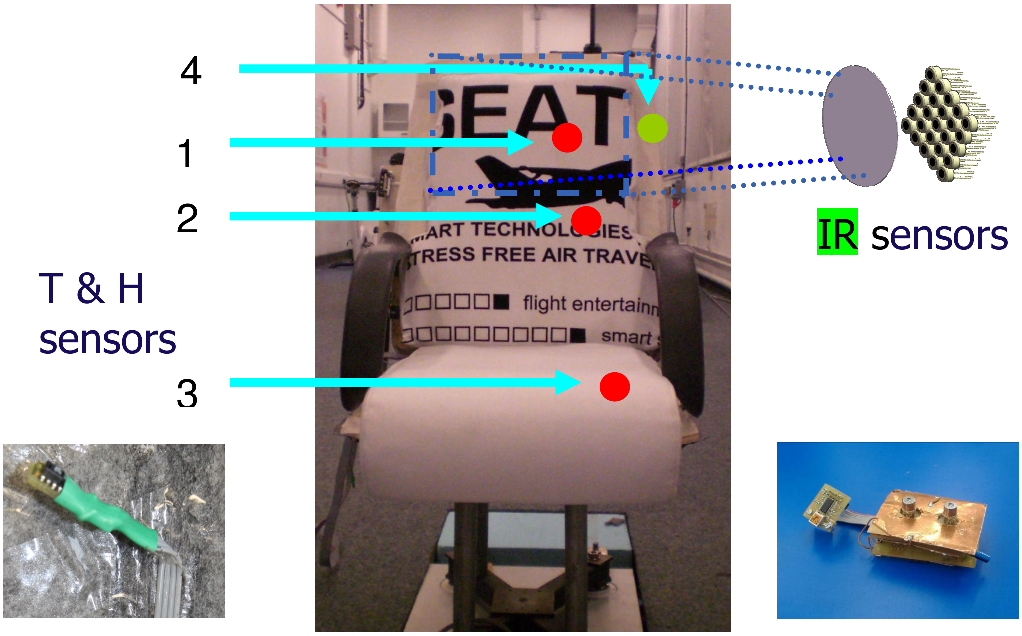


Figure 62: Prototype of the physical system for comfort monitoring

Figure 63: Aircraft cabin mock-up at Thales (Toulouse)

8.3 Underlying studies

Parallel studies were conducted to facilitate the development of the thermal comfort model. Those were identification of skin temperature mapping of adults at different environmental conditions (Chapter 5), non-invasive core temperature measurement methods (Chapter 6), evolution of physiological (core and skin temperature) and psychological (thermal sensation and comfort level) parameters of people when subjected to the same environment for long periods of time (Chapter 7). Furthermore the prediction of thermal sensation and comfort level based on personal skin temperature measurements was investigated, as detailed below.

8.3.1 Personal estimation of thermal sensation and comfort level

This study focuses in the relation between thermal sensation and comfort level and the environmental conditions, individual characteristics (*gender*, *age* and *BMI*), and core and local skin temperatures. A total of 1349 datasets were collected following the procedure detailed in Chapter 3.

Due to the V-shape of comfort level on T_{room}, a new version of comfort level (CL^*) was defined (see equation **68**). Significant parameters were identified (see correlation values in **Appendix R Table R1**). Both TS and CL^* appear to have significant correlation at 0.01 level with several parameters, from which T_{room}, $T7$ and $T9$, and $T3$ in the case of TS, present the highest correlations. The nature of the relation between TS and CL^* and T_{room} is shown in the **Figures 64** and **65**. Further description can be seen in **Appendix R Figure R1** and **R2**. Average values of TS and CL^* are linearly related, however the dispersion is large. The relation between TS and CL^* with T_{room} is shown in **66**.

$$CL^* = \begin{cases} CL & \text{if } TS \geq 0 \\ -CL & \text{if } TS < 0 \end{cases} \qquad \text{hence} \qquad CL = |CL^*| \tag{68}$$

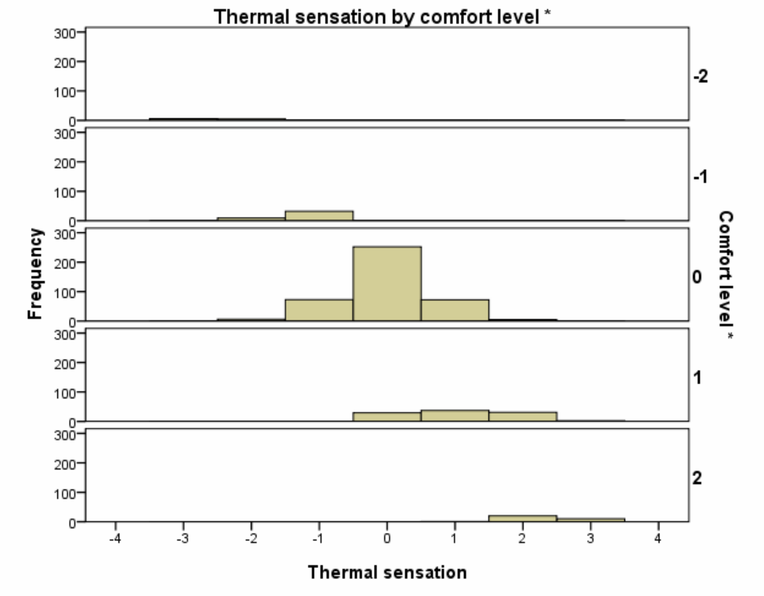


Figure 64: Thermal sensation and comfort level relation

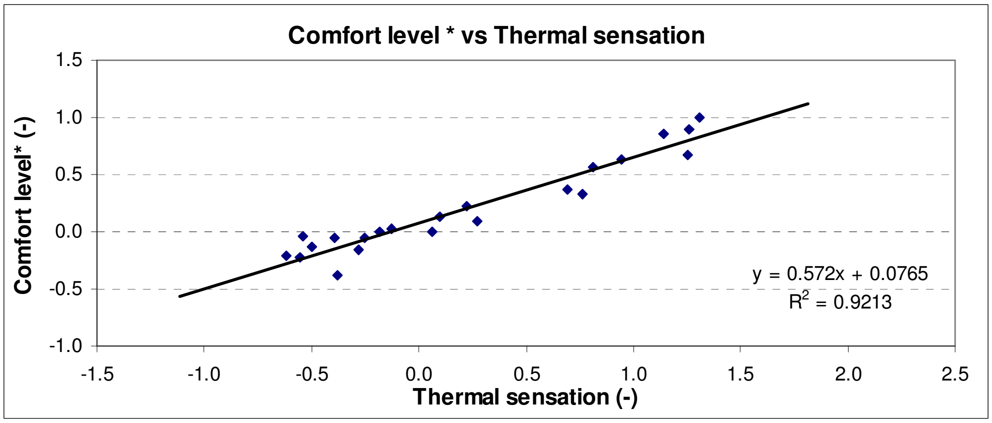


Figure 65: Comfort level versus thermal sensation

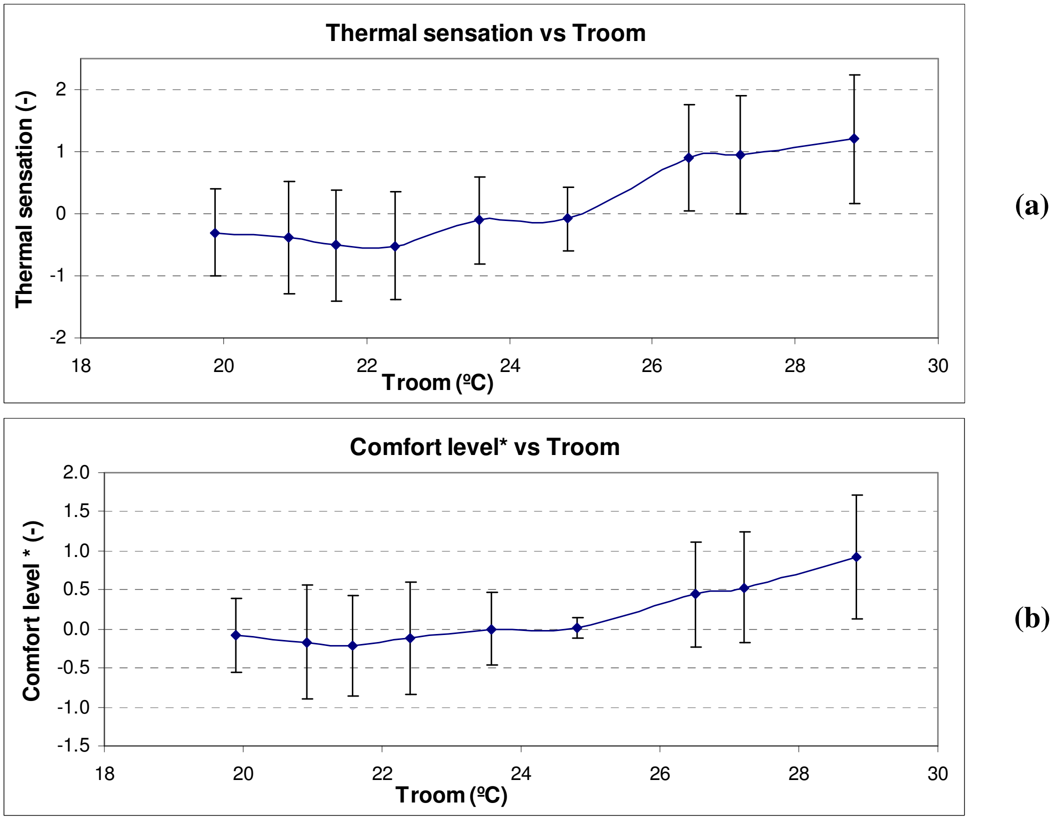


Figure 66: Thermal sensation and comfort level versus room temperature

Models for thermal sensation and comfort level were obtained following the bootstrap technique described in 5.2.2 and including significant parameters as detailed in equation **69**; coefficient values are given in **Table R2**. Other simpler models were developed based on parameters of high significance and their practicability for measuring (see **Table R3**). The predicted values given by the full models and one of their simplifications were compared with the voted values in **Figures 67** and **68**.

$$Vote_i = a_i + b_i.T_{room} + c_i.T_c + d_{j,i}.Tskin_j + e_i.Age + f_i.BMI + g_i.Gender + k_i.m_i.Time \quad \textbf{(69)}$$

$a_i, b_i, c_i, d_{j,i}, e_i, f_i, g_i$ *and* k_i are constants, being i = *TS* or *CL* and j = skin location

a_i *and* g_i have not units

b_i, c_i *and* d_i are in (ºC)$^{-1}$ and T_{room}, T_c and $Tskin_j$ must be given in ºC

e_i is in (years)$^{-1}$

f_i is in (Kg/m^2)$^{-1}$

h_i is in (nº of layers)$^{-1}$

gender was coded as 1 and 2 for male and female volunteers respectively

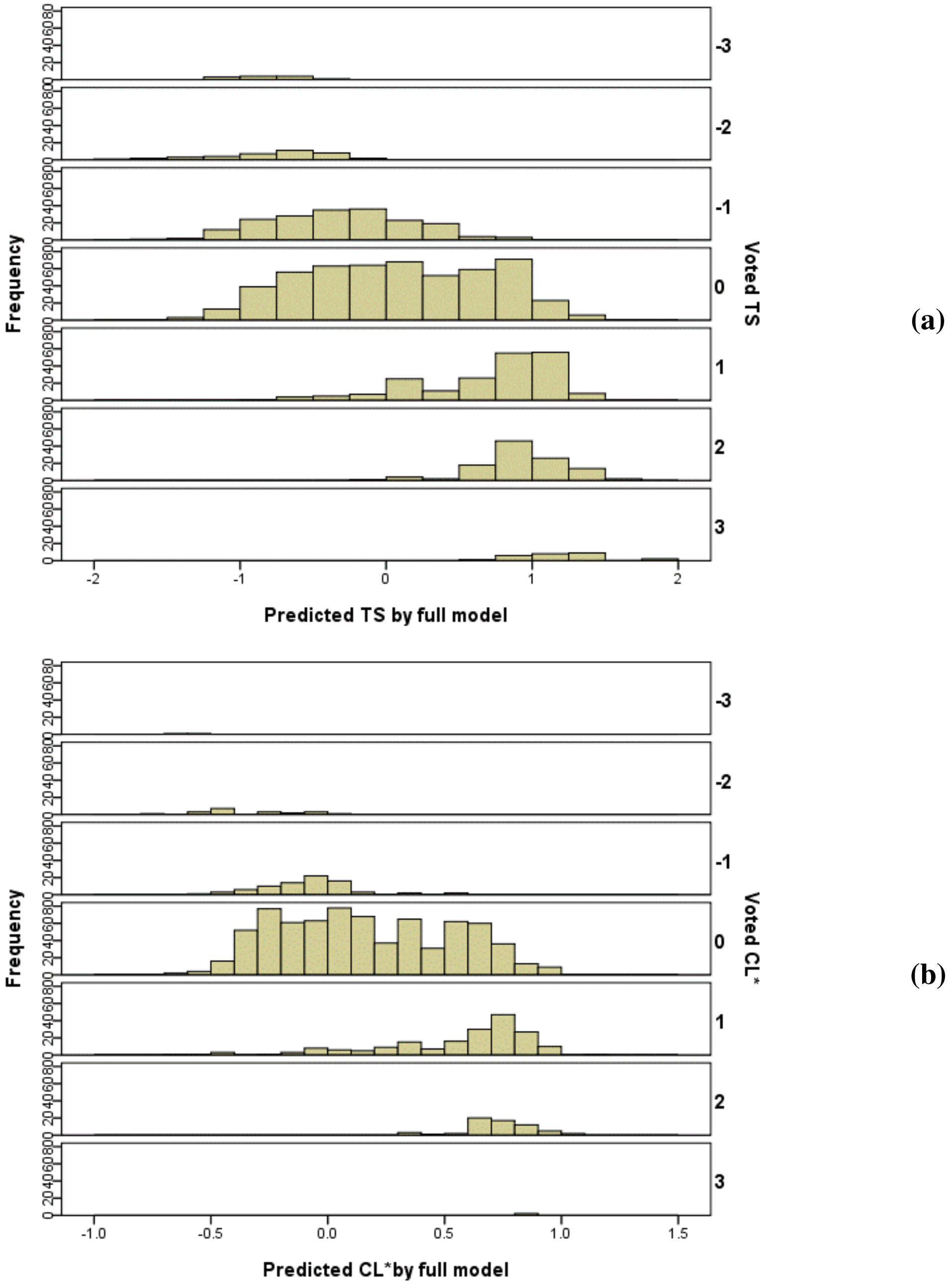


Figure 67: Comparison between voted *TS* and *CL** values and those predicted by the full models.

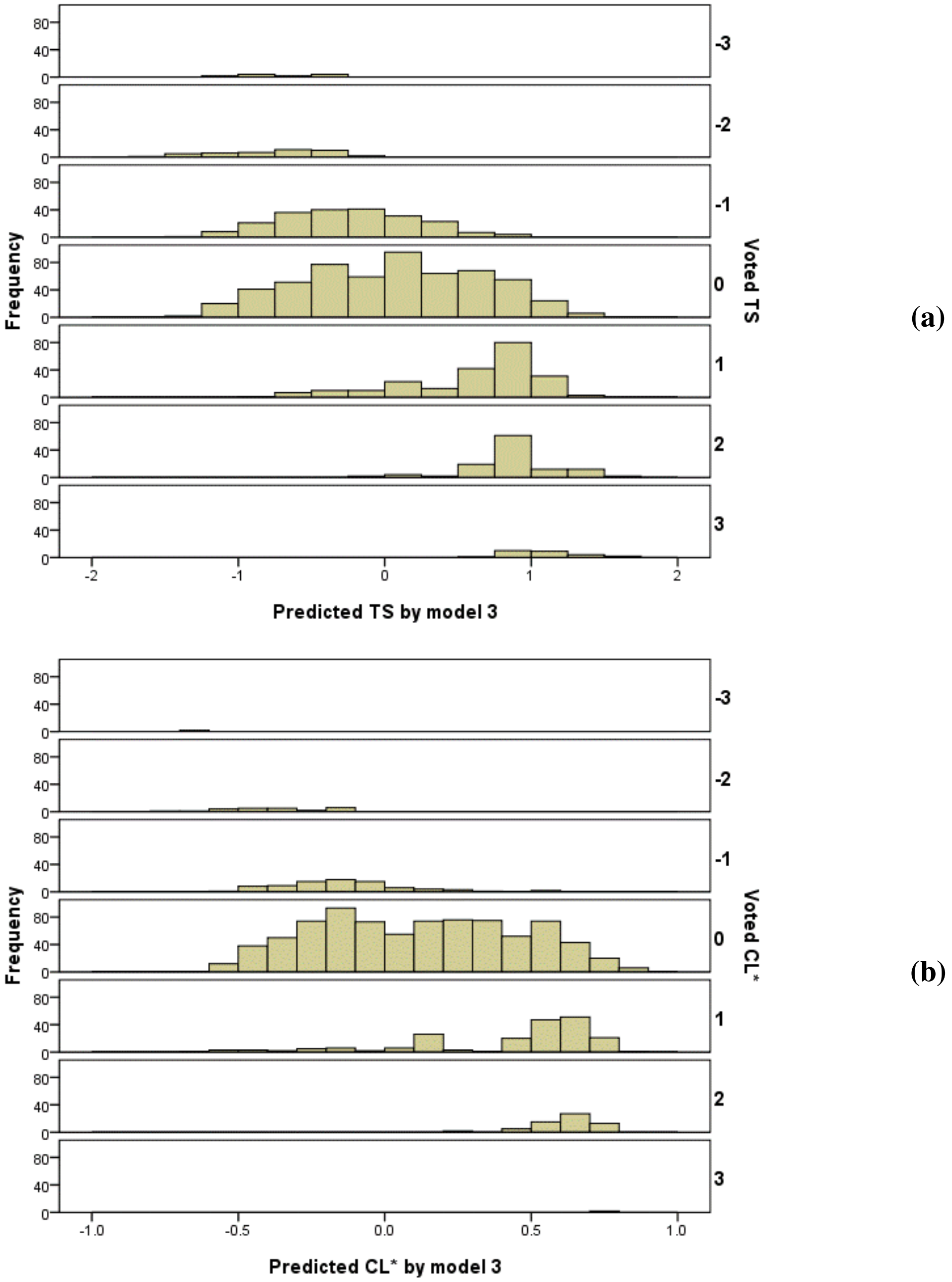


Figure 68: Comparison between voted *TS* and *CL** values and those predicted by one of the simplified models.

Temperature at hands, along with the room temperature, proved to be the best indicators of the thermal sensation and comfort level of a seated person. Temperature of the knees was shown to be significant but it was omitted in the simplified models due to its practicability. The inclusion of forehead temperature does not change the accuracy of the model, but being an exposed location, it was included as a potential backup for the prediction of *TS* and *CL* when hands temperature is not available. The inclusion of core temperature in the models does not improve performance, only 0.1% in the case of TS and 0.6% for *CL**, hence it has been withdrawn. When comparing the models for *TS* (the full model and the simplifications M1-M6) by means of the Akaike's technique, the full model was found to be the best. If the full model is discarded due to its little practicability, then M2 proves to be clearly better than the other options. When comparing all the models for *CL** using the same technique, only the full model and M2 remain within the model confidence set, with Akaike weights of 0.64 and 0.37 respectively. When repeating the analysis just with the simplified models, only M2 remains. Hence, model 2 both for *TS* and *CL** was found best, and so equations **70** and **71** are used within the *personal temperature module*.

$$TS = -5.99 + 0.090\,.T_{room} + 0.034\,.T0 + 0.092\,.T7 + 0.75\,m_{TS}.Time \qquad \textbf{(70)}$$

$$CL^* = -2.40 + 0.0896\,.T_{room} - 0.048\,.T0 + 0.070\,.T7 - 0.140\,.gender + 0.027\,m_{CL}.Time \qquad \textbf{(71)}$$

In general, as observed in **Figures 67** and **68**, the predicted values of *TS* and *CL** are quite conservative, showing higher comfort level than what voted in reality. This may be considered as prove of their reliability as when questioned people tend to be negative especially on personal matters. For predicted thermal sensation in the range of -1.0 to 1.5, the actual values have a range of 2, hence in extreme cases the model prediction could be off in ± 1. Same is observed for the comfort level* in the range of -0.5 to 1.0.

Based on these results, the module *personal temperature* generates outputs as indicated in **table 38**. The effect of assigning other reliability values to each of the cases was studied, but this one resulted to be the best.

Case	Proposed TS	Reliability
$\|TS - CL^*\| \leq 0.5$	$\frac{TS + CL^*}{2}$	1
$\|TS - CL^*\| > 0.5$ & $\|TS - CL^*\| < 2$	$\frac{0.382TS + 0.266CL^*}{0.648}$	2
$\|TS - CL^*\| \geq 2$	$\frac{0.382TS + 0.266CL^*}{0.648}$	3

Table 38: Decision in the *personal temperature module*

8.4 Assessment of the model

Basic thermal comfort module (BTC module) and *personal temperature module* (PT module) were assessed by comparing their results with the *TS* and *CL* voted by a group of people under different environmental conditions (**figures 69** and **70**). This subset of volunteers was previously defined in section 7.1.1. Then the two modules were combined. The global prediction of thermal sensation is given in equation **72**, and its reliability decided as detailed in **table 39**. Accuracy of the combination of these two modules depends on the reliabilities assigned to the outputs of each individual module. Among the investigated cases (**table R4**), case 3 (reported in **table 38**) was found to be the best (**figure 71**). Figures for cases 1 and 2 can be seen in **Appendix R**, **Tables R3-4**.

$$sugg_{global} = \frac{reliab_3.sugg_1 + reliab_1.sugg_3}{reliab_3 + reliab_1} \tag{72}$$

Case	Proposed TS	Reliability
$\|sugg_1 - sugg_3\| \leq 0.5$	$sugg_{global}$	1
$\|sugg_1 - sugg_3\| > 0.5$ & $\|sugg_1 - sugg_3\| \leq 1.5$	$sugg_{global}$	$min(reliab_1, reliab_3)$
$\|sugg_1 - sugg_3\| > 1.5$ & $\|sugg_1 - sugg_3\| < 2.5$	$sugg_{global}$	2
$\|sugg_1 - sugg_3\| \geq 2.5$	$sugg_{global}$	3

Table 39: Decision in the *personal temperature module*

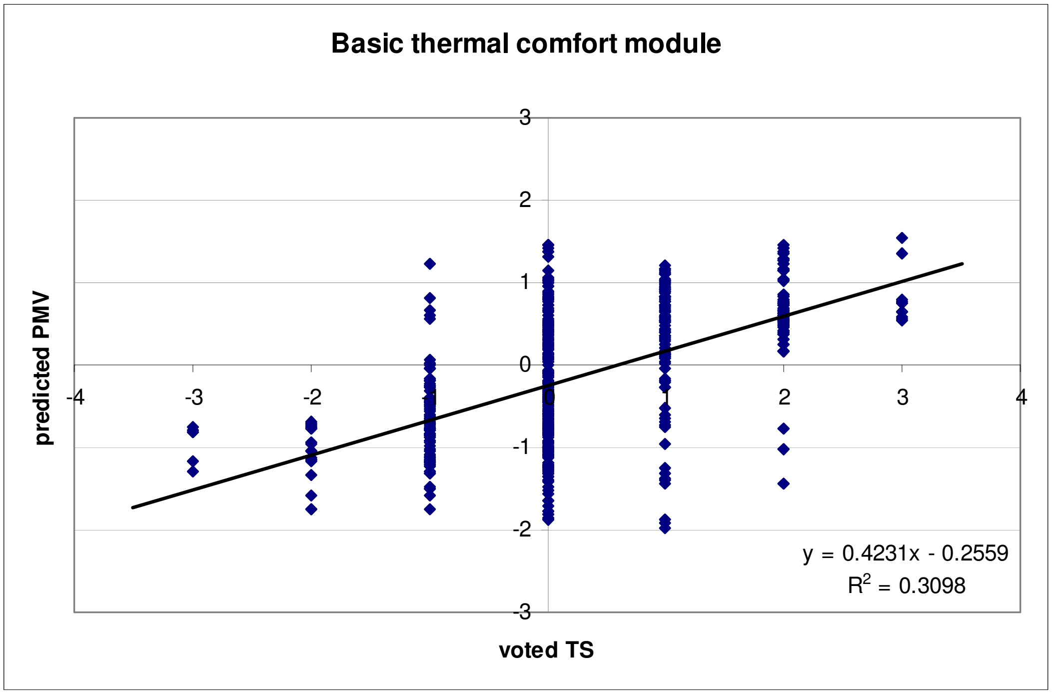


Figure 69: Accuracy of *basic thermal comfort model*

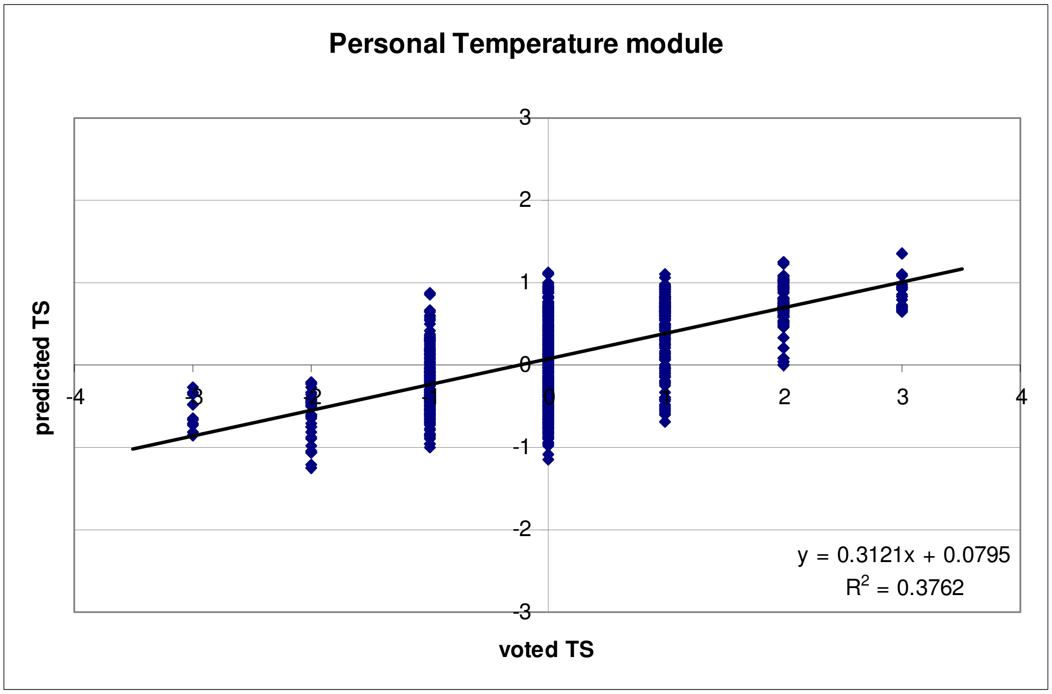


Figure 70: Accuracy of *personal temperature model*

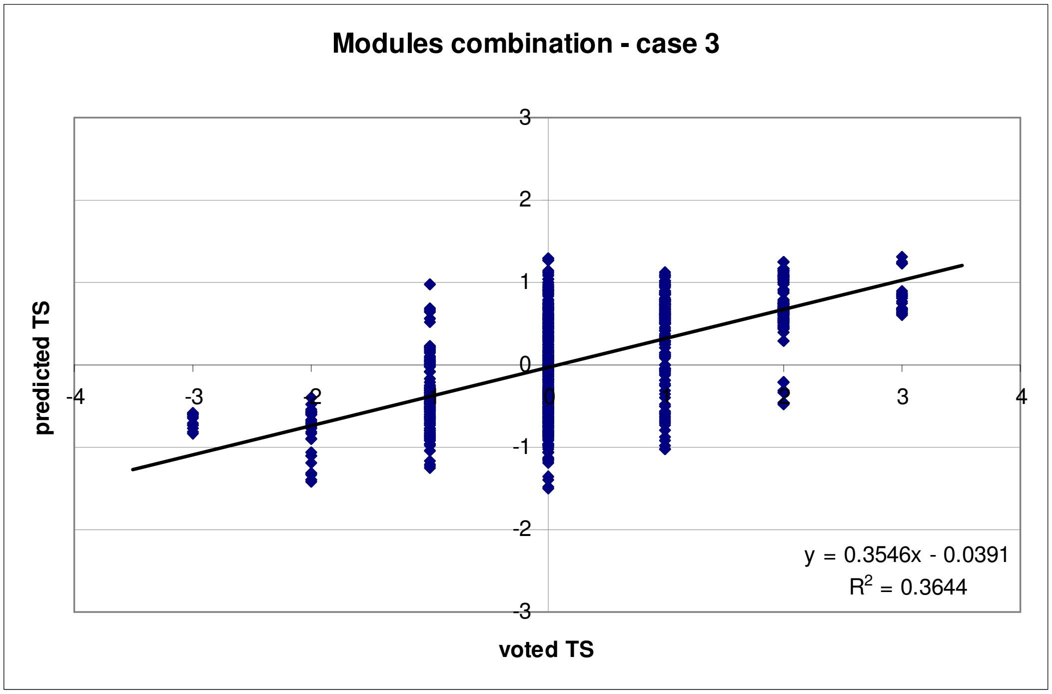


Figure 71: Accuracy of *TS* prediction when combining *basic thermal comfort model* and *personal temperature model* (combination 3)

8.5 Conclusions

A model for the prediction of the thermal sensation of a sedentary person sitting indoors has been presented in this chapter. This model combines the prediction made by standard methods for average people (PMV) with a more personalized methods accounting for skin temperatures and behavioural responses. This permits to create a better thermal comfort monitoring system which adapts itself to the needs or a given person, reaching a better understanding of his preferences and providing a more pleasant ambient temperature at all times.

Two of the modules of this global model have been assessed against actual thermal sensation votes of people at different environmental conditions. In general, thermal sensations are predicted to be milder than what voted by the volunteers, which seems reasonable as people tend to be negative when asked. R^2 values for the *basic thermal comfort model* and *personal temperature model* are 0.3098 and 0.3762 respectively. Variability is great due to the multiple physical and psychological factors affecting the thermal sensation that a person has within a given environment. It is noticeable that the PT model provides slightly greater accuracy than the BTC model, besides this is established as the standard. The combination of both models has a R^2 of 0.3644, hence provides a 5.5 % better prediction of the thermal sensation, which is a 17.6% more accurate than the BTC model in its own. The use of the combination of these two models is recommendable as it provides a more robust prediction of the thermal sensation, and regards not only the average people but also the minorities.

The inclusion of the behavioural adaptation model has not been assessed yet due to time constrains and it is due in future work. The improvement of the prediction of individual thermal comfort comes to the price of requiring a more complex physical system, i.e. larger and more complex set of sensors, but we believe this is the future of climate control systems.

9 Conclusions

9.1 Achievements

Thermoregulation as well as physiological (skin temperature and core temperature) and psychological (thermal sensation and thermal comfort) responses of a person to given environmental (e.g. temperature, humidity, air velocity) and personal (e.g. gender, age, clothing, activity level) conditions have been widely studied in the literature. Despite of the great interest in thermoregulation and thermal comfort, there are still areas which have not been fully addressed.

First of all, the **data field studies** of the skin temperature are limited. Most of the studies were performed in manikins or naked adults within environmental chambers in order to avoid the clothing effect. This does not reflect every day situations such as someone working in an office, travelling or going to the cinema, theatre, and so on. Also, female representation in these studies is very limited, and no data is available for young children. Furthermore, most of the data field studies focus in global parameters such as mean skin temperature, while they leave local skin temperatures unobserved. In order to overcome these weaknesses, skin temperature mapping was studied for 2 different cohorts: (1) children under the age of 2, and (2) adults while seated and performing low level activities.

For the first cohort 520 measurements were carried out in a total of 138 children at 16 different skin locations with equal female and male representation. Mean values of local skin temperature were obtained (**Appendix F** and **Figure 20**). The relevant factors (e.g. gender, age, body mass index, clothing and status such as sleeping or awake) for each location were identified by means of statistical methods. Clothing was observed to affect the skin temperature, its effect being stronger for greater insulative values. Also the status, defined as either awake or sleeping, was observed to have a significant effect in all local skin temperatures but at the back of the neck. Gender was found relevant only when considering the temperature of the hands. Temperature at lower limbs seems to be lower for those children of shorter age, which is consistent with the lower temperature at extremities found by Svedberg et al. in non-walking children between 2 and 7 years old [Svedberg, 2005]. Also the child's constitution, quantified by body mass index (BMI), rules the temperature at lower limbs and back of the body, where the increase of BMI is perhaps more visible. This temperature mapping is a straight contribution to the state of art as there is not other studies performed on young age children.

For the second cohort 806 measurement sessions were undertaken on 159 healthy and self-clothed adults, with equal female and male representation, under environmental temperatures conditions ranging 18 to 31°C. Volunteers were seated and either relaxing (e.g. watching a movie) or performing light activities (e.g. office work), hence typical every-day activities. The combination of these 4 characteristics (significant female representation, self-clothed people, typical indoor environmental temperatures and typical everyday low level activities) is what makes interesting this study, as it can be used for a better understanding and modelling of the people reactions at a great part of everyday life. Similarly to the previous case, typical values and relevant factors for each local skin temperature and the core temperature were identified. Observations were consistent with what found in the literature. Regarding the expected values, the ranking of skin temperatures observed in our study are in agreement with previously reported works [Burton, 1955][Werner, 1980a][Houdas, 1982][Webb, 1992][Huizenga, 2004][Munir, 2009]. Also, larger skin temperature variations with the environmental temperature were found in the limbs while forehead and trunk were more stable. Greater variability of skin temperature (i.e. standard deviation) was observed at colder environments as reported in the literature [Munir, 2009][Webb, 1992]. Only differences are in the absolute values, certainly due to the fact that many of the previous studies were performed in naked or severely underdressed people. Regarding the relevant factors, particularly interesting is the non-linear dependency of both core and local skin temperature on the environmental temperature, only pointed previously by Werner et al. [Werner, 1980a]. Also gender was found to be relevant for core temperature and skin temperature at forehead, hands, knees and shins. Clothing and core temperature increase the skin temperature while BMI decreases it at most of the locations, as also observed by Hardy et al. [Hardy, 1954] and Huizenga et al. [Huizenga, 2001]. The results were used for a further contribution to the state of art by deriving models for the prediction of core temperature and each local skin temperature. Multiple region (i.e. defined for different ranges of environmental temperature) multilinear regressions were obtained by means of the statistical bootstrap technique (equation **39**, coefficients enclosed in **Table**). This technique is very robust as it compensates for possible violation of the classical assumptions derived from the use of several samples taken from the same person for the database. The accuracy of these models is more limited than the current mean skin temperature models due to the large variability of local skin temperature even when the same individual characteristics and environmental conditions apply. However the models where the skin temperature is predicted for the body as a whole can not identify probable discomfort due to local conditions, while the new developed local skin temperature models could be applied.

Secondly, the great potential of **core temperature** for the **identification** of health problems and risks in every-day life is overlooked. In most of the cases the measurement of core body temperature aims to the identification of fever, i.e. abnormally high body core temperature. Fever might occur due to a health problem or the exposure to extreme hot conditions. In any case, its early detection can alert of high risk levels and eventually save lives. Furthermore, if feverish people is detected the spread of epidemics could be avoided. However, nowadays there are very limited options for continuous core temperature monitoring systems which could be used in non-clinical environments. Existing systems are either intrusive or only used at punctual times, e.g. during the security control at airports in case of epidemics. As a contribution to the state of art, two practical non-intrusive and continuous core temperature monitoring systems were developed, addressed to long-term and every-day use.

The first system addressed the identification of fever in children under 2 years old. This system identifies children with a statistically high probability of fever based only on the temperature of their skin. The temperature sensors are embedded on the clothing and do not require cables or any metal, hence can be worn without noticing it. This system is being developed in conjunction with a Spanish textile company (AITEX) and a patent is under consideration. Several options were studied, such as (1) different locations across the body and (2) the use of one or several sensors, either (a) at different locations and (b) at the same location. The individual locations found to be more efficient are upper arm (*T5*), scapula (*T3*), lower arm (*T6*), lower back (*T9*) and posterior thigh (*T11*). When used in its own, a fever alert given by one of these locations is right in a 40% of the cases on average if α_i (i.e. the detected false positives) is set at 10%; 30% if α_i is set at 20%. Better performance is achieved when several locations are used. The set T5-T3-T11 gives right alert in 67% of the cases if α_i is set at 10%, 49% if α_i is set at 20%. The set T5-T3-T6-T9-T11 gives right alert in 85% of the cases if α_i is set at 10% and 62% if α_i is set at 20%. When using different sensors at the same location, the specific probability of fever occurrence can be observed by the children cares, allowing different degrees of alarm, while all enable personalization. The downside for this option is that for 5 sensors placed at the same location the percentage of true alert is slightly lower, but still 70% for T5. Based on these results the set T5-T3-T6-T9-T11 was recommended as having the greater rate of success among the studied. On the other hand, the beta error is not null, like in other alert devices. This 5-sensor set misses 11% of the cases of children with fever. This value is fairly reasonable taking into account that this is not a clinical device and by non means attempts to substitute traditional methods for fever identification that one might use at home. This system is intended as support, allowing identification of high probabilities of fever occurrence even when the children carers would not have thought of measuring their core temperatures. However traditional methods should be used to conclusively diagnose fever.

The second sort of systems is directed to core temperature estimation in adults, either for long periods of time (e.g. while working at an office) or for mass adults screen (e.g. at airports), or even used along with existing comfort models for personalised environment. Several contact-less options were proposed, based on (1) skin temperature and environmental temperature, and (2) on infrared images of ears. The first system is based on the relation between core temperature and skin temperature and environmental temperature. Several locations were studied from which the combination of forehead (T0) and hands (T7) when combined with room temperature and humidity was observed to reflect the core temperature more closely according with the Akaike's technique. Forehead temperature is widely described in the literature and popular for a rough identification of fever. However, this work shows that its combination with the temperature at other locations and the environmental temperature improves the accuracy of the core body temperature estimation. A multi-linear regression model was derived using the aforementioned parameters. The proposed model presents a standard error estimate of 0.31°C, which might seem high but is quite acceptable for a contactless system. Constrains for the T0 and T7 values do not apply. The second system is based on the relation between core temperature and that measured at the ear aperture with an infrared camera, reflecting the inner ear temperature. Besides the wide recognition of tympanic temperature as an approximation of the core temperature, no report of contactless methods for its measurement was found in the literature. Our study proved that core temperature can be successfully estimated by a combination of descriptors extracted from the IR images, such as maximum and average temperature around the ear aperture, and provided a model for it. Room temperature was also included in this model. Both systems, based on skin temperatures and infrared images of ears, are novel systems for the estimation of core temperature in a contactless way (i.e. would allow non invasive temperature monitoring) hence they are an important contribution to the state of art. Their typical error is 0.3°C which is good for non-clinical systems such as these ones.

Thirdly, physiological (core temperature and skin temperature) and psychological (thermal sensation and comfort level) responses to the same steady-state environmental conditions are study in the literature. However the total time a person has spent within that environment has not been accounted for, although it is of great interest as it is the typical situation in every-day life (e.g. people watching a movie spend 3 hours in the cinema, people working spend in the office about 4 hours before going for lunch, and so on). As a contribution to the state of art, the **effect of long periods of time** under the same conditions on the fore mention parameters while keeping low activity level (varying from watching a movie to chatting to performing typical office activities) has been studied.

Physiological and psychological responses were monitored in 106 self-clothed and healthy adults, with equal female and male representation, who remained seated for periods of 165 to 195 minutes while performing low level activities. Local skin temperature, thermal sensation and comfort level were observed to change significantly with long periods of time. Among the studied locations, lower limbs presented the greatest change on temperature while forehead, upper arms and chest were the most stable. These findings were expected, as for thermoregulation temperature at limbs is the first that changes in order to keep the body heat balance, while temperature at locations closer to the core stay constant for longer. Regarding the thermal sensation, it was observed that people might feel the environment like hotter or colder than they originally did (depending on the environmental temperature) when they stay for long periods of time under the same conditions, which would decrease their level of comfort. In general, the rate of change in any of the above responses depends on the room temperature except the temperature at the abdomen area or the core temperature (which makes sense as they are meant to remain constant for a range of room temperatures). Multi-linear regression models were derived for the rate of change of each skin temperature, the core temperature, the thermal sensation, and the comfort level after the relevant factors at each case were identified (i.e. from the set of environmental temperature, environmental humidity, core temperature, age, BMI, gender and clothing). R-values for these models range 0.35-0.70, which are significant taking into account the great complexity of the thermoregulatory system and how subjective the thermal sensation is. After this study there is proof that time within an environment should be accounted for. This knowledge leads to more accurate human response prediction models applicable to daily activities, e.g. working in offices, relaxing while watching a movie or travelling.

Fourthly, **thermal comfort models** have been developed for the prediction of level of comfort and thermal sensation of adults in indoor environments. The most widely used model is the Fanger's steady-state model, which is based on statistical studies hence it considers only the average response of a large group of people. The ongoing research in thermal comfort aims to propose more efficient environmental control systems based on thermal comfort models, both as energy-saving and adaptability to different individuals. As contribution to the state-of-art this work presents a novel thermal sensation and comfort level monitoring system which adapts for each particular person, such that also applies to the minorities. The system is based on statistical studies in the literature and Fanger's steady-state model, as appropriated for most indoor conditions. However the proposed system is personalized by means of a real time thermal sensation model, earlier developed based on temperature measurements of the subjects. Just this addition improves the accuracy on a 17.6%. Furthermore, the system identifies behavioural responses of the person such as the use of personal air conditioning devices, and uses that information as feedback to adapt itself for that particular person. The effect of time, when remaining seated for long periods, is also included in the model. Outdoor environmental conditions to which the volunteer was subjected to are also taken into account. As an active system, the model indicates not just the comfort level but estimates the preferred temperature for each person, leading to a personalized response for a greater comfort. This thermal comfort model was developed within the international FP6 project SEAT, sponsored by the European Commission DG H.3 Research (Aeronautics Unit). This model was specifically tailored for its use in long haul flights, but it could be used for the majority of sedate activities. This model adapt in real time to particular individuals, something which allows a better understanding of the comfort situation of a given person and a better adaptation to his/her requirements.

Several are the applications of the research presented in this work. (1) Continuous core temperature monitoring in children for early detection of fever. This is especially interesting when the rate of children per carer is high (e.g. nurseries or schools). (2) Core temperature monitoring systems for adults, either for long periods of time or mass screen in largely busy spaces such as airports. (3) Thermal comfort monitoring system for the adaptation of the environmental conditions to the needs of its occupants. (4) System for the identification of optimal environmental conditions in a largely occupied space, such as cinemas or planes.

9.2 Future work

Wide has been the interest of thermoregulation and thermal comfort in the literature and after our contribution still much remains to be done. The following next steps are proposed to complement the investigations presented in this work:

(1) Readjustment of the estimated errors for the fever recognition system in infants as they are very conservative. The current development of the fever detection system for infants was based on a fairly healthy group of infants as measurements were taken in nurseries, were children with high fever are not allowed. Hence, the obtained mapping of skin temperatures of the feverish children is characteristic for mild fevers, which present typically lower values than in case of high fever, reason why the accuracy of the system seems lower than it can be. Therefore, a more extensive data collection in highly feverish children, and the re-assessment of the model is recommended.

(2) Evaluation of the fever recognition system in infants in an independent sample and a further follow up of the system accuracy when used by untrained people.

(3) Development of a core temperature monitoring system which uses environmental conditions and both skin and inner ear infrared temperature measurements. The two methods (skin temperature versus infrared images of ears) were studied independently and found to give an approximation of the core temperature with a typical 0.3°C of error. Combining the two systems is very likely to improve the detection performance. Also a larger data collection of IR images of ears and their corresponding core temperature is advisable.

(4) The forehead temperature is required for the prediction models of core temperature and thermal sensation, hence must be correctly identified. The development of a more robust routine for the identification of forehead temperature from the 16-IR-array-sensors is recommended.

(5) The local skin temperature models were obtained by a bootstrap technique using all the available data in the basis that this technique compensates the violation of classical assumptions. Models were then evaluated using the complete data sample. Further evaluation is recommended in an independent data sample.

(6) The current thermal comfort level model uses, when available, information from the postural module which identifies the position of a person in his/her seat based on readings from a force plate placed under the seat. This is not really practicable for every day situations, hence the development of an alternative activity model is recommended. The current postural module has not been reported in this document as it was not part of this research work.

(7) The proposed thermal comfort model is composed of three modules whose predictions would be combined in the decision module. Those are (a) basic thermal comfort model, (b) personal temperature module, and (c) behavioural adaptation module. So far, the system has been evaluated only with (a) and (b) working together because of the lack of data. Hence, a field study to observe behavioural adaptation regarding individual units or air supply is proposed. Next would be the evaluation of the full model.

(8) Steps of environmental temperature are known to affect the thermal sensation and so they should be studied and included in the thermal comfort model for more accurate responses.

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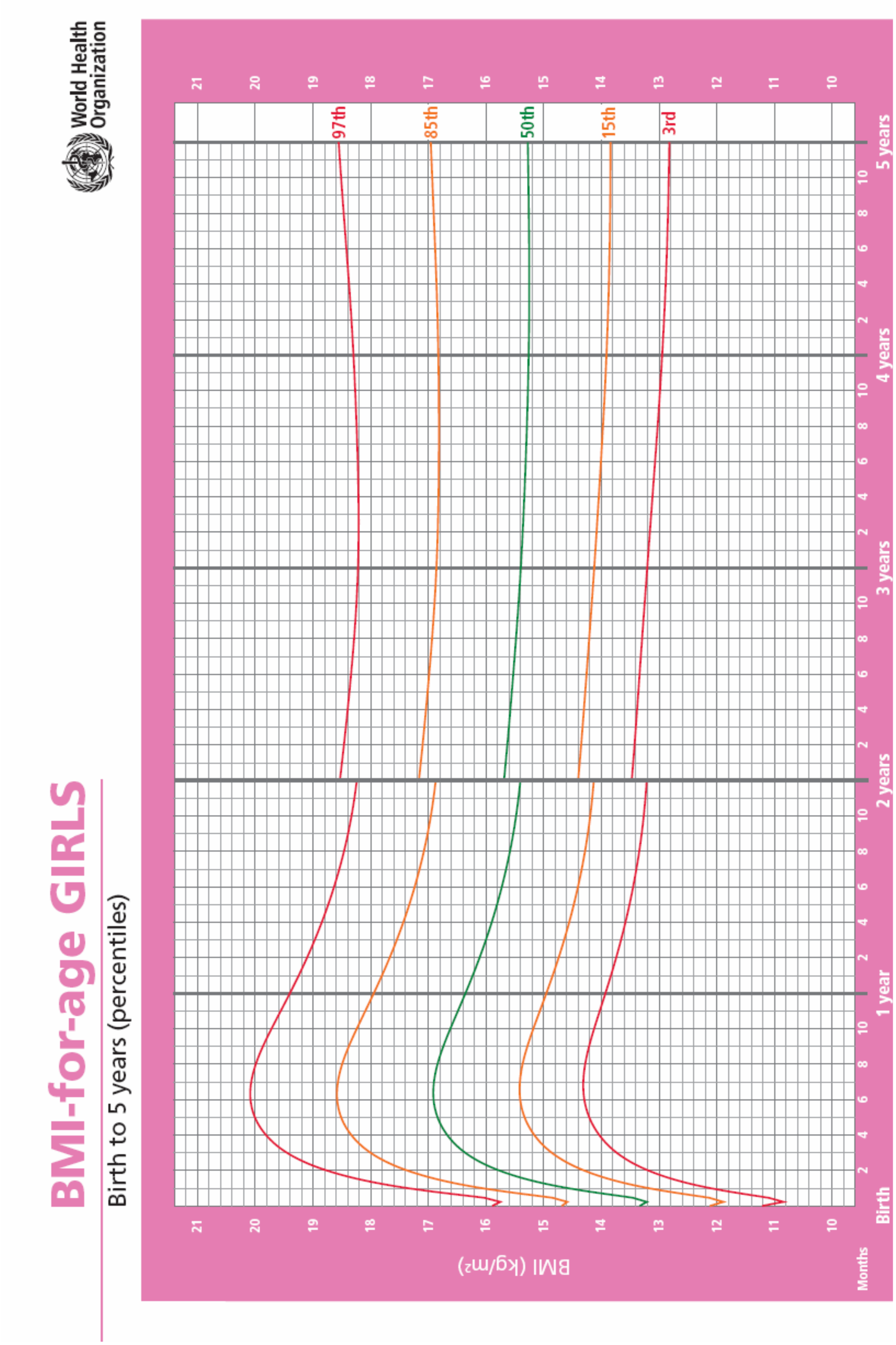
Appendices

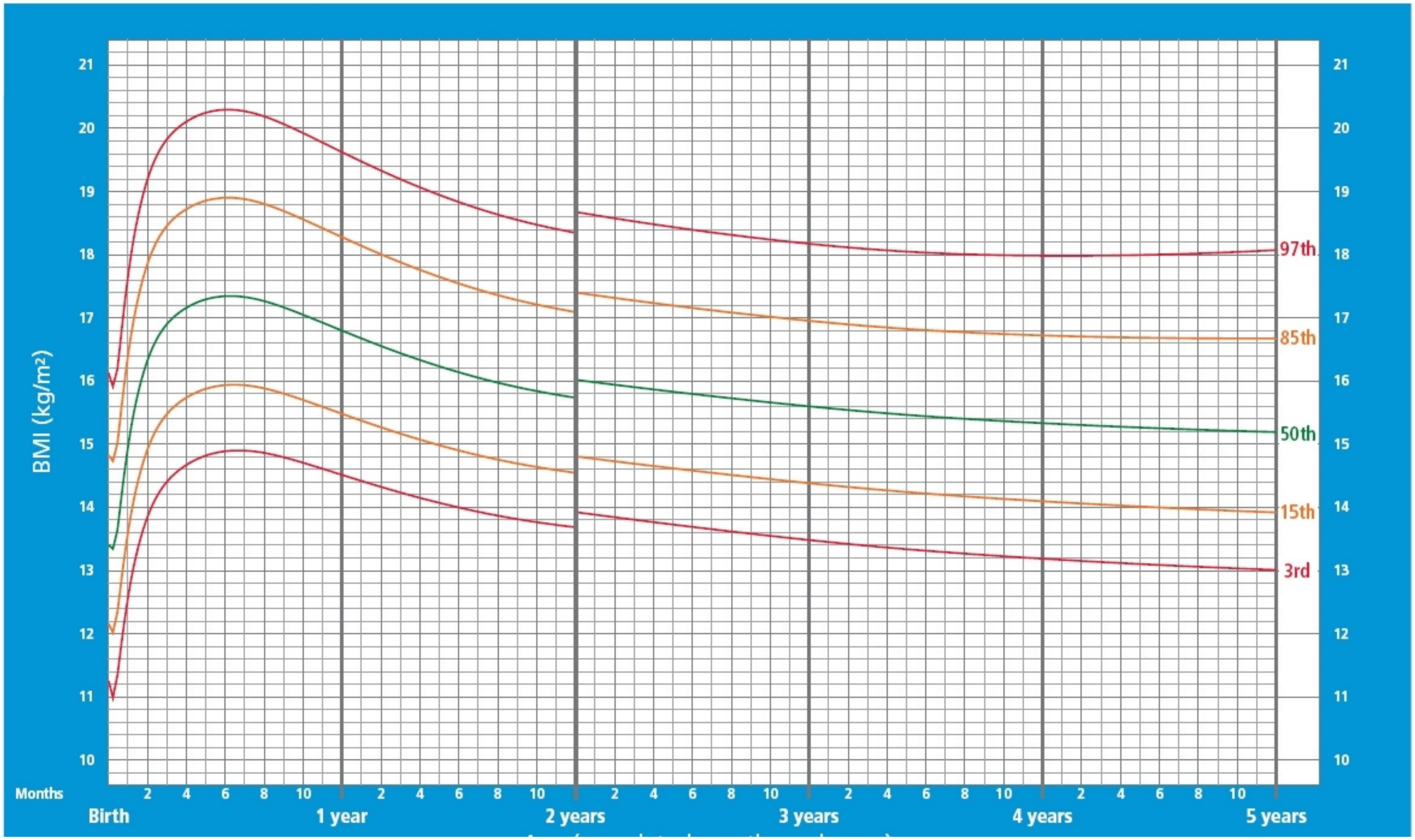
Appendix A: WHO Child Growth Standards



BMI-for-age BOYS

Birth to 5 years (percentiles)

World Health Organization



Appendix B: Thermal insulation of individual garments

Garment description	I_{clu} (clo)
Underwear	
Panties	0.03
Pants, short legged	0.04
Underpants with long legs	0.10
Singlet	0.04
T-shirt	0.09
Shirt with long sleeves	0.12
Panties and bra	0.03
Shirts, blouses	
Short sleeves	0.15
Light-weight, long sleeves	0.20
Normal, long sleeves	0.25
Flannel shirt, long sleeves	0.30
Light-weight blouse, long sleeves	0.15
Trousers	
Shorts	0.06
Light-weight	0.20
Normal	0.25
Flannel	0.28
Dresses, skirts	
Light skirt (summer)	0.15
Heavy skirt (winter)	0.25
Light dress, short sleeves	0.20
Winter dress, long sleeves	0.40
Sweaters	
Sleeveless vest	0.12
Thin sweater	0.20
Sweater	0.28
Thick sweater	0.35
Jackets	
Light, summer jacket	0.25
Jacket	0.35
Smock	0.30
Outdoor clothing	
Coat	0.60
Down jacket	0.55
Parka	0.70
Fibre-pelt overalls	0.55
Sundries	
Socks	0.02
Thick, ankle socks	0.05
Thick, long socks	0.10
Nylon stockings	0.03
Shoes (thin soled)	0.02
Shoes (thick soled)	0.04
Boots	0.10
Gloves	0.05

Table B1: Sample of thermal insulation of individual garments retrieved from ISO 9920: 1995

Appendix C: Ethical approval QMREC2008/31

The research work presented in Chapter 2 was approved by QMUL ethics committee, reference QMREC2008/31. The forms are attached.

C-1) Information sheet

Fever recognition in children aged between 0 and 24 months using skin temperature distribution

REC Protocol Number QMREC2008/31

We would like to invite you to take part in our research project. You do not have to take part if you do not want to. If you decide not to take part in the project, you will not be disadvantaged in any way.

Before you decide whether or not to take part, read this carefully. You need to understand why we are carrying out this research and what is involved Please take the time to read the following information carefully and discuss it with others if you want to. Ask us if there is anything that you do not understand or if you need any more information.

We want to find out if a child has a fever by measuring his/her skin temperature. After we measure the temperature of a significant number of children, it will be possible to design smart clothing. This clothing will monitor the child's temperature and will raise an alarm in case the child has a fever.

For our study, we need to check the temperature of your baby at different times of the day. This measurement process will not put your baby at any risk and will cause very little disturbance. We will measure two different temperatures of your baby: temperature on the skin and temperature in the ear. The thermometers we use are approved by NHS. (Please see the pictures of them at the bottom of the page)

The study **only** involves children aged 0 to 24 months and no further restriction in place. During the study we will be not checking if the children have a raised temperature that parents or nurses have missed.

If you agree to take part in this study we will:

- Measure the core temperature of your baby. This will be done with an ear thermometer like the one that doctors use. We will place it in your baby's ear and wait for few a seconds until the thermometer gives the temperature. Each time an ear temperature is taken, the thermometer will have a clean, fresh cover put over it (that will not be used on any other baby). This is to make sure that your baby will not be put at any risk of picking up any germs from the thermometer or another child.
- Measure the skin temperature of your baby at different parts of the body like head, arms, legs, feet, back and tummy. We will use a simple infrared

thermometer for measuring the skin temperature. We will need to place the sensor close to your baby's skin for a couple of seconds. This sensor does not have to touch the baby.
- Ask what is the weight, height and age of your baby

We will measure the temperature of your baby in the nursery, so we will not disturb you. We will take his/her temperature at different times of the day (before lunch, after lunch, while he/she is sleeping and playing). We will take these measurements over a maximum of 5 days. We only need 3-4 minutes to measure the temperature in each case.

None of this information could be used to identify your child. We will not record any personal data. Even if we publish the results, we do not need personal data.

The information will be used by Queen Mary, University of London and AITEX. AITEX is a company from Spain which works on fabrics. AITEX will manufacture the smart clothing we described before.

If you do decide to take be part in this study, you will not have to travel anywhere. We will give you the information in the nursery and we will take the measurements there as well. However, if you happen to spend some extra money in travelling or other small costs, we will reimburse you.

If you do decide to take part you will be given this information sheet to keep and also be asked to sign a consent form. You may withdraw at any time and without giving a reason.

Please note that we have to inform the authorities if we realize that a child is under serious threat of abuse.

Our university (Queen Mary, University of London) has insurance. In the unlikely event of your baby suffering any problem as a consequence of your participation in this study, you will be compensated.

In these pictures you can see the thermometers we will use.

Ear thermometer

Skin thermometer

C-2) Consent form

Please complete this form after you have read the Information Sheet and/or listened to an explanation about the research.

Title of Study: “Fever recognition in children aged between 0 and 24 months using skin temperature distribution”

Queen Mary Research Ethics Committee Ref: QMREC2008/31

- Thank you for considering taking part in this research. The person organizing the research must explain the project to you before you agree to take part.
- If you have any questions arising from the Information Sheet or explanation already given to you, please ask the researcher before you decide whether to join in. You will be given a copy of this Consent Form to keep and refer to at any time.
- *I understand that if I decide at any other time during the research that I no longer wish to participate in this project, I can notify the researchers involved and be withdrawn from it immediately.*
- *I consent to the processing of the personal information of my child for the purposes of this research study. I understand that such information will be treated as strictly confidential and handled in accordance with the provisions of the Data Protection Act 1998.*
- ***Optional :*** *I agree to be contacted in the future by QMUL researchers who would like to invite me to participate in follow up studies to this project, or in future studies of a similar nature.* ***Tick here for approval [ ]***

Participant’s Statement:

I ____ agree that the research project named above has been explained to me to my satisfaction and I agree to take part in the study. I have read both the notes written above and the Information Sheet about the project, and understand what the research study involves.

Signed: Date:

Investigator’s Statement:

I ____ confirm that I have explained the nature, demands and any foreseeable risks (where applicable) of the proposed research to the volunteer.

Signed: Date:

Appendix D: Ethical approval QMREC2008/72

The research work presented in Chapter 3, 4 and 5 was approved by QMUL ethics committee, reference QMREC2008/31. The forms are attached.

D-1) Information sheet

Relation between the core body temperature and surface temperature distribution in adults

Queen Mary Research Ethics Committee Ref: QMREC2008/72

We would like to invite you to take part in our research project. You do not have to take part if you do not want to. If you decide not to take part in the project, you will not be disadvantaged in any way as your identity is not going to be noted or revealed.

Before you decide whether or not to take part, read this carefully. You need to understand why we are carrying out this research and what is involved. Please take the time to read the following information carefully and discuss it with others if you want to. Ask us if there is anything that you do not understand or if you need any more information.

We want to find out the core temperature of an adult by measuring his/her skin temperature. After we measure the temperature of a significant number of adults, it will be possible to design a smart environment control system. This system will monitor the persons' temperature and will modify the room temperature according to the needs of the person.

For our study, we need to check your temperature. This measurement process will not put you at any risk and will cause very little disturbance. We will measure two different temperatures: temperature on the surface of the body and temperature in the ear. The thermometers we use are approved by NHS. (Please see the pictures of them at the bottom of the page). Also a thermal camera will be used. This camera takes only pictures of the heat, so the person can not be recognized on them.

The study **only** involves people over 18 years and no further restriction in place.

If you agree to take part in this study **we will**:

- **Measure your core temperature.** This will be done with an ear thermometer like the one that doctors use. We will place it in your ear and wait for few a seconds until the thermometer gives the temperature. Each time an ear temperature is taken, the thermometer will have a new, clean and fresh cover put over it (that will not be used on any other person). This is to make sure that you will not be put at any risk of picking up any germs from another person through the thermometer.
- **Measure your surface temperature** at different parts of the body like head, neck, arms, forearms, legs, feet, back, upper chest and stomach area. Those measurements will be taken over the clothing. We will use a simple infrared thermometer for measuring the surface temperature. We will need to place the sensor close to the surface for a couple of seconds. This sensor does not have to touch you.
- **Measure your skin temperature** at different parts of the body like head, neck, arms, forearms, lower legs, feet, back, upper chest and stomach area. Those measurements will be taken under the clothing if you feel comfortable with it. We will

use in this case the same infrared thermometer as for the surface temperature. We will need to place the sensor close to your skin for a couple of seconds. This sensor does not have to touch you. You will not be asked to undress but to pull up for few seconds your sleeves, trousers or your top in order to measure on arms, lower legs, back and stomach area. In case you do not feel comfortable with us measuring on some of those locations, please indicate it to the researcher and we will skip them. There will be a female researcher on stand-by for taking measurements of female volunteers if required, with full privacy.

- **Take infrared images** from the different parts of the body like head, neck, arms, forearms, legs, feet, back, upper chest and stomach area. In any case a person can not be recognized by such images as they only show the temperature values in each point.
- **Ask what your weight, height and age is** (optional: you can decide whether to provide this data or not).
- **Ask roughly what garments you are wearing**, like skirt, trousers, jacket, long sleeves top or T-shirt.

None of this information can be used to identify you. We will not record any personal data. Even if we publish the results, we do not need personal data.

We will measure the temperature of your body in the School of Engineering and Materials Science. We will ask you to stay in the laboratory between two and three hours, depending on how much time you can spare. In this way we can record your temperature at different times. The maximum we spend in one measurement is 5 minutes. You can bring something to read, to work or also for entertainment. We can project a movie so you have a small cinema session.

The information will be used only by Queen Mary, University of London.

If you do decide to take part in this study, you will not have to travel anywhere. We will give you the information by e-mail or in person, if you prefer it that way. All meetings and measurement sessions will take place at the installations of the University.

If you do decide to take part, you will be given this information sheet to keep and also be asked to sign a consent form. You may withdraw at any time and without giving a reason.

Our university (Queen Mary, University of London) has insurance. In the unlikely event of you suffering any problem as a consequence of your participation in this study, you will be compensated

In these pictures you can see the thermometers we will use.

Ear thermometer

Skin thermometer

D-2) Consent form

Relation between the core body temperature and surface temperature distribution in adults

Queen Mary Research Ethics Committee Ref: QMREC2008/72

Please complete this form after you have read the Information Sheet and/or listened to an explanation about the research.

. • *Thank you for considering taking part in this research. The person organizing the research must explain the project to you before you agree to take part.*

. • *If you have any questions arising from the Information Sheet or explanation already given to you, please ask the researcher before you decide whether to join in. You will be given a copy of this Consent Form to keep and refer to at any time.*

. • *I understand that if I decide at any other time during the research that I no longer wish to participate in this project, I can notify the researchers involved and be withdrawn from it immediately.*

. • *I consent to the processing of my personal information for the purposes of this research study. I understand that such information will be treated as strictly confidential and handled in accordance with the provisions of the Data Protection Act 1998.*

. • ***Optional :** I agree to be contacted in the future by QMUL researchers who would like to invite me to participate in follow up studies to this project, or in future studies of a similar nature. **Tick here for approval [ ]***

.

.

Participant's Statement:

I ____ agree that the research project named above has been explained to me to my satisfaction and I agree to take part in the study. I have read both the notes written above and the Information Sheet about the project, and understand what the research study involves.

Signed: Date:

Investigator's Statement:

I, Dr. Peter Dabnichki, confirm that we have explained the nature, demands and any foreseeable risks (where applicable) of the proposed research to the volunteer.

Signed: Date:

Appendix E: Features of the measuring devices

TH03F Thermometer

Manufacturer	Radiant Innovation Inc
Europe Representative	Medscope Ltd.
Accuracy	± 0.1˚C during 34 – 42.2 ˚C ± 4% or ± 2˚C whichever is greater otherwise
Measuring time	0.6 seconds
Storage environment	Temperature within (-20, 50) ˚C
Operating environment	Temperature within (10, 40) ˚C
Compliance with	ASTM E1965-98, IEC60601-1, IEC60601-1-2(EMC) standards.

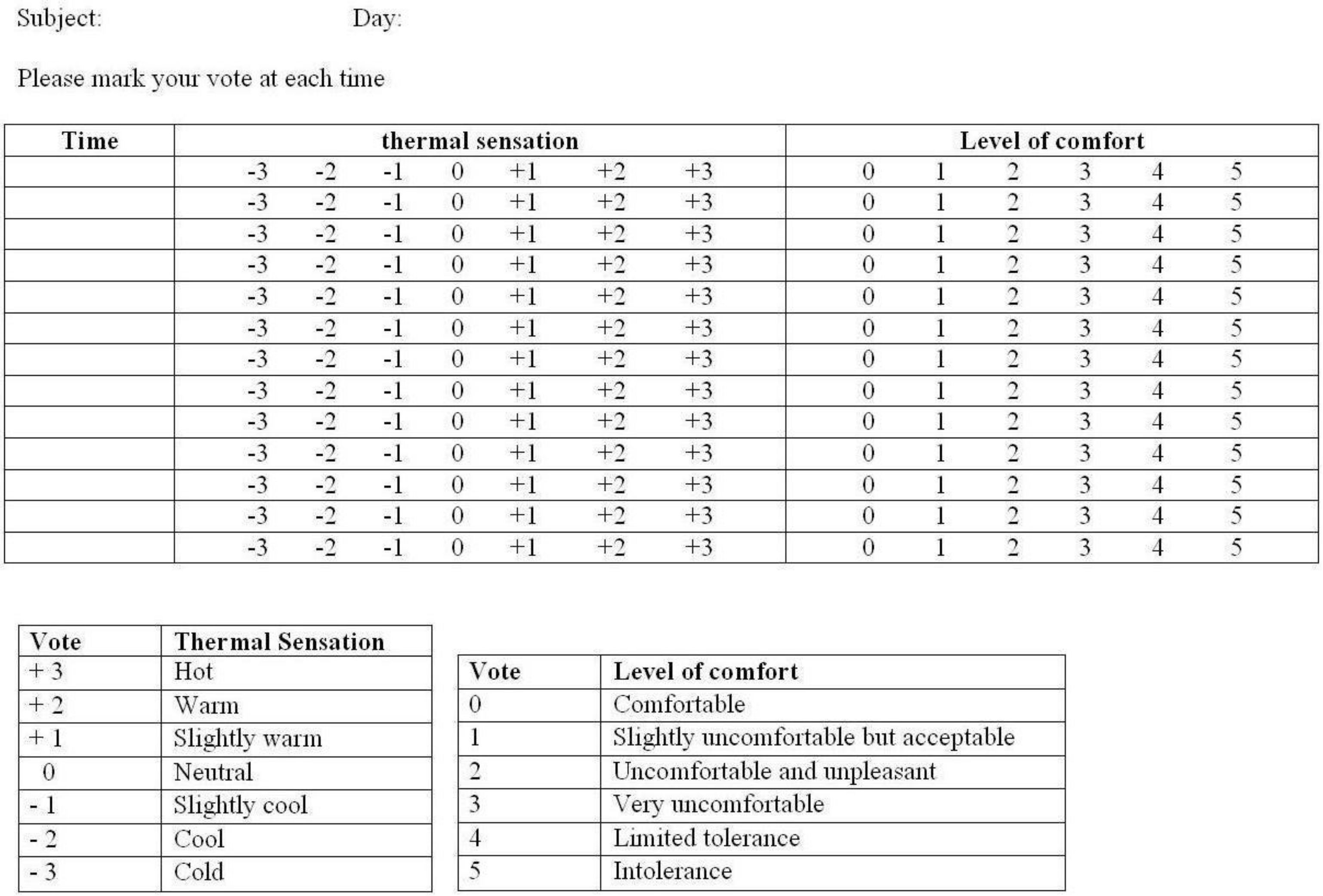
Gentle Temp 510

Manufacturer	OMRON HEALTHCARE Co,. Ltd.
EU Representative	OMRON HEALTHCARE EUROPE B.V.
Model	MC-510-E2
Sensor	Thermopile
Precision	± 0.1˚C during 34 – 42.2 ˚C according to NEN-EN 12470- 5 Clinical thermometers – Part 5 Performance on infra-red ear thermometers (with maximum device). Based on the measurement of the standard black body at the room temperature of 25 ˚C (RH 50%)
Measuring time	10 seconds
Storage environment	Temperature within (-20, 60) ˚C, RH within (30, 95)%
Operating environment	Temperature within (10, 40) ˚C, RH within (30, 85) %
Compliance with	ASTM E1965-98, IEC60601-1, IEC60601-1-2(EMC) standards.

Fluke TiR1

Manufacturer	Fluke Corporation
EU Representative	Fluke Europe B.V.
Temperature range	(-20, 100) ˚C
Accuracy	±5 ˚C or 5% (whichever is greater)
Precision	≤ 0.07 ˚C at 30 ˚C (70 mK)
Storage environment	Temperature within (-20, 50) ˚C without batteries, RH within (10, 90)
Operating environment	Temperature within (-10, 50) ˚C, RH within (10, 90)
Field of view	23˚ * 17˚
Spatial Resolution (IFOV)	2.5 mRad
Minimum focus distance	15 cm
Image frequency	9 Hz refresh rate
Focus	Manual
Detector type	160 x 120 Focal plane array, uncooled microbolometer
Infrared lens type	20 mm EFL, F/0.8 lens
Infrared spectral band	7.5 µm to 14 µm
Compliance with	Safety Standards: IEC/EN 61010-1 2nd Edition Pollution Degree 2 Electromagnetic Compatibility: EN61326-1; IEC/EN 61326 and CFR 47, Part 15 Class A Vibration: 2G, IEC 68-2-29 Shock: 25G, IEC 68-2-6
Others	On-screen emissivity correction

Appendix F: Thermal sensation and comfort questionnaire



Subject: Day:

Please mark your vote at each time

Time	thermal sensation							Level of comfort					
	-3	-2	-1	0	+1	+2	+3	0	1	2	3	4	5
	-3	-2	-1	0	+1	+2	+3	0	1	2	3	4	5
	-3	-2	-1	0	+1	+2	+3	0	1	2	3	4	5
	-3	-2	-1	0	+1	+2	+3	0	1	2	3	4	5
	-3	-2	-1	0	+1	+2	+3	0	1	2	3	4	5
	-3	-2	-1	0	+1	+2	+3	0	1	2	3	4	5
	-3	-2	-1	0	+1	+2	+3	0	1	2	3	4	5
	-3	-2	-1	0	+1	+2	+3	0	1	2	3	4	5
	-3	-2	-1	0	+1	+2	+3	0	1	2	3	4	5
	-3	-2	-1	0	+1	+2	+3	0	1	2	3	4	5
	-3	-2	-1	0	+1	+2	+3	0	1	2	3	4	5
	-3	-2	-1	0	+1	+2	+3	0	1	2	3	4	5
	-3	-2	-1	0	+1	+2	+3	0	1	2	3	4	5

Vote	Thermal Sensation
+ 3	Hot
+ 2	Warm
+ 1	Slightly warm
0	Neutral
- 1	Slightly cool
- 2	Cool
- 3	Cold

Vote	Level of comfort
0	Comfortable
1	Slightly uncomfortable but acceptable
2	Uncomfortable and unpleasant
3	Very uncomfortable
4	Limited tolerance
5	Intolerance

Appendix G: Identification of alpha and beta errors

G-1) Z-test

Two normal distributions can be compared using the *z-test* when the samples are large enough could. The main uses of the *z-test* are the comparison of the average of a sample with an external standard and the comparison of the averages of two samples. The *z-tests* define the observed significance level as shown in equation **G1**. Hence, z indicates how many SEs away an observed value is from its expected value.

$$Z = \frac{observed - \exp ected}{SE} \tag{G1}$$

In the specific case where one wants to compare two distributions to determine whether the two sets of data belong to the same population the *null hypothesis* says: the two samples are equivalent and hence, the difference in their values averages zero. Let us to define two distributions X_1 and X_2. X_1 is characterized by its mean value, μ_1, standard deviation, σ_1 and number of samples, n_1. In the same way, X_2 is characterized by μ_2, σ_2 and n_2. Then the statistical Z-test is as given in the equation **G2**.

$$Z = \frac{|\mu_1 - \mu_2|}{\sqrt{\frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2}}} \tag{G2}$$

The use of *one-tailed z-test* or *two-tailed z-test* depends on the specific form of the alternative hypothesis. The *one-tailed z-test* is appropriate when the alternative hypothesis says that the average of the parameter for the whole population is bigger than a given value. The *two-tailed z-test* is appropriate when the alternative hypothesis says tat the mentioned average differs from the given value, being either bigger or smaller.

For the identification of significant difference using one-tailed z-test, the Z_{limit} = 1.64 (see **Appendix H**). Instead, when a two-tailed test is being carried out, the limit value is Z_{limit} = 1.96. Obtained value Z is compared with Z_{limit} and according to **Table G1** one can see if both of the distributions belong to the same one. For the identification of high difference, the Z_{limit} are 2.33 and 2.58 for one and two-tailed tests respectively. In this reseach we used the *two-tailed z-test*, as it is more restrictive than the *one-tailed z-test*.

Case	Meaning
$Z > Z_{limit}$	Distributions X_1 and X_2 can be considered as different
$Z \leq Z_{limit}$	Distributions X_1 and X_2 can be considered as belonging to the same one.

Table G1: Z cases for identification of significant difference between two distributions.

G-2) Overlap between two distributions: alpha and beta errors

When two distributions partially overlap, the identification of a new element into one of the two categories can not always be done easily and without risk of mistaken.

Let us say that there are two distributions H_0 and H_a. A new element X_i has to be associated with one of those categories. However X_i value falls in the region where both distributions overlap. To resolve this problem a statistical test is proposed. Assuming that X_i belongs to the distribution H_0, the next procedure is follow:

The elements of a Statistical Test:

1. Null hypothesis, H_0: hypothesis to be tested (it was assumed that X_i belongs to this category)
2. Alternative hypothesis, H_a: research hypothesis. Hypothesis which will be accepted in case H_0 is rejected.
3. Test statistic: function of the sample measurements
4. Rejection region, *RR*: specifies the values of the test statistic for which the null hypothesis is to be rejected in favour of the alternative hypothesis.

For any rejection region defined by a threshold value of X, there are always two types of errors which can be made. We can decide in favour of H_a when H_0 is true (make a *type I error*), or we can decide in favour of H_0 when H_a is true (make a *type II error*).

A *type I error* is made if H_0 is rejected when H_0 is true, that means loosing a true positive. The *probability of a type I error* is denoted by α. The value of α is called the *level* of the test. A *type II error* is made if H_0 is accepted when H_a is true, that means creating a false positive. The *probability of a type II error* is denoted by β. See **figure G1** for easier error identification.

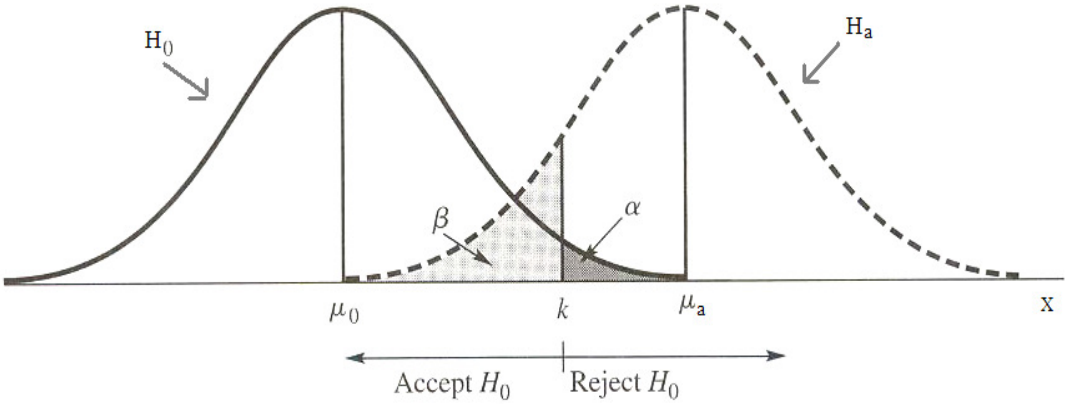


Figure G1: Representation of errors alpha and beta.

Having set the threshold value as *k*, two things can happen:

- $X_i \leq k$ and then the X_i sample is be associated with the distribution H_0
- $X_i > k$ and then the X_i sample is be associated with the distribution H_a

However, as it can be in the figure, there is always risk of make a mistake, that is:

- Loose a true positive: if X_i is bigger than *k* but it still belongs to H_0. X_i will be rejected. The probability of this to happen is equals to the area named as alpha.
- Accept a false positive: if X_i is equals or smaller than *k* but it still belongs to H_a. X_i will be rejected. The probability of this to happen is equals to the area named as beta.

When setting a threshold to categorize new samples into one of those two distributions, one has to decide which the sort of error (alpha or beta) will try to minimize. In the best of the cases, a value for k can be chosen which compromise both of the errors, always in favour of the more serious error for each given case.

G-3) Selecting threshold in alpha-beta graphs

This section presents simple methods for the identification of a threshold and its error value by using any given alpha and beta error graph. Some times more than one alpha error curve or beta error curve is given. This is the case when two or more groups are being analysed separately and their characteristic error curves are significantly different. Then, one needs to decide weather the threshold under decision will be applied to one individual subgroup between the studied ones or to several of them. The method for the identification of the appropriate threshold value in both of the cases is presented below.

Let us say that we have two groups of people (hence two sets of alpha and beta error curves as presented in **figure G2**) and that we want to know the best temperature value for the identification of a fever. If a precise threshold wants to be selected, each of the studied subgroups has to be analysed individually. Due to the fact that there is two subgroups, two thresholds need to be determined, one for each of the subgroups. The procedure can be seen in the **figure G3** and it is as follows:

1) Select the desirable alpha (or beta) error value. In the case of **figure G3**, an alpha error of 20% was selected (this is just an example).
2) Values of 20 are identify in the alpha curves (see red dots)
3) Check the corresponding beta (or alpha) error value and see whether it is within a reasonable range. In this case, the beta error for subgroup 1 would be 65% while it is 55% for the subgroup 2.
4) Identify the threshold temperature for each of the subgroups. In this case, the temperature limit for the subgroup 1 should have to be 32.0°C while the temperature limit for subgroup 2 would be 32.8°C

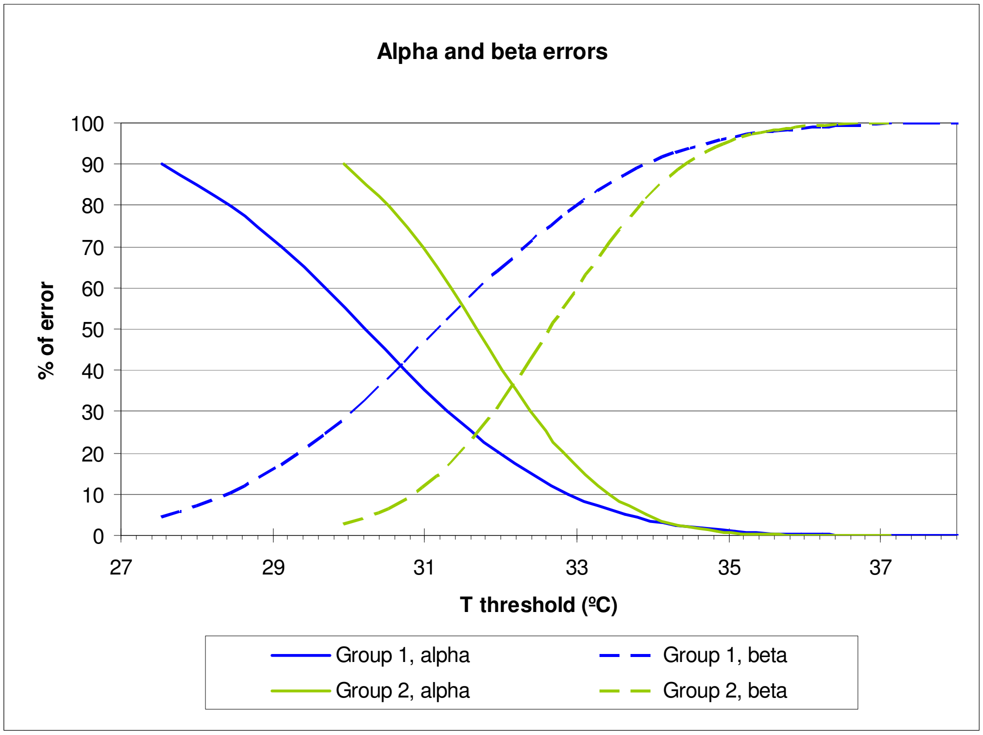


Figure G2: Example of location with 2 different studied subgroups of babies

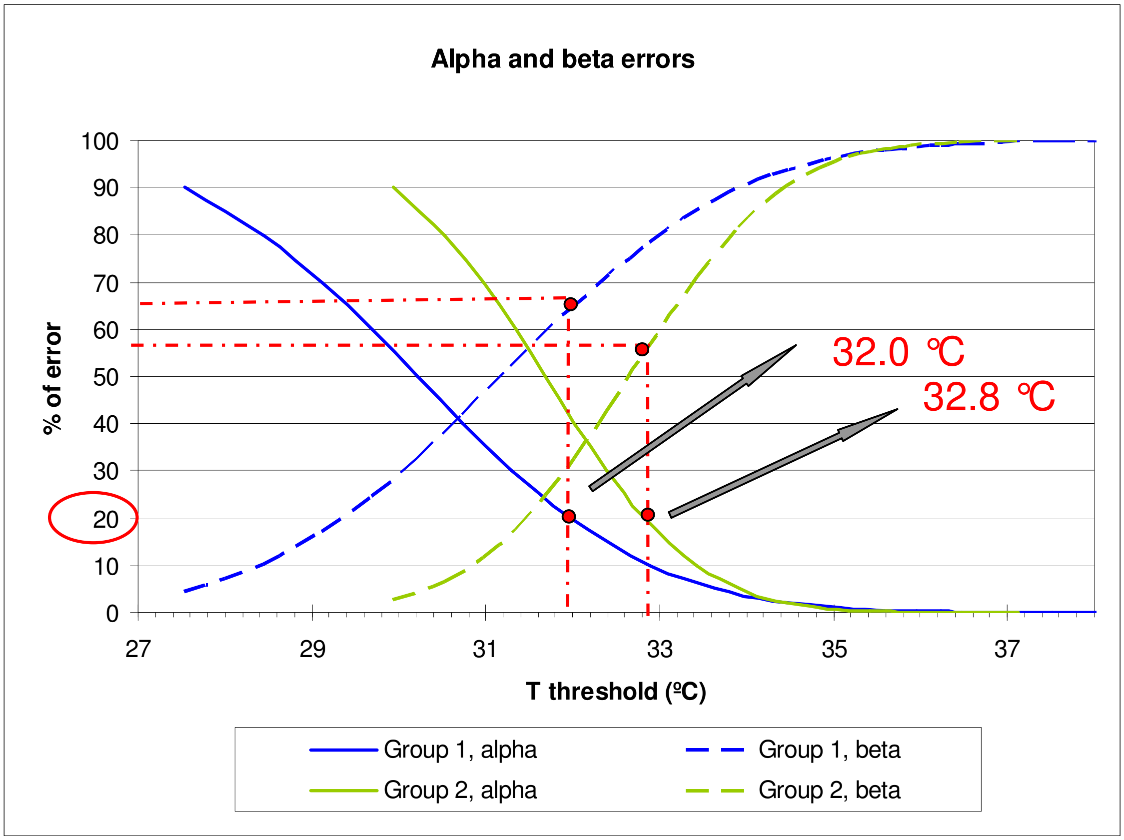


Figure G3: Example of location with 2 different studied subgroups of babies

Although a precise threshold can be defined for different subgroups, sometimes it is not really worth, especially if the precision of the sensor is poor. In those cases, we might want to set a limit temperature valid for several subgroups at the time. This will avoid us to have several thresholds but just one. In those cases an extrapolation of the graphs needs to be done. Following the previous example, if only one temperature limit is desirable, curves for alpha and beta errors are extrapolated as indicated in **figure G4**. The identification of the limit temperature would be done as explained before.

Extrapolation of alpha and beta curves can be done not just between two groups but many. Everything depends on how precise one wants to set the threshold. In any case the procedure would be the same.

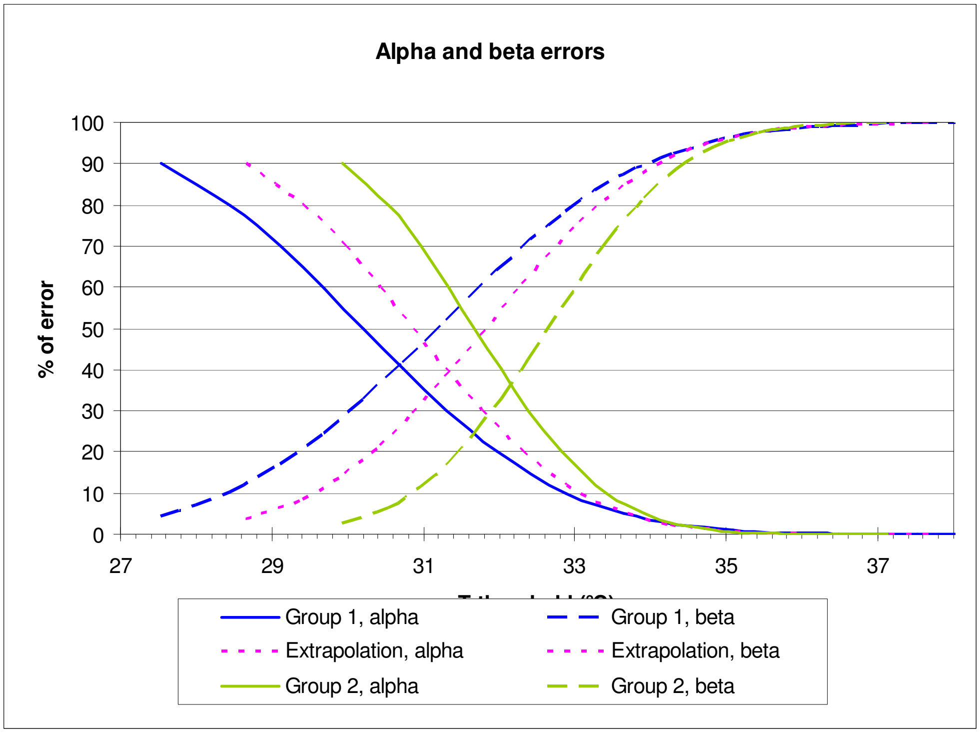
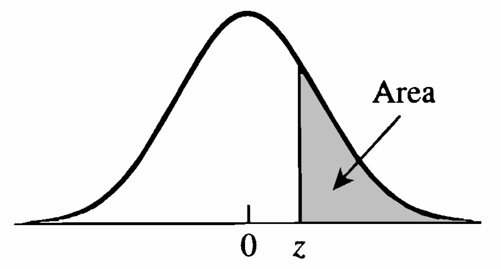


Figure G4: Example of extrapolation between 2 different studied subgroups of babies

Appendix H: Tabulation of normal curve areas



Normal curve areas
Standard normal probability in right-hand tail
(for negative values of z areas are found by symmetry)

	Second decimal place of z									
z	**.00**	**.01**	**.02**	**.03**	**.04**	**.05**	**.06**	**.07**	**.08**	**.09**
.0	.5000	.4960	.4920	.4880	.4840	.4801	.4761	.4721	.4681	.4641
.1	.4602	.4562	.4522	.4483	.4443	.4404	.4364	.4325	.4286	.4247
.2	.4207	.4168	.4129	.4090	.4052	.4013	.3974	.3936	.3897	.3859
.3	.3821	.3783	.3745	.3707	.3669	.3632	.3594	.3557	.3520	.3483
.4	.3446	.3409	.3372	.3336	.3300	.3264	.3228	.3192	.3156	.3121
.5	.3085	.3050	.3015	.2981	.2946	.2912	.2877	.2843	.2810	.2776
.6	.2743	.2709	.2676	.2643	.2611	.2578	.2546	.2514	.2483	.2451
.7	.2420	.2389	.2358	.2327	.2296	.2266	.2236	.2206	.2177	.2148
.8	.2119	.2090	.2061	.2033	.2005	.1977	.1949	.1922	.1894	.1867
.9	.1841	.1814	.1788	.1762	.1736	.1711	.1685	.1660	.1635	.1611
1.0	.1587	.1562	.1539	.1515	.1492	.1469	.1446	.1423	.1401	.1379
1.1	.1357	.1335	.1314	.1292	.1271	.1251	.1230	.1210	.1190	.1170
1.2	.1151	.1131	.1112	.1093	.1075	.1056	.1038	.1020	.1003	.0985
1.3	.0968	.0951	.0934	.0918	.0901	.0885	.0869	.0853	.0838	.0823
1.4	.0808	.0793	.0778	.0764	.0749	.0735	.0722	.0708	.0694	.0681
1.5	.0668	.0655	.0643	.0630	.0618	.0606	.0594	.0582	.0571	.0559
1.6	.0548	.0537	.0526	.0516	.0505	.0495	.0485	.0475	.0465	.0455
1.7	.0446	.0436	.0427	.0418	.0409	.0401	.0392	.0384	.0375	.0367
1.8	.0359	.0352	.0344	.0336	.0329	.0322	.0314	.0307	.0301	.0294
1.9	.0287	.0281	.0274	.0268	.0262	.0256	.0250	.0244	.0239	.0233
2.0	.0228	.0222	.0217	.0212	.0207	.0202	.0197	.0192	.0188	.0183
2.1	.0179	.0174	.0170	.0166	.0162	.0158	.0154	.0150	.0146	.0143
2.2	.0139	.0136	.0132	.0129	.0125	.0122	.0119	.0116	.0113	.0110
2.3	.0107	.0104	.0102	.0099	.0096	.0094	.0091	.0089	.0087	.0084
2.4	.0082	.0080	.0078	.0075	.0073	.0071	.0069	.0068	.0066	.0064
2.5	.0062	.0060	.0059	.0057	.0055	.0054	.0052	.0051	.0049	.0048
2.6	.0047	.0045	.0044	.0043	.0041	.0040	.0039	.0038	.0037	.0036
2.7	.0035	.0034	.0033	.0032	.0031	.0030	.0029	.0028	.0027	.0026
2.8	.0026	.0025	.0024	.0023	.0023	.0022	.0021	.0021	.0020	.0019
2.9	.0019	.0018	.0017	.0017	.0016	.0016	.0015	.0015	.0014	.0014
3.0	.00135									
3.5	.000 233									
4.0	.000 031 7									
4.5	.000 003 40									
5.0	.000 000 287									

From R.E. Walpole, Introduction to Statistics (New York: Macmillan, 1968).

Appendix I: Characterization of body and local skin temperature distributions

I-1) Core temperature

Core temperature

		Value	Std. Error
Number of cases	540		
Mean		36.59	0.02
Median		36.60	
Std. Deviation		0.40	
Range		2.62	
Kurtosis		0.84	0.21
Skewness		0.14	0.11

Table I1: Characterization of the core temperature distribution

Gender	N	Mean	Std. Error of Mean	Median	Std. Deviation	Kurtosis	Std. Error of Kurtosis	Range
Male	336	36.54	0.02	36.55	0.41	0.91	0.27	2.62
Female	204	36.66	0.03	36.65	0.37	0.81	0.34	2.48
Total	540	36.59	0.02	36.60	0.40	0.84	0.21	2.62

Table I2: Characterization of the core temperature distribution based on the gender

Age (months)	N	Mean	SEM	Median	SD	Kurtosis	Std. Error of Kurtosis	Range
0 to 8	35	36.55	0.05	36.50	0.28	1.48	0.78	1.45
8 to 16	294	36.57	0.02	36.60	0.40	1.28	0.28	2.62
16 to 24	211	36.61	0.03	36.60	0.43	0.24	0.33	2.50
Total	540	36.59	0.02	36.60	0.40	0.84	0.21	2.62

Table I3: Characterization of the core temperature distribution based on the age category

BMI (Kg/m2)	N	Mean	Std. Error of Mean	Median	Std. Deviation	Kurtosis	Std. Error of Kurtosis	Range
BMI<=16.53	99	36.59	0.05	36.65	0.45	0.71	0.48	2.48
16.53<BMI<19.25	321	36.58	0.02	36.55	0.41	0.50	0.27	2.62
BMI>=19.25	95	36.60	0.03	36.65	0.33	3.57	0.49	2.50
Total	515	36.59	0.02	36.60	0.40	0.86	0.21	2.62

Table I4: Characterization of the core temperature distribution for different sets of babies based on their BMI

Status	N	Mean	Std. Error of Mean	Median	Std. Deviation	Kurtosis	Std. Error of Kurtosis	Range
Awake	440	36.65	0.02	36.65	0.38	0.92	0.23	2.62
Asleep	99	36.32	0.04	36.30	0.40	2.55	0.48	2.48
Total	539	36.59	0.02	36.60	0.40	0.84	0.21	2.62

Table I5: Characterization of the core temperature distribution for three different sets of babies based on their status.

Extra clothing	N	Mean	Std. Error of Mean	Median	Std. Deviation	Kurtosis	Std. Error of Kurtosis	Range
No blanket	46	36.40	0.06	36.35	0.40	5.11	0.69	2.48
With blanket	50	36.23	0.05	36.20	0.36	-0.65	0.66	1.40
Total	96	36.31	0.04	36.30	0.38	2.87	0.49	2.48

Table I6: Characterization of the core temperature distribution for two different sets of sleeping babies based on use of blanket.

I-1) Local skin temperature

This appendix presents the main features which characterise the surface temperature of children under two at each of the locations indicated in **Figure 11**.

T1, T2, T3, T4

		T1	T2	T3	T4
N	Valid	539	538	537	531
	Missing	1	2	3	9
Mean		33.80	34.53	34.59	33.96
Std. Error of Mean		0.03	0.04	0.04	0.04
Median		33.80	34.60	34.63	34.03
Std. Deviation		0.75	0.90	0.84	1.00
Kurtosis		0.10	1.79	1.08	0.72
Std. Error of Kurtosis		0.21	0.21	0.21	0.21
Skewness		-0.09	-0.30	-0.59	-0.55
Std. Error of Skewness		0.11	0.11	0.11	0.11
Range		4.70	8.40	6.13	6.20

Table I7: Characterization of the temperature distribution for the total of N-number of cases for locations: T1: Forehead, T2: Neck on back side, T3: Right scapula, T4: Left upper chest

T5, T6, T7, T8

		T5	T6	T7	T8
N	Valid	535	535	537	530
	Missing	5	5	3	10
Mean		32.80	30.96	32.04	34.50
Std. Error of Mean		0.05	0.06	0.08	0.04
Median		32.80	30.90	32.30	34.53
Std. Deviation		1.05	1.36	1.83	0.93
Kurtosis		0.87	0.19	0.62	0.56
Std. Error of Kurtosis		0.21	0.21	0.21	0.21
Skewness		-0.18	0.11	-0.69	-0.26
Std. Error of Skewness		0.11	0.11	0.11	0.11
Range		7.43	8.13	11.13	6.23

Table I8: Characterization of the temperature distribution for the total of N-number of cases for locations: T5: Right arm in upper location, T6: Left arm in lower location, T7: Left hand, T8: Right abdomen

T9, T10, T11, T12

		T9	T10	T11	T12
N	Valid	528	531	531	536
	Missing	12	9	9	4
Mean		33.90	31.75	32.57	31.67
Std. Error of Mean		0.04	0.06	0.05	0.06
Median		34.00	31.67	32.70	31.73
Std. Deviation		1.02	1.37	1.24	1.45
Kurtosis		0.77	0.18	0.01	0.44
Std. Error of Kurtosis		0.21	0.21	0.21	0.21
Skewness		-0.58	0.22	-0.49	-0.05
Std. Error of Skewness		0.11	0.11	0.11	0.11
Range		7.03	9.20	7.27	9.70

Table I9: Characterization of the temperature distribution for the total of N-number of cases for locations: T9: Left paravertebral, T10: Right anterior thigh, T11: Left posterior thigh, T12: Right shin

T13, T14, T15, T16

		T13	T14	T15	T16
N	Valid	534	514	425	432
	Missing	6	26	115	108
Mean		31.29	32.84	35.15	31.07
Std. Error of Mean		0.06	0.08	0.04	0.07
Median		31.34	33.18	35.27	31.10
Std. Deviation		1.50	1.92	0.77	1.48
Kurtosis		0.37	0.46	3.92	0.34
Std. Error of Kurtosis		0.21	0.22	0.24	0.23
Skewness		-0.34	-0.82	-1.37	-0.37
Std. Error of Skewness		0.11	0.11	0.12	0.12
Range		9.83	10.83	5.80	8.80

Table I10: Characterization of the temperature distribution for the total of N-number of cases for locations: T13: Left calf, T14: Right instep, T15: Neck in lateral location, T16: Left wrist

T4S, T5S, T8S, T15S

		T4S	T5S	T8S	T15S
N	Valid	284	316	281	130
	Missing	256	224	259	410
Mean		30.2	30.0	31.96	31.3
Std. Error of Mean		0.1	0.1	0.09	0.2
Median		30.5	30.2	32.27	31.6
Std. Deviation		1.9	1.5	1.48	1.7
Kurtosis		0.88	0.18	0.63	1.61
Std. Error of Kurtosis		0.29	0.27	0.29	0.42
Skewness		-0.87	-0.48	-0.80	-1.01
Std. Error of Skewness		0.15	0.14	0.15	0.21
Range		10.20	7.70	8.27	9.90

Table I11: Characterization of the temperature distribution for the total of N-number of cases for locations: T4S: Left upper chest – 0ver clothing. T5S: Right arm in upper location – Over clothing. T8S: Right abdomen – Over clothing. T15S: Neck in lateral location – Over clothing

Gender	**Male**			**Female**			**Difference**	
	Mean	**SEM**	**SD**	**Mean**	**SEM**	**SD**	**Δ(Mean)**	**Error of Δ(Mean)**
T1	33.75	0.04	0.76	33.88	0.05	0.72	-0.12	0.07
T2	34.50	0.05	0.95	34.59	0.06	0.81	-0.09	0.08
T3	34.64	0.05	0.86	34.51	0.06	0.80	0.13	0.07
T4	33.95	0.05	0.98	33.97	0.07	1.04	-0.02	0.09
T5	32.86	0.06	1.05	32.70	0.07	1.03	0.16	0.09
T6	31.01	0.07	1.34	30.9	0.1	1.4	0.15	0.12
T7	31.9	0.1	1.9	32.3	0.1	1.6	-0.41	0.15
T8	34.54	0.05	0.92	34.42	0.07	0.94	0.12	0.08
T9	33.93	0.06	1.01	33.86	0.07	1.03	0.08	0.09
T10	31.83	0.08	1.38	31.6	0.1	1.3	0.20	0.12
T11	32.62	0.07	1.26	32.49	0.09	1.20	0.13	0.11
T12	31.66	0.08	1.40	31.7	0.1	1.5	-0.03	0.13
T13	31.25	0.08	1.52	31.4	0.1	1.5	-0.11	0.13
T14	32.9	0.1	1.9	32.8	0.1	1.9	0.09	0.18
T15	35.16	0.05	0.83	35.13	0.05	0.65	0.03	0.07
T16	31.0	0.1	1.6	31.2	0.1	1.3	-0.19	0.14
T4S	30.2	0.2	2.0	30.2	0.2	1.8	-0.07	0.23
T5S	30.1	0.1	1.5	30.0	0.1	1.5	0.08	0.17
T8S	32.0	0.1	1.5	31.9	0.1	1.4	0.07	0.18
T15S	31.3	0.2	1.7	31.4	0.3	1.7	-0.07	0.32

Table I12: Skin temperature distribution for each location according to the gender of the babies. Difference presents the variation of the mean of the distribution for female babies with respect to male babies.

Age category	**0 to 8 months**			**8 to 16 months**			**16 to 24 months**		
	N	**Mean**	**SD**	**N**	**Mean**	**SD**	**N**	**Mean**	**SD**
T1	35	33.36	0.56	293	33.91	0.74	211	33.72	0.75
T2	34	34.56	1.07	293	34.60	0.87	211	34.44	0.90
T3	35	34.43	0.96	292	34.60	0.84	211	34.60	0.82
T4	35	34.00	0.92	290	33.91	1.02	206	34.01	0.99
T5	33	32.71	0.93	293	32.69	0.99	209	32.97	1.13
T6	34	30.95	1.09	292	30.89	1.28	209	31.05	1.50
T7	35	30.25	1.97	293	31.98	1.60	209	32.42	1.92
T8	34	34.44	1.00	292	34.41	0.90	204	34.64	0.93
T9	34	33.87	0.95	291	33.77	0.93	204	34.10	1.12
T10	35	30.95	0.77	291	31.58	1.34	205	32.14	1.38
T11	35	32.13	1.02	291	32.44	1.19	205	32.83	1.29
T12	35	30.55	1.06	294	31.38	1.42	207	32.27	1.30
T13	35	30.37	1.27	291	31.09	1.51	208	31.73	1.39
T14	31	31.47	1.61	285	32.30	2.01	199	33.82	1.31
T15	34	35.08	0.95	208	35.18	0.81	183	35.13	0.68
T16	34	30.29	1.58	209	30.92	1.25	189	31.38	1.63
T4S	17	28.95	1.77	157	30.34	1.77	110	30.17	2.04
T5S	22	29.27	1.59	171	30.04	1.39	123	30.20	1.50
T8S	21	31.00	1.79	149	31.87	1.27	111	32.27	1.60
T15S	18	31.06	2.10	60	31.34	1.74	52	31.40	1.58

Table I13: Summary of the main characteristics of the temperature distributions at each location with respect to age.

BMI	<=16.53 Kg/m^2			16.53<BMI<19.25 Kg/m^2			>=19.25 Kg/m^2		
	N	Mean	SD	N	Mean	SD	N	Mean	SD
T1	99	33.87	0.72	321	33.81	0.77	94	33.67	0.69
T2	98	34.63	0.90	320	34.56	0.90	95	34.4	0.9
T3	99	34.73	0.93	319	34.61	0.77	95	34.5	0.9
T4	97	34.4	1.0	315	33.81	1.00	94	33.9	0.9
T5	97	32.8	1.3	318	32.83	0.98	95	32.6	1.0
T6	98	30.7	1.4	319	31.09	1.29	93	30.6	1.3
T7	99	32.1	2.0	319	32.0	1.8	94	31.7	1.7
T8	96	34.9	1.0	317	34.43	0.92	94	34.35	0.87
T9	98	34.4	1.1	317	33.84	0.97	90	33.6	1.0
T10	96	31.9	1.3	318	31.77	1.37	93	31.4	1.3
T11	96	32.6	1.4	318	32.59	1.17	94	32.3	1.2
T12	96	32.0	1.4	321	31.63	1.43	94	31.3	1.5
T13	96	31.2	1.6	319	31.36	1.45	94	30.9	1.5
T14	89	33.2	1.9	314	32.7	1.9	90	32.5	1.9
T15	92	35.17	0.88	226	35.13	0.70	85	35.15	0.85
T16	95	31.0	1.4	227	31.1	1.5	87	30.8	1.4

Table I14: Summary of the main temperature distributions characteristics at each location with respect to BMI.

Status	Awake			Asleep			Difference	
	Mean	SEM	SD	Mean	SEM	SD	Δ(Mean)	Error of Δ(Mean)
T1	33.90	0.03	0.70	33.35	0.08	0.79	-0.55	0.09
T2	34.57	0.04	0.90	34.40	0.09	0.88	-0.2	0.1
T3	34.72	0.04	0.78	33.98	0.09	0.84	-0.74	0.09
T4	33.85	0.05	0.98	34.5	0.1	0.9	0.6	0.1
T5	32.86	0.05	1.02	32.5	0.1	1.1	-0.4	0.1
T6	30.81	0.06	1.23	31.6	0.2	1.7	0.8	0.2
T7	31.82	0.09	1.83	33.0	0.1	1.5	1.2	0.2
T8	34.42	0.04	0.93	34.85	0.09	0.83	0.4	0.1
T9	33.86	0.05	1.05	34.11	0.09	0.84	0.2	0.1
T10	31.51	0.06	1.18	32.9	0.2	1.6	1.4	0.2
T11	32.48	0.06	1.22	33.0	0.1	1.2	0.5	0.1
T12	31.49	0.06	1.33	32.5	0.2	1.7	1.0	0.2
T13	31.12	0.07	1.42	32.1	0.2	1.6	1.0	0.2
T14	32.6	0.1	2.0	33.7	0.1	1.3	1.1	0.2
T15	35.20	0.04	0.76	34.91	0.09	0.76	-0.3	0.1
T16	30.84	0.07	1.40	32.1	0.2	1.4	1.3	0.2
T4S	30.2	0.1	1.9	29.7	0.4	1.7	-0.5	0.4
T5S	30.12	0.09	1.43	29.6	0.3	1.6	-0.5	0.3
T8S	31.97	0.09	1.49	31.9	0.3	1.5	-0.1	0.3
T15S	31.4	0.1	1.6	30.2	0.7	2.4	-1.2	0.7

Table I15: Skin temperature distributions for two cohorts based on status (awake vs. asleep). Difference presents the variation of the mean of the distribution for sleeping babies with respect to awake babies.

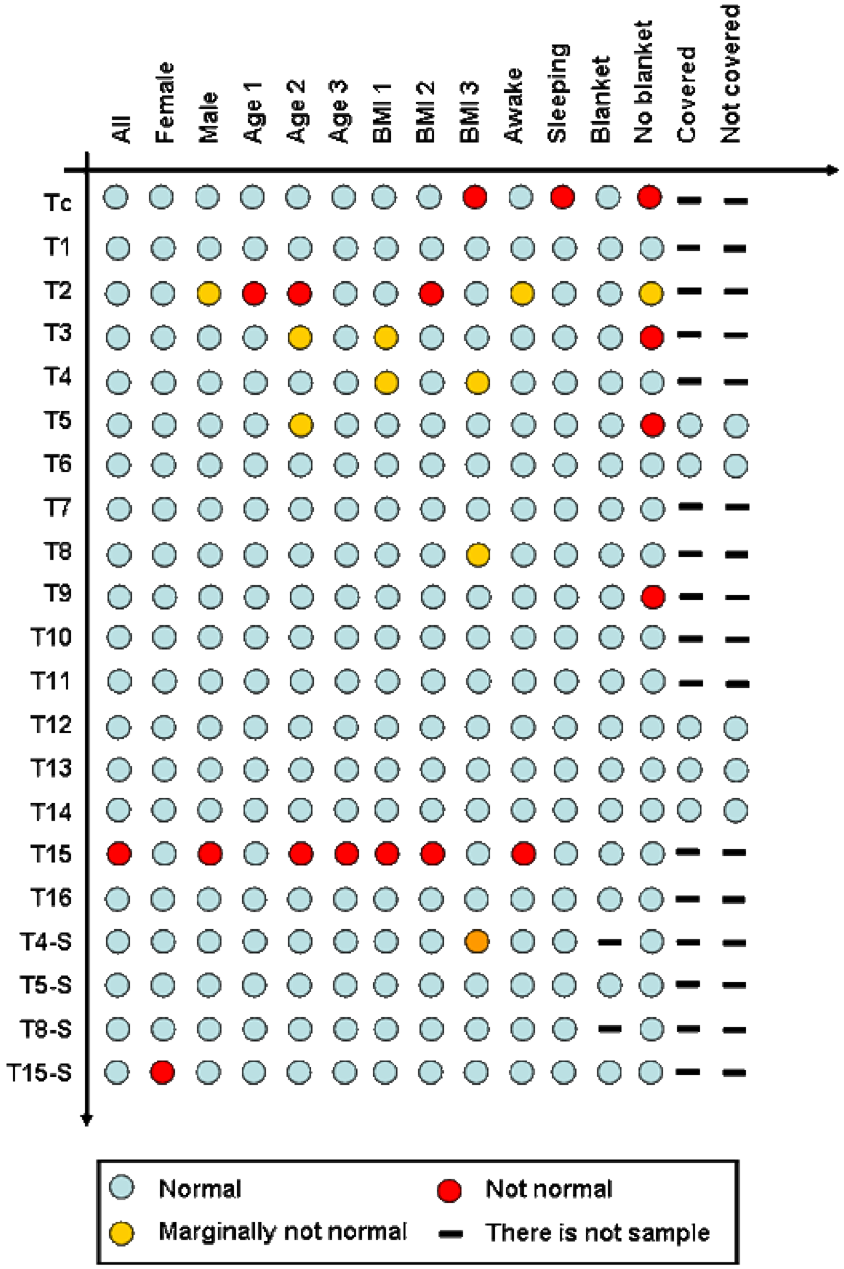
	Sleeping without blanket			Sleeping with blanket			Difference (without blanket)-(with blanket)	
	Mean	SEM	SD	Mean	SEM	SD	Δ(Mean)	Error of Δ(Mean)
T1	33.47	0.13	0.89	33.22	0.10	0.68	0.24	0.03
T2	34.31	0.13	0.90	34.44	0.12	0.85	-0.12	0.04
T3	34.03	0.13	0.89	33.90	0.11	0.80	0.13	0.04
T4	34.11	0.16	1.05	34.83	0.09	0.63	-0.73	0.04
T5	32.26	0.16	1.04	32.70	0.16	1.11	-0.44	0.06
T6	30.99	0.19	1.26	32.17	0.26	1.84	-1.2	0.1
T7	32.46	0.25	1.69	33.52	0.14	1.03	-1.06	0.07
T8	34.55	0.14	0.93	35.18	0.09	0.60	-0.63	0.03
T9	33.81	0.14	0.92	34.35	0.10	0.68	-0.55	0.04
T10	32.22	0.23	1.51	33.55	0.19	1.33	-1.33	0.09
T11	32.63	0.20	1.31	33.31	0.15	1.07	-0.68	0.07
T12	31.72	0.23	1.57	33.20	0.20	1.39	-1.5	0.1
T13	31.57	0.23	1.53	32.62	0.22	1.54	-1.0	0.1
T14	33.19	0.20	1.34	34.23	0.14	0.93	-1.03	0.06
T15	34.85	0.16	0.91	34.90	0.10	0.59	-0.05	0.04
T16	31.55	0.28	1.62	32.61	0.17	1.07	-1.06	0.09
T5S	29.36	0.37	1.68	29.70	0.41	1.64	-0.3	0.2

Table I16: Skin temperature distributions for 2 cohorts based on the use of blanket while sleeping (without vs. with). Difference presents the variation of the mean of the distribution for babies sleeping with a blanket on with respect to babies sleeping without it.

Clothing category	Location exposed			Location covered		
	N	Mean	SD	N	Mean	SD
T5	13	31.1	1.3	445	32.8	1.0
T6	295	30.8	1.4	160	31.2	1.3
T12	137	31.5	1.5	322	31.7	1.4
T13	137	31.3	1.4	321	31.2	1.5
T14	154	32.4	2.0	287	33.1	1.7

Table I17: Summary of the main characteristics of temperature distributions at several locations for different groups of subjects, with respect to their clothing.

Appendix J: Identification of relevant factors of local skin temperature in babies



	All	Female	Male	Age 1	Age 2	Age 3	BMI 1	BMI 2	BMI 3	Awake	Sleeping	Blanket	No blanket	Covered	Not covered
Tc	○	○	○	○	○	○	○	○	🔴	○	🔴	○	🔴	—	—
T1	○	○	○	○	○	○	○	○	○	○	○	○	○	—	—
T2	○	○	🟡	🔴	🔴	○	○	🔴	○	🟡	○	○	🟡	—	—
T3	○	○	○	○	🟡	○	🟡	○	○	○	○	○	🔴	—	—
T4	○	○	○	○	○	○	🟡	○	🟡	○	○	○	○	—	—
T5	○	○	○	○	🟡	○	○	○	○	○	○	○	🔴	○	○
T6	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
T7	○	○	○	○	○	○	○	○	○	○	○	○	○	—	—
T8	○	○	○	○	○	○	○	○	🟡	○	○	○	○	—	—
T9	○	○	○	○	○	○	○	○	○	○	○	○	🔴	—	—
T10	○	○	○	○	○	○	○	○	○	○	○	○	○	—	—
T11	○	○	○	○	○	○	○	○	○	○	○	○	○	—	—
T12	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
T13	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
T14	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
T15	🔴	○	🔴	○	🔴	🔴	🔴	🔴	○	🔴	○	○	○	—	—
T16	○	○	○	○	○	○	○	○	○	○	○	○	○	—	—
T4-S	○	○	○	○	○	○	○	○	🟠	○	○	—	○	—	—
T5-S	○	○	○	○	○	○	○	○	○	○	○	○	○	—	—
T8-S	○	○	○	○	○	○	○	○	○	○	○	—	○	—	—
T15-S	○	🔴	○	○	○	○	○	○	○	○	○	○	○	—	—

○	Normal	🔴	Not normal
🟡	Marginally not normal	—	There is not sample

Table J1: Study of the normality of temperature distribution attending to several factors

Location	Gender	Age	BMI	Status	Blanket	Clothing
T1	1A	**1A**	1A	**1A**	1A	---
T2	2	3	3	**2**	2	---
T3	1A	1A	1A	**1A**	2	---
T4	1A	1A	**1A**	**1A**	**2**	---
T5	1A	**1B**	1B	**1A**	1A	**1A**
T6	1A	1B	**1A**	**1B**	**1B**	**1A**
T7	**1B**	**1A**	1A	**1B**	**1B**	---
T8	1A	**1A**	**1A**	**1A**	**1B**	---
T9	1A	**1A**	**1A**	**1B**	**2**	---
T10	1A	**1B**	**1A**	**1B**	**1A**	---
T11	1A	**1A**	1A	**1A**	**1A**	---
T12	1A	**1A**	**1A**	**1B**	**1A**	1A
T13	1A	**1A**	1A	**1A**	**1A**	1A
T14	1A	**1B**	**1A**	**1B**	**1B**	**1B**
T15	2	3	3	**2**	1A	---
T16	1B	**1B**	1A	**1A**	**1B**	---
T4S	1A	**1A**	1A	1A	---	---
T5S	1A	**1A**	**1A**	**1A**	1A	---
T8S	1A	**1B**	1A	1A	---	---
T15S	2	3	1A	1B	1B	---

Table J2: Statistical test used to compare the temperature distributions and results. (1A) ANOVA with homogeneous variance, (1B) ANOVA with different variances, (2) Mann-Whitney U test, and (3) Kruskal-Wallis. (Black) Distributions were found to be equivalent, and (Red) Distributions were found to be different hence the parameter is relevant.

Appendix K: Relation between core and local skin temperature in babies

Location	Clothing	Linear regression	R^2	Level of relation
T1 vs. Tc		y = 0.8550x + 2.5188	0.2124	🟥
T2 vs. Tc		y = 0.6275x + 11.575	0.0779	🟨
T3 vs. Tc		y = 0.8047x + 5.1469	0.1461	🟥
T4 vs. Tc		y = 0.0537x + 31.989	0.0005	🟦
T5 vs. Tc	Exposed	y = 0.9446x – 3.429*	0.0765	🟥
T5 vs. Tc	Covered	y = 0.6143x + 10.356	0.0559	🟨
T6 vs. Tc	Exposed	y = 0.0470x + 29.08	0.0002	🟦
T6 vs. Tc	Covered	y = 0.2019x + 23.787	0.0042	🟩
T7 vs. Tc		y = 0.6639x + 7.7499	0.0215	🟨
T8 vs. Tc		y = 0.1501x + 29.006	0.0042	🟩
T9 vs. Tc		y = 0.3313x + 21.784	0.0169	🟩
T10 vs. Tc		y = 0.1663x + 25.67	0.0024	🟩
T11 vs. Tc		y = 0.4946x + 14.476	0.0259	🟨
T12 vs. Tc	Exposed	y = 0.5414x + 11.744	0.017	🟨
T12 vs. Tc	Covered	y = 0.4602x + 14.792	0.007	🟨
T13 vs. Tc	Exposed	y = -0.0489x + 33.137	0.0002	🟦
T13 vs. Tc	Covered	y = 0.5300x + 11.834	0.0194	🟨
T14 vs. Tc	Exposed	y = 0.4121x + 17.377	0.0064	🟨
T14 vs. Tc	Covered	y = 0.4979x + 14.922	0.0136	🟨
T15 vs. Tc		y = 0.6024x + 13.108	0.0898	🟨
T16 vs. Tc		y = 0.4648x + 14.063	0.0144	🟨

* Low number of samples

Table K1: Linear regressions of skin versus core temperature at each location. Colour represents the strength of the relation between them. Red) Strong. Yellow) Medium. Green) Low. Blue) Null.

Tc	Tc < 37.3°C			Tc >= 37.3°C		
	N	**Mean**	**SD**	**N**	**Mean**	**SD**
T1	518	33.76	0.72	21	34.74	0.85
T2	517	34.51	0.87	21	35.1	1.3
T3	517	34.55	0.83	21	35.50	0.74
T4	510	33.95	0.98	21	34.1	1.5
T5	428	32.79	0.99	17	34.0	1.2
T6	154	31.1	1.3	6	32.1	1.1
T7	516	32.0	1.8	21	32.9	1.9
T8	509	34.48	0.91	21	35.1	1.2
T9	508	33.9	1.0	21	34.9	1.0
T10	510	31.7	1.4	21	32.3	1.5
T11	510	32.5	1.2	21	33.3	1.1
T12	308	31.69	1.38	14	32.4	1.5
T13	307	31.21	1.53	14	31.6	1.6
T14	274	33.1	1.7	13	33.9	1.3
T15	408	35.13	0.77	17	35.65	0.56
T16	415	31.0	1.5	17	31.7	1.6
T4S	271	30.2	1.9	13	29.9	1.8
T5S	305	30.1	1.4	11	29.9	1.9
T8S	268	31.9	1.5	13	32.2	1.3
T15S	121	31.3	1.7	9	31.2	2.3

Table K2: Characterization of local skin temperature distributions for babies with T_c under and over 37.3ºC

Tc limit of 37.3℃			
	Dif (ºC)	δ(Dif) (ºC)	Colour code
T5	1.16	0.30	🟥
Tc	1.01	0.05	🟥
T9	1.00	0.22	🟥
T1	0.98	0.18	🟥
T3	0.95	0.16	🟥
T6	0.94	0.45	🟥
T7	0.86	0.42	🟥
T14	0.77	0.36	🟥
T12	0.74	0.42	🟥
T11	0.73	0.25	🟥
T16	0.69	0.41	🟥
T2	0.63	0.28	🟥
T10	0.60	0.34	🟥
T8	0.57	0.26	🟪
T15	0.52	0.15	🟪
T13	0.36	0.45	🟨
T8S	0.28	0.38	▧
T4	0.13	0.33	🟦
T5S	-0.12	0.57	🟦
T15S	-0.16	0.76	🟦
T4S	-0.35	0.51	🟦

(a)

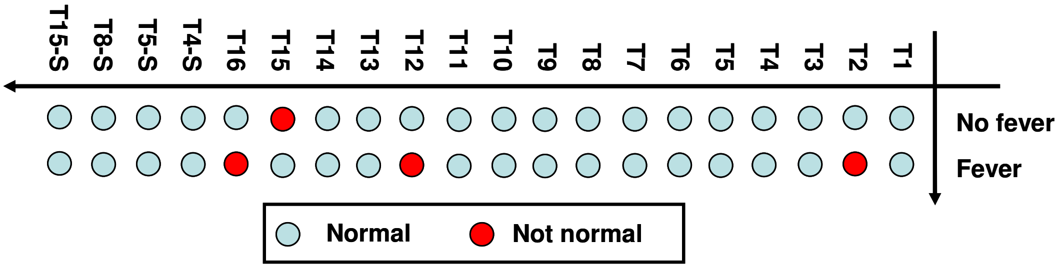
$$Dif = \mu_1 - \mu_2$$

$$\delta(Dif) = \sqrt{\delta\mu_1^{\,2} + \delta\mu_2^{\,2}}$$

Colour code	Range of temperature (ºC)
🟥	>= 0.60
🟪	0.45=< T <0.60
🟨	0.30=< T <0.45
▧	0.15=< T <0.30
🟦	>0.15

(b)

Table K3: (a) Difference of mean skin temperature values (in descending order) between two cohorts: I) *Tc<37.3°C*. II) *Tc≥37.3°C*. *Difference = mean$_{II}$ – mean*. (b) Colour scale.



	T15-S	T8-S	T5-S	T4-S	T16	T15	T14	T13	T12	T11	T10	T9	T8	T7	T6	T5	T4	T3	T2	T1
No fever	○	○	○	○	○	●	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Fever	○	○	○	○	●	○	○	○	●	○	○	○	○	○	○	○	○	○	●	○

○ **Normal** ● **Not normal**

Table K4: Study of the normality of temperature distribution attending to the occurance of fever.

Location	Fever	Location	Fever
T1	**1A**	**T11**	**1A**
T2	**2**	**T12**	2
T3	**1A**	**T13**	1A
T4	1B	**T14**	1A
T5	**1A**	**T15**	**2**
T6	1A	**T16**	**2**
T7	**1A**	**T4S**	1A
T8	**1A**	**T5S**	1A
T9	**1A**	**T8S**	1A
T10	**1A**	**T15S**	1A

Table K5: Statistical test used to compare the temperature distributions and results. (1A) ANOVA with homogeneous variance, (1B) ANOVA with different variances, (2) Mann-Whitney U test. (Black) Distributions were found to be equivalent, and (Red) Distributions were found to be different hence the fever is relevant parameter.

Appendix L: Characterization of skin temperature distribution at several cohorts of healthy and febrile babies.

This appendix presents the characterization of local skin temperature distribution at several cohorts of healthy and febrile babies. Values given in normal letters have been obtained directly from the data while values given in italics have been estimated, as indicated in section 4.2.4.

Group	Mean temperature (°C)	SD (°C)
Awake, age category 1, no fever	33.43	0.55
Awake, age category 1, fever	*34.41*	*0.65*
Awake, age category 2, no fever	33.99	0.64
Awake, age category 2, fever	*34.97*	*0.75*
Awake, age category 3, no fever	33.77	0.69
Awake, age category 3, fever	*34.75*	*0.81*
Asleep, age category 1, no fever	*32.88*	*0.65*
Asleep, age category 1, fever	*33.86*	*0.77*
Asleep, age category 2, no fever	33.37	0.75
Asleep, age category 2, fever	*34.35*	*0.88*
Asleep, age category 3, no fever	33.27	0.74
Asleep, age category 3, fever	*34.25*	*0.87*

Table L1: Characterization of temperature distribution in the forehead (location T1) for 12 cohorts of babies given by activity, age and high or normal core temperature

Group	Mean temperature (°C)	Standard deviation (°C)
Awake, no fever	34.69	0.77
Awake, fever	35.48	0.75
Asleep, no fever	33.95	0.80
Asleep, fever	*34.74*	*0.81*

Table L2: Characterization of temperature distribution in the right scapula (location T3) for 4 cohorts of babies given by activity and high or normal core temperature

Group	Mean temperature (°C)	Standard deviation (°C)
Awake or sleeping with blanket, no fever	32.85	0.97
Awake or sleeping with blanket, fever	33.72	1.04
Sleeping without blanket, no fever	32.21	0.89
Sleeping without blanket, fever	*33.08*	*0.95*

Table L3: Characterization of temperature distribution in the right arm in upper location (location T5) for 4 cohorts of babies given by activity and high or normal core temperature

Group	Mean temperature (°C)	Standard deviation (°C)
Awake or sleeping without blanket, no fever	31.02	1.18
Awake or sleeping without blanket, fever	32.32	1.68
Sleeping with a blanket, no fever	31.33	1.26
Sleeping with a blanket, fever	*32.63*	*1.79*

Table L4: Characterization of temperature distribution in the left arm in lower location (location T6) for 4 cohorts of babies given by activity and high or normal core temperature

Group	Mean temperature (°C)	Standard deviation (°C)
Awake, age category 1, no fever	30.21	2.09
Awake, age category 1, fever	*31.18*	*2.16*
Awake, age category 2, no fever	31.77	1.57
Awake, age category 2, fever	*32.74*	*1.62*
Awake, age category 3, no fever	32.10	1.95
Awake, age category 3, fever	*33.07*	*2.01*
Sleeping without a blanket, age category 1, no fever	*30.86*	*1.73*
Sleeping without a blanket, age category 1, fever	*31.83*	*1.78*
Sleeping without a blanket, age category 2, no fever	32.42	1.30
Sleeping without a blanket age category 2, fever	*33.39*	*1.34*
Sleeping without a blanket, age category 3, no fever	32.94	2.00
Sleeping without a blanket, age category 3, fever	*33.91*	*2.06*
Sleeping with a blanket, age category 1, no fever	*31.68*	*1.36*
Sleeping with a blanket, age category 1, fever	*32.65*	*1.40*
Sleeping with a blanket, age category 2, no fever	33.24	1.02
Sleeping with a blanket, age category 2, fever	*34.21*	*1.05*
Sleeping with a blanket, age category 3, no fever	33.76	0.99
Sleeping with a blanket, age category 3, fever	*34.73*	*1.02*

Table L5: Characterization of temperature distribution in the left hand (location T7) for 18 cohorts of babies given by activity, age category and high or normal core temperature

Group	Mean temperature (°C)	Standard deviation (°C)
Awake or sleeping without blanket, no fever	34.40	0.91
Awake or sleeping without blanket, fever	35.08	1.22
Sleeping with a blanket, no fever	35.13	0.63
Sleeping with a blanket, fever	*35.81*	*0.85*

TableL6: Characterization of temperature distribution in the right abdomen (location T8) for 4 cohorts of babies given by activity and high or normal core temperature

Group	Mean temperature (℃)	Standard deviation (℃)
Awake or sleeping without a blanket, BMI category 1, no fever	34.31	1.04
Awake or sleeping without a blanket, BMI category 1, fever	*35.08*	*0.92*
Awake or sleeping without a blanket, BMI category 2, no fever	33.74	0.97
Awake or sleeping without a blanket, BMI category 2, fever	34.51	0.86
Awake or sleeping without a blanket, BMI category 3, no fever	33.56	1.04
Awake or sleeping without a blanket, BMI category 3, fever	*34.33*	*0.92*
Sleeping with a blanket, BMI category 1, no fever	*34.83*	*1.10*
Sleeping with a blanket, BMI category 1, fever	*35.60*	*0.97*
Sleeping with a blanket, BMI category 2, no fever	34.36	0.68
Sleeping with a blanket, BMI category 2, fever	*35.13*	*0.60*
Sleeping with a blanket, BMI category 3, no fever	*33.34*	*1.13*
Sleeping with a blanket, BMI category 3, fever	*34.11*	*1.00*

Table L7: Characterization of temperature distribution in the left paravertebral (location T9) for 12 cohorts of babies given by activity, BMI category and high or normal core temperature

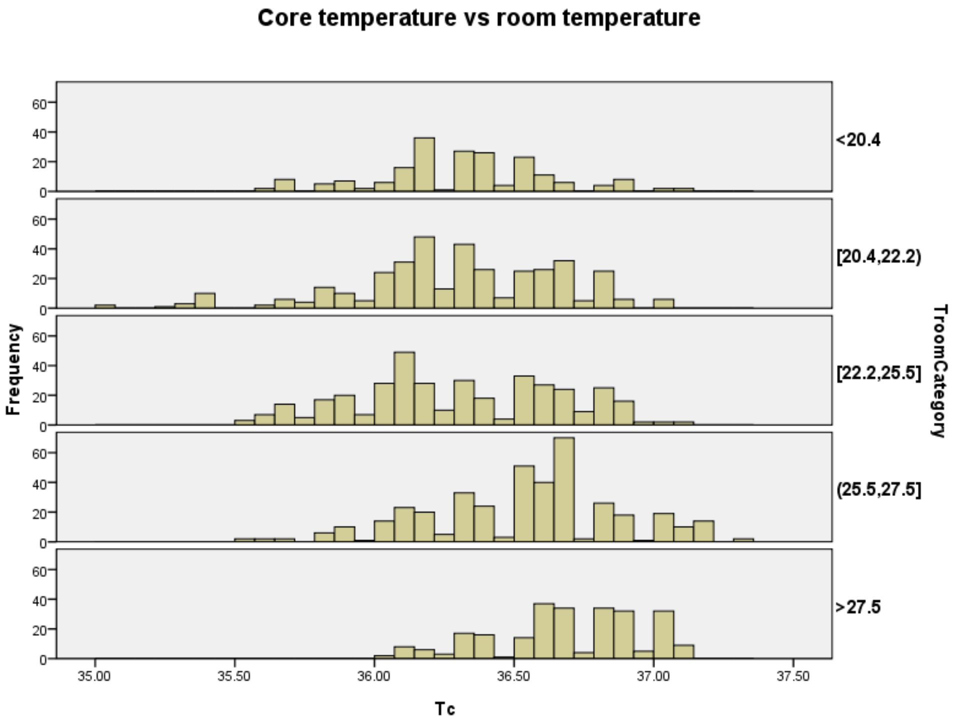
Group	Mean temperature (℃)	Standard deviation (℃)
Awake or sleeping without blanket, age category 1 or 2, no fever	32.32	1.16
Awake or sleeping without blanket, age category 1 or 2, fever	33.35	1.47
Awake or sleeping without blanket, age category 3, no fever	32.70	1.30
Awake or sleeping without blanket, age category 3, fever	33.20	1.03
Sleeping with a blanket, age category 1 or 2, no fever	33.16	0.95
Sleeping with a blanket, age category 1 or 2, fever	*34.19*	*1.21*
Sleeping with a blanket, age category 3, no fever	33.47	1.15
Sleeping with a blanket, age category 3, fever	*33.97*	*0.91*

Table L8: Characterization of temperature distribution in the left posterior thigh (location T11) for eight cohorts of babies given by activity, age and high or normal core temperature

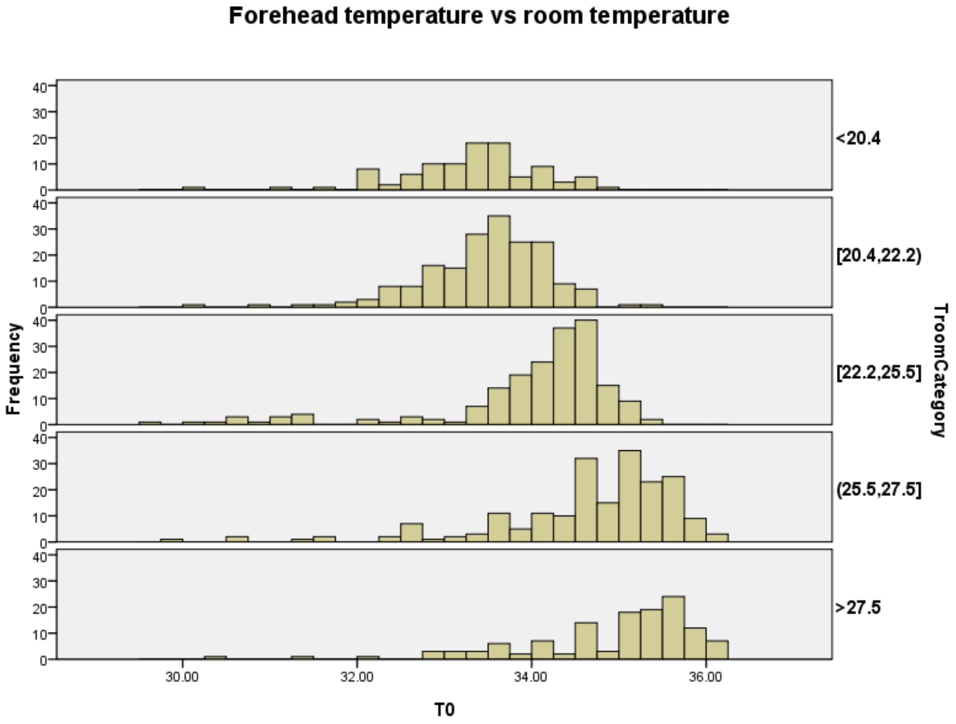
Group	Mean temperature (℃)	Standard deviation (℃)
Awake, age category 1, no fever	30.20	1.63
Awake, age category 1, fever	*31.11*	*1.94*
Awake, age category 2, no fever	30.76	1.14
Awake, age category 2, fever	*31.67*	*1.36*
Awake, age category 3, no fever	31.02	1.56
Awake, age category 3, fever	*31.93*	*1.86*
Sleeping without a blanket, age category 1, no fever	*30.93*	*1.92*
Sleeping without a blanket, age category 1, fever	*31.84*	*2.29*
Sleeping without a blanket, age category 2, no fever	*31.49*	*1.34*
Sleeping without a blanket age category 2, fever	*32.40*	*1.60*
Sleeping without a blanket, age category 3, no fever	*31.75*	*1.84*
Sleeping without a blanket, age category 3, fever	*32.66*	*2.19*
Sleeping with a blanket, age category 1, no fever	*31.99*	*1.26*
Sleeping with a blanket, age category 1, fever	*32.90*	*1.50*
Sleeping with a blanket, age category 2, no fever	*32.55*	*0.88*
Sleeping with a blanket, age category 2, fever	*33.46*	*1.05*
Sleeping with a blanket, age category 3, no fever	*32.81*	*1.21*
Sleeping with a blanket, age category 3, fever	*33.72*	*1.44*

Table L9: Characterization of temperature distribution in the left wrist (location T16) for 18 cohorts of babies given by activity, age and high or normal core temperature

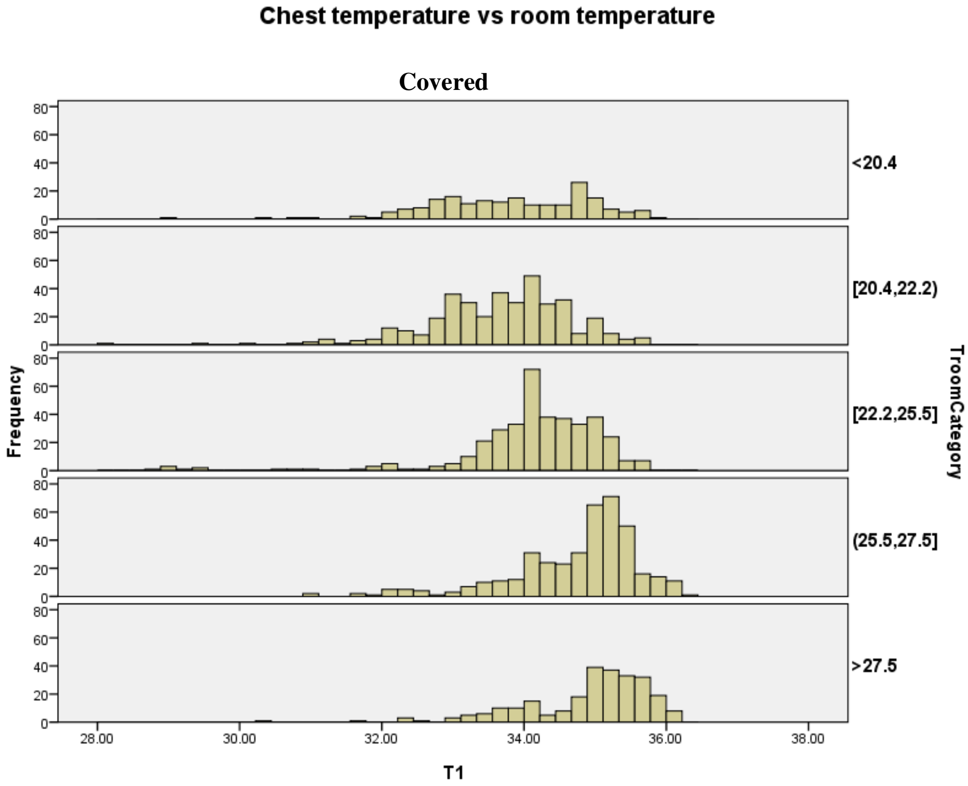
Appendix M: Core and skin temperature mapping in adults at different environments



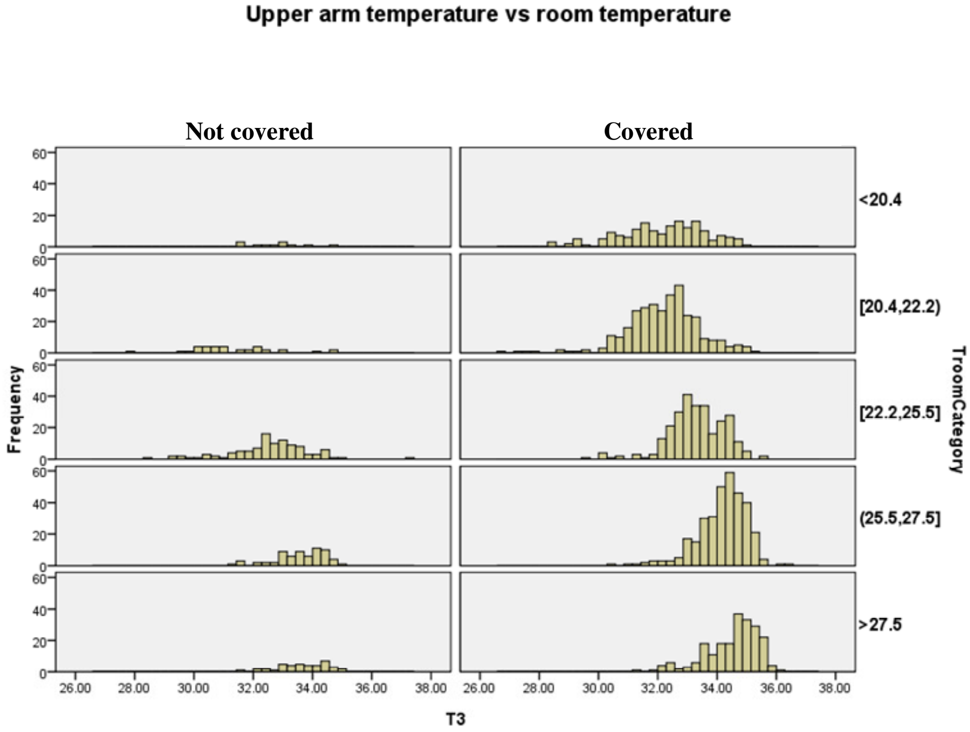
(a)



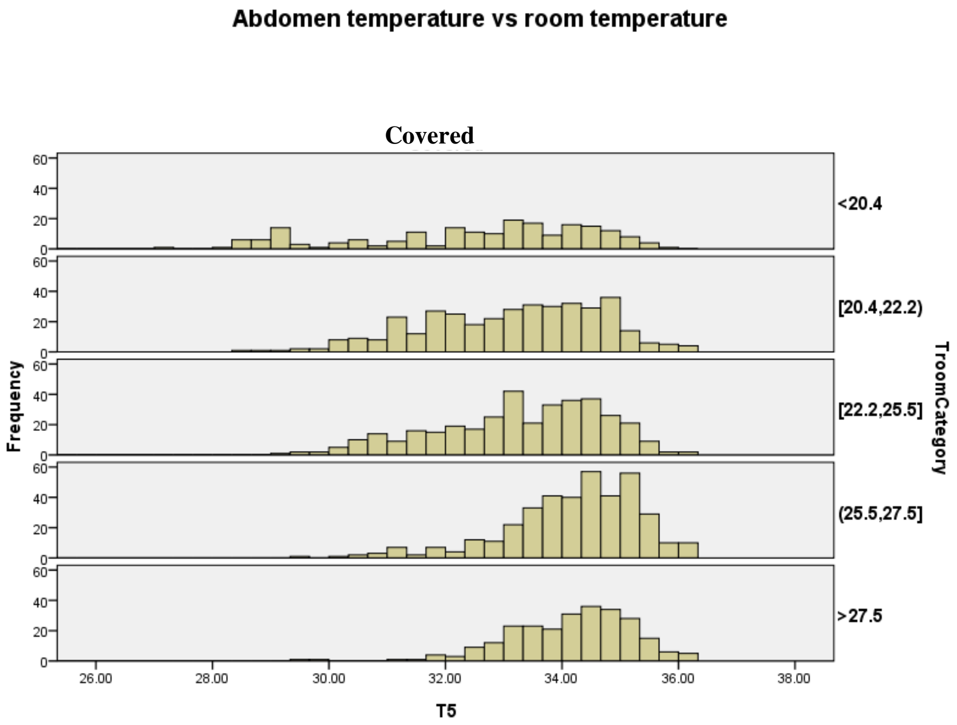
(b)


Chest temperature vs room temperature
Covered
Frequency
0
20
40
60
80
<20.4
[20.4,22.2)
[22.2,25.5]
(25.5,27.5]
>27.5
TroomCategory
28.00
30.00
32.00
34.00
36.00
38.00
T1

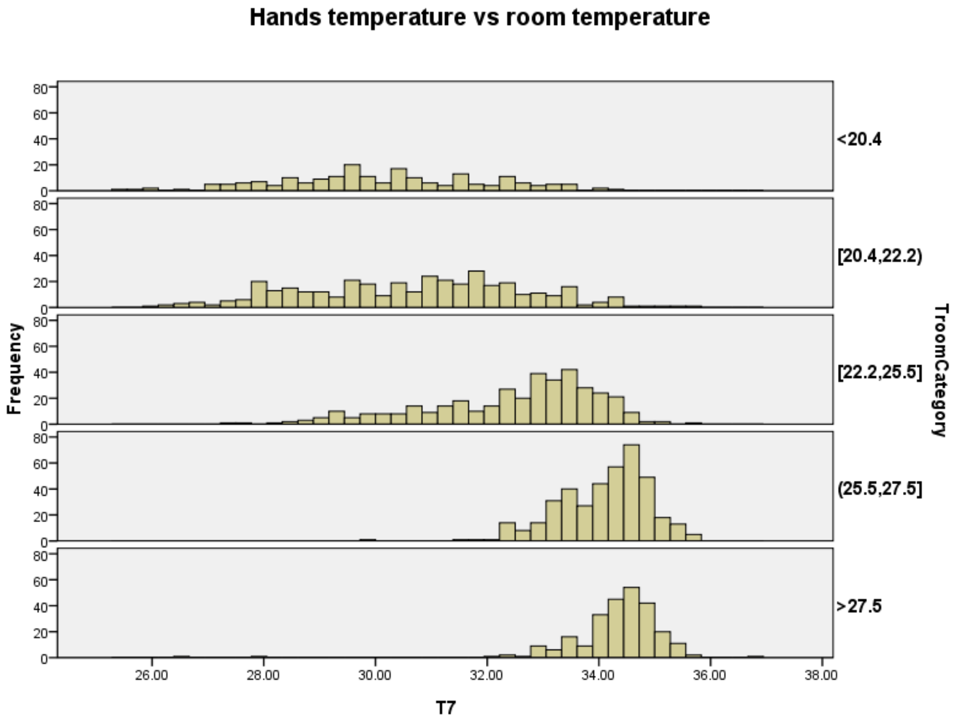
(c)


Upper arm temperature vs room temperature
Not covered
Covered
Frequency
0
20
40
60
<20.4
[20.4,22.2)
[22.2,25.5]
(25.5,27.5]
>27.5
TroomCategory
26.00
28.00
30.00
32.00
34.00
36.00
38.00
T3

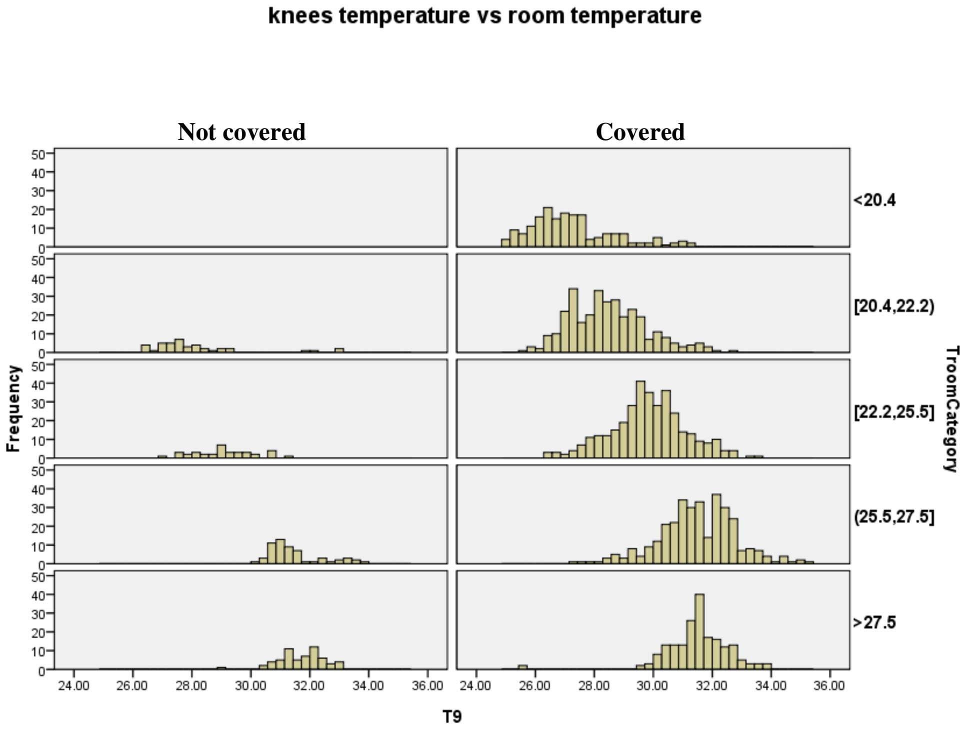
(d)


Abdomen temperature vs room temperature
Covered
Frequency
60
40
20
0
<20.4
[20.4,22.2)
[22.2,25.5]
(25.5,27.5]
>27.5
TroomCategory
26.00
28.00
30.00
32.00
34.00
36.00
38.00
T5

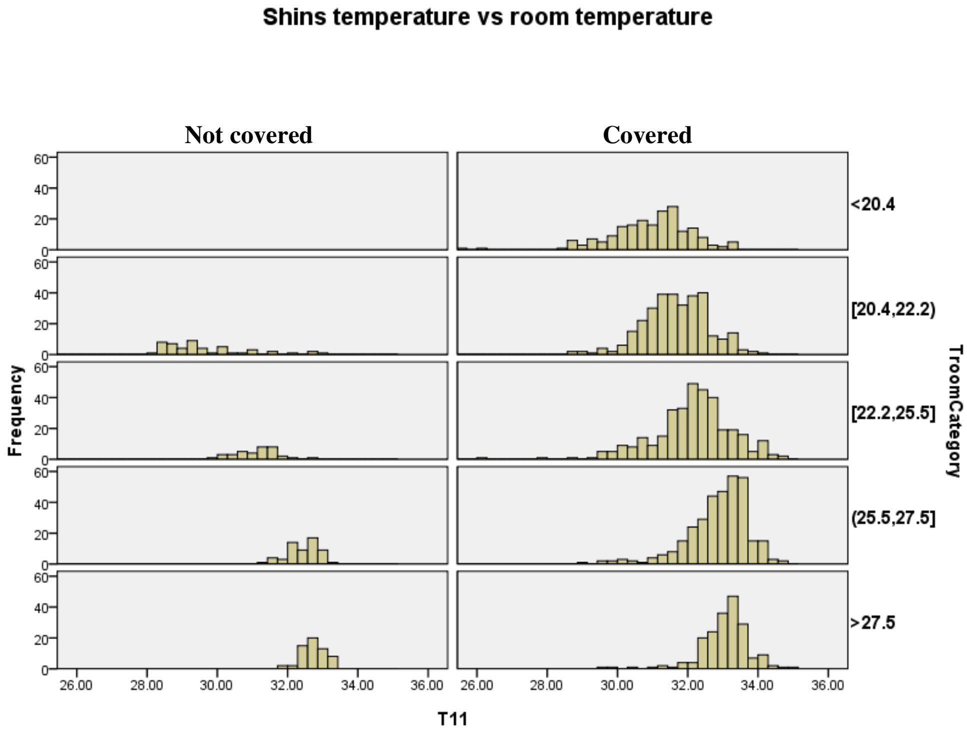
(e)


Hands temperature vs room temperature
Frequency
80
60
40
20
0
<20.4
[20.4,22.2)
[22.2,25.5]
(25.5,27.5]
>27.5
TroomCategory
26.00
28.00
30.00
32.00
34.00
36.00
38.00
T7

(f)



(g)



(h)

Figure M1: Local skin temperature distributions at different room temperatures

T room		Tc	T0	T1	T3	T3	T5	T7	T9	T9	T11	T11
			NC	C	NC	C	C	NC	NC	C	NC	C
[18.6, 20.4)	Mean	36.3	33.3	33.8	32.8	32.2	32.5	30.1		27.2		30.9
	SD	0.30	0.8	1.1	0.93	1.4	2.0	1.8		1.4		1.2
	N	196	98	198	12	172	198	198		184		196
[20.4, 22.2)	Mean	36.3	33.5	33.6	31.3	32.2	33.1	30.7	28.1	28.5	29.7	31.7
	SD	0.37	0.7	1.0	1.5	1.2	1.5	2.0	1.6	1.3	1.2	0.91
	N	374	187	373	34	330	374	374	40	314	50	314
[22.2, 25.5]	Mean	36.3	34.0	34.1	32.5	33.3	33.3	32.5	29.1	29.8	31.1	32.1
	SD	0.36	1.1	1.0	1.4	1.0	1.4	1.5	1.0	1.3	0.63	1.1
	N	380	190	378	104	274	364	380	36	344	36	344
(25.5, 27.5]	Mean	36.5	34.6	34.7	33.6	34.2	34.1	34.1	31.5	31.5	32.4	32.9
	SD	0.34	1.0	0.9	0.83	0.83	1.3	0.81	0.92	1.3	0.44	0.89
	N	398	200	400	66	334	390	398	58	328	58	336
(27.5, 30.5]	Mean	36.7	34.9	34.9	33.7	34.5	34.1	34.3	31.7	31.5	32.7	33.1
	SD	0.26	1.0	0.9	0.84	0.92	1.1	0.92	0.75	1.1	0.35	0.71
	N	254	126	254	40	214	254	254	60	192	60	191

Table M1: Statistical characterization of temperature distribution at each location and for each of the studied room temperature categories. C stands for covered (with cloths) and NC for not-covered (exposed) location

<table>
<tr><th>T room</th><th>Tc</th><th>T0</th><th>T1</th><th>T3</th><th>T3</th><th>T5</th><th>T7</th><th>T9</th><th>T9</th><th>T11</th><th>T11</th></tr>
<tr><td></td><td></td><td>NC</td><td>C</td><td>NC</td><td>C</td><td>C</td><td>NC</td><td>NC</td><td>C</td><td>NC</td><td>C</td></tr>
<tr><td>TR1 vs TR2</td><td>||</td><td>||</td><td>||</td><td></td><td>||</td><td>*</td><td>*</td><td></td><td>*</td><td>*</td><td>*</td></tr>
<tr><td>TR2 vs TR3</td><td>||</td><td>*</td><td>*</td><td>*</td><td>*</td><td>||</td><td>*</td><td>*</td><td>*</td><td>*</td><td>*</td></tr>
<tr><td>TR3 vs TR4</td><td>*</td><td>*</td><td>*</td><td>*</td><td>*</td><td>*</td><td>*</td><td>*</td><td>*</td><td>*</td><td>*</td></tr>
<tr><td>TR4 vs TR5</td><td>*</td><td>|</td><td>|</td><td>||</td><td>*</td><td>||</td><td>*</td><td>||</td><td>||</td><td>*</td><td>*</td></tr>
</table>

Table M2: Summary of significant differences among the temperature distributions defined in **Table M1**. Asterisk represents significant difference between the groups at 0.01 significance level in a two-tailed test. Bars represent no-significant difference between the groups at 0.05 (double bar) and 0.01 (single bar) significance level.

Appendix N: Core and local skin temperature prediction models

Dependent variable	Region 1	Region 2	Region 3
Tc	[18,6, 22,9]	(22,9, 30,5]	---
T0	[18,6, 22,1]	(22,1, 26,6)	(26,6, 30,5]
T1	[18,6, 22,1]	(22,1, 26,6)	(26,6, 30,5]
T3	[18,6, 22,9]	(22,9, 26,6)	(26,6, 30,5]
T5	[18,6, 23,8]	(23,8, 26,6)	(26,6, 30,5]
T7	[18,6, 22,1]	(22,1, 26,6)	(26,6, 30,5]
T9	---	[18,6, 26,6)	(26,6, 30,5]
T11	[18,6, 22,9]	(22,9, 25,7)	[25,7, 30,5]

Table N1: Room temperature regions where the skin temperature was analyzed separately

	Tc		T0		T1		T3	
	Coeff	**SE**	**Coeff**	**SE**	**Coeff**	**SE**	**Coeff**	**SE**
a (ºC)	35.5686	0.0022	5.539	0.069	20.859	0.057	8.776	0.063
b (NU)	0.047780	0.000065	0.14626	0.00026	0.13595	0.00019	0.25511	0.00024
c (ºC/%)	-0.003869	0.000021	-0.008996	0.000067	-0.008946	0.000051	-0.011935	0.000064
d (NU)	---	---	0.7398	0.0019	0.3122	0.0016	0.5182	0.0017
e (ºC/years)	-0.004342	0.000024	-0.008170	0.000088	-0.011274	0.000055	-0.012059	0.000069
f (ºC.m^2/Kg)	-0.010451	0.000043	-0.03531	0.00021	-0.03138	0.00015	---	---
g (ºC)	0.14464	0.00041	-0.3321	0.0015	-0.1905	0.0013	-0.1059	0.0013
h (ºC/nº$_{layers}$)	---	---	---	---	0.3149	0.0012	0.32409	0.00094

(a)

	T5		T7		T9		T11	
	Coeff	**SE**	**Coeff**	**SE**	**Coeff**	**SE**	**Coeff**	**SE**
a (ºC)	23.437	0.079	15.308	0.100	5.832	0.081	23.533	0.060
b (NU)	0.18702	0.00033	0.48255	0.00036	0.47260	0.00032	0.22867	0.00022
c (ºC/%)	0.006453	0.000080	0.012685	0.000088	0.003445	0.000075	0.002115	0.000061
d (NU)	0.2177	0.0022	0.1347	0.0028	0.3125	0.0023	0.0810	0.0017
e (ºC/years)	-0.032406	0.000075	-0.002384	0.000077	---	---	-0.011536	0.000056
f (ºC.m^2/Kg)	-0.08704	0.00024	0.05184	0.00018	0.05556	0.00016	-0.00118	0.00013
g (ºC)	0.1594	0.0017	-0.7529	0.0018	-0.3506	0.0017	-0.2706	0.0011
h (ºC/nº$_{layers}$)	0.1370	0.0018	---	---	0.2644	0.0019	0.8682	0.0015

(b)Table N2: Computed coefficients of the skin temperature multi-linear regressions

Dependent variable	Constant		slope		R
	value	error	value	error	
Tc	0.0	1.7	1.000	0.046	0.48
T0	0.0	1.5	1.000	0.043	0.64
T1	0.1	1.4	.998	0.040	0.53
T3	0.00	0.91	1.000	0.027	0.68
T5	1.8	1.3	.959	0.041	0.51
T7	0.00	0.69	1.000	0.021	0.76
T9	0.00	0.60	1.000	0.020	0.79
T11	0.01	0.97	1.000	0.030	0.64

Table N3: Computed coefficients of the linear regression between the obtained and predicted skin temperatures at each location.

Location	Tc	T0	T1	T3	T5	T7	T9	T11
Average SD	0.33	0.92	0.99	1.08	1.46	1.41	1.18	0.81
Coefficient on gender	0.145	-0.332	-0.191	-0.106	0.159	-0.753	-0.351	-0.271
%SD of change	***44.2***	***35.9***	19.3	9.82	10.9	***53.3***	***29.7***	***33.3***

Table N4: Change on the core and skin temperature due to the gender, calculated as percentage of the SD characteristic of the location.

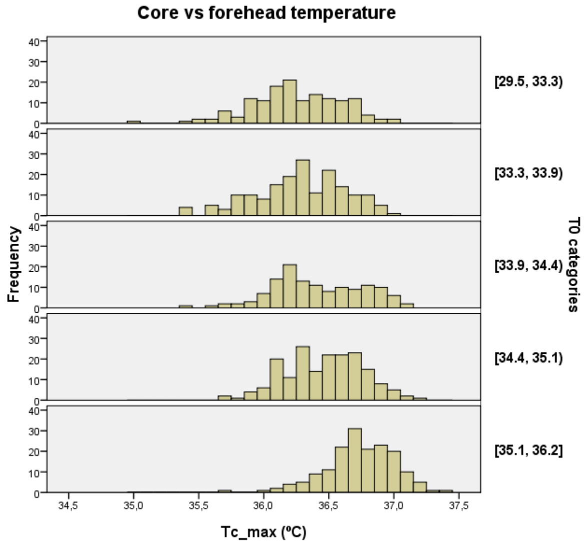
		a_i (ºC)	n_ij (ºC)	m_ij (ºC)	c (%)	d (ºC)	e (years)	f	g	h
Tc	R1	35.567 (0.002)	0.04 (0.11)	---	0.0020 (0.0015)	---	-0.0005 (0.0021)	-0.0007 (0.0039)	0.389 (0.026)	---
	R2	35.567 (0.002)	-0.12 (0.17)	0.0645 (0.0058)	-0.0054 (0.0012)	---	-0.0034 (0.0012)	-0.0135 (0.002)	-0.006 (0.021)	---
T0	R1	5.539 (0.069)	9.5 (5.7)	---	-0.0006 (0.0050)	0.49 (0.16)	-0.0091 (0.0076)	0.039 (0.023)	-0.01 (0.11)	---
	R2	5.539 (0.069)	0.7 (5.6)	0.077 (0.049)	-0.0034 (0.0052)	0.78 (0.15)	-0.0194 (0.0059)	-0.033 (0.016)	-0.67 (0.12)	---
	R3	5.539 (0.069)	-0.4 (5.9)	0.031 (0.057)	-0.0148 (0.0053)	0.85 (0.16)	0 (0.0098)	-0.065 (0.014)	-0.21 (0.13)	---
T1	R1	20.859 (0.057)	10.8 (5)	---	-0.0116 (0.0050)	0.13 (0.14)	-0.0267 (0.006)	-0.062 (0.02)	0.02 (0.11)	0.05 (0.078)
	R2	20.859 (0.057)	1.0 (4.1)	0.272 (0.039)	-0.0023 (0.0043)	0.16 (0.12)	-0.002 (0.0027)	-0.011 (0.0077)	-0.7 (0.16)	0.83 (0.17)
	R3	20.859 (0.057)	-18.6 (4.7)	-0.017 (0.033)	-0.0107 (0.0040)	0.93 (0.12)	-0.0022 (0.0052)	-0.0438 (0.0098)	-0.018 (0.086)	0.382 (0.08)
T3	R1	8.776 (0.063)	-2.9 (5.6)	---	-0.0145 (0.0064)	0.76 (0.16)	-0.0213 (0.005)	---	-0.38 (0.13)	0.34 (0.083)
	R2	8.776 (0.063)	9.0 (5.2)	0.240 (0.053)	-0.0047 (0.0045)	0.27 (0.15)	-0.0042 (0.0046)	---	-0.017 (0.086)	0.354 (0.072)
	R3	8.776 (0.063)	-3.2 (4.0)	---	-0.0228 (0.0040)	0.81 (0.11)	-0.0243 (0.007)	---	0.148 (0.077)	0.299 (0.047)
T5	R1	23.437 (0.079)	5.0 (5.6)	0.305 (0.055)	0.0080 (0.0064)	0.06 (0.15)	-0.0428 (0.0051)	-0.12 (0.02)	-0.02 (0.12)	-0.14 (0.12)
	R2	23.437 (0.079)	-3.5 (8.8)	-0.057 (0.081)	-0.0142 (0.0072)	0.46 (0.25)	-0.0059 (0.0083)	-0.064 (0.022)	-0.09 (0.13)	0.63 (0.18)
	R3	23.437 (0.079)	-18 (5.4)	---	0.0187 (0.0050)	0.81 (0.15)	-0.0614 (0.0076)	-0.041 (0.011)	0.95 (0.12)	-0.06 (0.12)
T7	R1	15.308 (0.100)	3.6 (9.7)	0.167 (0.088)	0.0364 (0.0097)	0.18 (0.26)	-0.016 (0.01)	0.108 (0.035)	-1.14 (0.19)	---
	R2	15.308 (0.100)	-12.4 (6.9)	0.611 (0.049)	0.0192 (0.0064)	0.38 (0.19)	-0.0061 (0.0048)	0.084 (0.012)	-1.03 (0.1)	---
	R3	15.308 (0.100)	10.6 (5.1)	0.006 (0.065)	-0.0085 (0.0038)	0.22 (0.17)	0.004 (0.0072)	0.0179 (0.006)	-0.07 (0.082)	---
T9	R2	5.832 (0.081)	-5.6 (4.6)	0.592 (0.020)	-0.0057 (0.0044)	0.39 (0.13)	---	0.0557 (0.0096)	-0.297 (0.093)	0.61 (0.12)
	R3	5.832 (0.081)	8.4 (5.9)	---	0.0066 (0.0057)	0.44 (0.16)	---	0.0649 (0.0095)	-0.44 (0.11)	-0.15 (0.1)
T11	R1	23.533 (0.060)	1.0 (4.2)	0.302 (0.039)	0.0065 (0.005)	-0.02 (0.12)	-0.0074 (0.0039)	0.003 (0.012)	-0.29 (0.1)	1.77 (0.15)
	R2	23.533 (0.060)	-6.8 (9.0)	0.38 (0.12)	-0.0103 (0.0064)	0.21 (0.22)	-0.0149 (0.0062)	-0.017 (0.017)	-0.53 (0.16)	0.76 (0.19)
	R3	23.533 (0.060)	-8.3 (4.7)	0.100 (0.028)	0.0058 (0.0035)	0.38 (0.13)	-0.0167 (0.0053)	0.0284 (0.0068)	0.062 (0.077)	0.348 (0.051)

Table N5: Computed coefficients of the multi-linear regressions based on the modification 4, for core and local skin temperatures

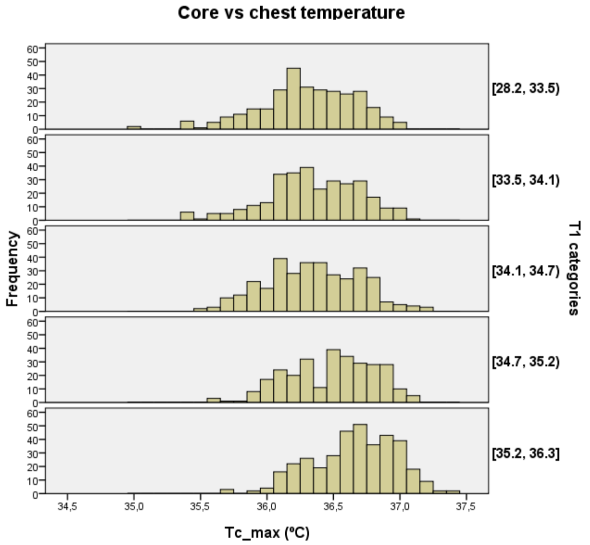
Appendix O: Insides of non-intrusive methods for core temperature estimation

Skin temperature (ºC)						
Location	Cohort 1	Cohort 2	Cohort 3	Cohort 4	Cohort 5	N
	P0 to P20	P20 to P40	P40 to P60	P60 to P80	P80 to P100	
T0	[29.5, 33.3)	[33.3, 33.9)	[33.9, 34.4)	[34.4, 35.1)	[35.1, 36.2]	801
T1	[28.2, 33.5)	[33.5, 34.1)	[34.1, 34.7)	[34.7, 35.2)	[35.2, 36.3]	1603
T3	[26.7, 32.1)	[32.1, 33.0)	[33.0, 33.8)	[33.8, 34.5)	[34.5, 37.4]	1579
T5	[27.5, 32.3)	[32.3, 33.4)	[33.4, 34.2)	[34.2, 34.8)	[34.8, 36.3]	1578
T7	[25.5, 30.3)	[30.3, 32.5)	[32.5, 33.6)	[33.6, 34.4)	[34.4, 36.7]	1604
T9	[25.1, 27.9)	[27.9, 29.5)	[29.5, 30.7)	[30.7, 31.7)	[31.7, 35.3]	1552
T11	[27.8, 31.2)	[31.2, 31.9)	[31.9, 32.6)	[32.6, 33.2)	[33.2, 34.9]	1579

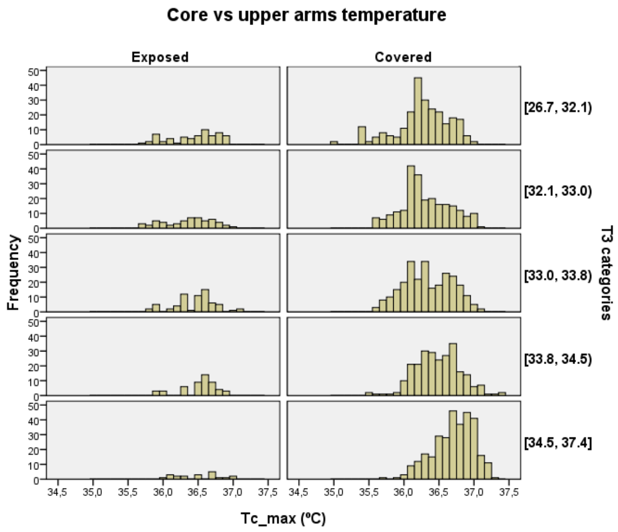
Table O1: Skin temperature categories



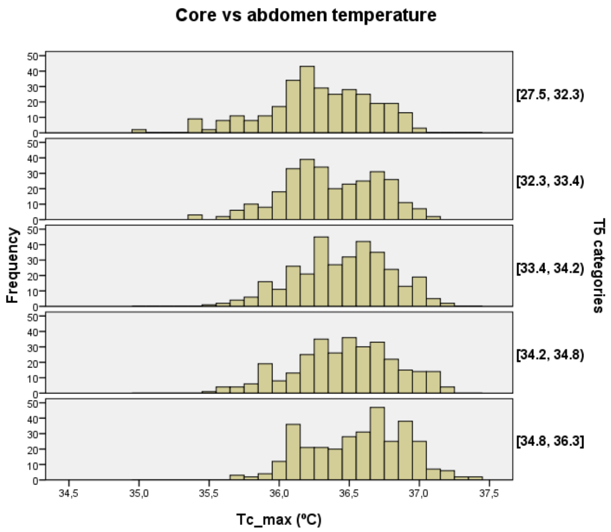
(a)



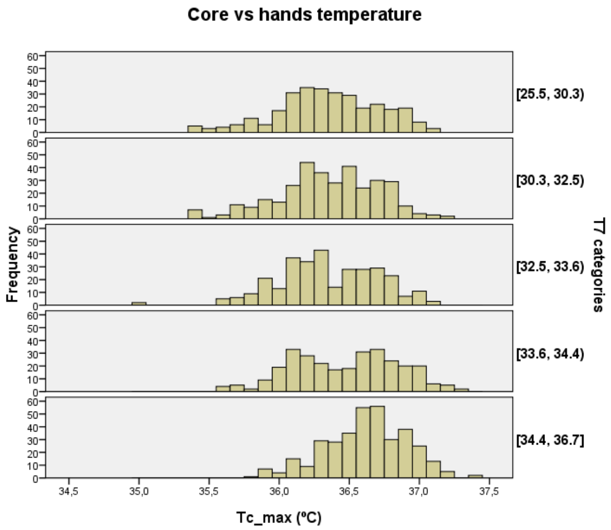
(b)


Core vs upper arms temperature
Exposed
Covered
Frequency
0
10
20
30
40
50
[26.7, 32.1)
[32.1, 33.0)
[33.0, 33.8)
[33.8, 34.5)
[34.5, 37.4]
T3 categories
34,5
35,0
35,5
36,0
36,5
37,0
37,5
Tc_max (ºC)

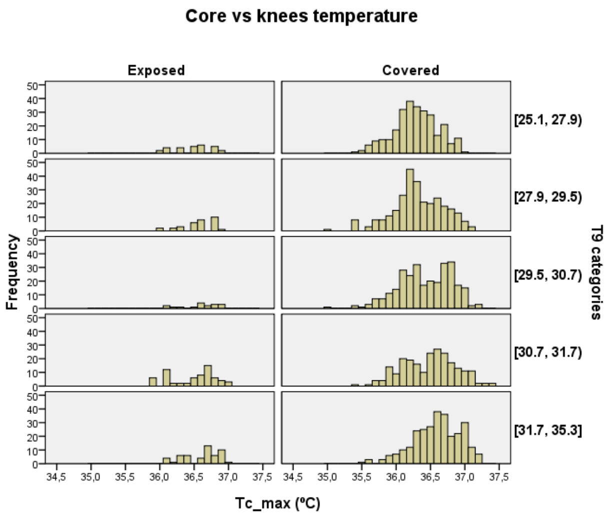
(c)


Core vs abdomen temperature
Frequency
0
10
20
30
40
50
[27.5, 32.3)
[32.3, 33.4)
[33.4, 34.2)
[34.2, 34.8)
[34.8, 36.3]
T5 categories
34,5
35,0
35,5
36,0
36,5
37,0
37,5
Tc_max (ºC)

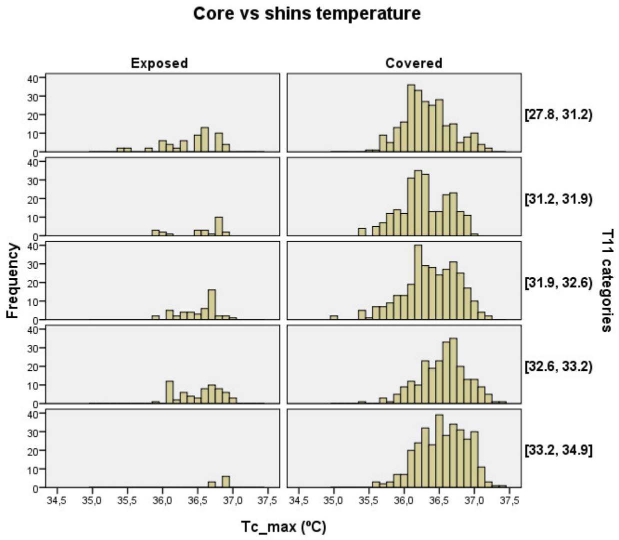
(d)


Core vs hands temperature
Frequency
0
10
20
30
40
50
60
[25.5, 30.3)
[30.3, 32.5)
[32.5, 33.6)
[33.6, 34.4)
[34.4, 36.7]
T7 categories
34,5
35,0
35,5
36,0
36,5
37,0
37,5
Tc_max (ºC)

(e)



(f)



(g)

Figure O1: Core temperature distributions at different local skin temperatures ranges

Tc max		T0		T1		T3		T3		T5	
		NC		C		NC		C		C	
		Tskin	Tc	Tskin	Tc	Tskin	Tc	Tskin	Tc	Tskin	Tc
Cohort 1	Mean	32.34	36.25	32.58	36.30	30.90	36.44	31.08	36.27	31,01	36,28
	SD	0.84	0.35	0.92	0.36	0.94	0.35	0.92	0.38	0,98	0,38
	N	145	=	310	=	62	=	251	=	306	=
Cohort 2	Mean	33.55	36.28	33.77	36.34	32.49	36.36	32.53	36.31	32,87	36,37
	SD	0.18	0.35	0.17	0.35	0.25	0.35	0.25	0.35	0,31	0,34
	N	174	=	301	=	56	=	240	=	298	=
Cohort 3	Mean	34.11	36.41	34.35	36.34	33.32	36.45	33.35	36.34	33,75	36,45
	SD	0.14	0.35	0.18	0.35	0.25	0.29	0.23	0.34	0,23	0,34
	N	131	=	332	=	66	=	266	=	331	=
Cohort 4	Mean	34.67	36.46	34.90	36.49	34.13	36.52	34.10	36.49	34,47	36,47
	SD	0.19	0.30	0.14	0.32	0.21	0.26	0.20	0.32	0,16	0,36
	N	182	=	290	=	51	=	251	=	309	=
Cohort 5	Mean	35.47	36.74	35.48	36.66	34.67	36.50	34.96	36.71	35,23	36,56
	SD	0.28	0.27	0.24	0.32	0.15	0.32	0.37	0.29	0,37	0,35
	N	167	=	366	=	20	=	312	=	330	=

(a)

Tc max		T7		T9		T9		T11		T11	
		NC		NC		C		NC		C	
		Tskin	Tc	Tskin	Tc	Tskin	Tc	Tskin	Tc	Tskin	Tc
Cohort 1	Mean	28.8	36.35	27.27	36.48	26.84	36.28	29.63	36.40	30.32	36.33
	SD	1.0	0.36	0.44	0.28	0.69	0.32	0.88	0.39	0.64	0.34
	N	301	=	28	=	271	=	60	=	252	=
Cohort 2	Mean	31.41	36.35	28.63	36.56	28.66	36.32	31.48	36.54	31.54	36.29
	SD	0.65	0.36	0.48	0.24	0.48	0.37	0.19	0.35	0.20	0.35
	N	336	=	32	=	283	=	25	=	249	=
Cohort 3	Mean	33.06	36.35	30.14	36.59	30.05	36.43	32.24	36.51	32.21	36.38
	SD	0.33	0.36	0.39	0.27	0.34	0.39	0.19	0.27	0.20	0.40
	N	313	=	17	=	290	=	47	=	313	=
Cohort 4	Mean	33.97	36.47	31.12	36.49	31.18	36.48	32.81	36.52	32.84	36.55
	SD	0.23	0.38	0.29	0.33	0.28	0.39	0.17	0.30	0.16	0.34
	N	298	=	66	=	231	=	63	=	236	=
Cohort 5	Mean	34.80	36.62	32.45	36.61	32.42	36.59	33.24	36.83	33.58	36.55
	SD	0.33	0.29	0.54	0.26	0.68	0.34	0.07	0.10	0.34	0.34
	N	352	=	51	=	283	=	9	=	325	=

(b)

Table O2: Core and local skin temperature distribution for each of the studied skin temperature categories. C stands for covered (with clothing) and NC for not-covered (exposed) location.(=) The number of samples for skin and core temperature in each cohort is the same

<table>
<tr><th>Local Tskin</th><th>T0</th><th>T1</th><th>T3</th><th>T3</th><th>T5</th><th>T7</th><th>T9</th><th>T9</th><th>T11</th><th>T11</th></tr>
<tr><th></th><th>NC</th><th>C</th><th>NC</th><th>C</th><th>C</th><th>NC</th><th>NC</th><th>C</th><th>NC</th><th>C</th></tr>
<tr><td>Cohort 1 vs. cohort 2</td><td>||</td><td>||</td><td>||</td><td>||</td><td>*</td><td>||</td><td>||</td><td>||</td><td>||</td><td>||</td></tr>
<tr><td>Cohort 2 vs. cohort 3</td><td>*</td><td>||</td><td>||</td><td>||</td><td>*</td><td>||</td><td>||</td><td>*</td><td>||</td><td>*</td></tr>
<tr><td>Cohort 3 vs. cohort 4</td><td>||</td><td>*</td><td>||</td><td>*</td><td>||</td><td>*</td><td>||</td><td>||</td><td>||</td><td>*</td></tr>
<tr><td>Cohort 4 vs. cohort 5</td><td>*</td><td>*</td><td>||</td><td>*</td><td>*</td><td>*</td><td>|</td><td>*</td><td></td><td>||</td></tr>
</table>

Table O3: Summary of statistical differences among the core temperature distributions defined in **Table**. (*) Significant difference between the groups at 0.01 significance level in a two-tailed test. (||) No-significant difference at 0.05 (|) and 0.01 significance level.

Parameter	Correlation withTc	Significance level
T_{room}	0.362	0.01
H_{room}	-0.253	0.01
T0	0.419	0.01
T1	0.293	0.01
T3	0.356	0.01
T5	0.263	0.01
T7	0.227	0.01
T9	0.296	0.01
T11	0.226	0.01
Weight	-0.239	0.01
Height	-0.168	0.01
Age	-0.219	0.01
BMI	-0.138	0.01
Gender	0.111	0.01
Loc3C	-0.007	---
Loc9C	-0.107	0.01
Loc11C	-0.063	0.05

Table O4: Correlation values between core temperature and each individual potential factor

Model	Constant	Slope	R-value	Std. error estimate
16-parameters	-0.0 (1.4)	1.000 (0.038)	0.561	0.307
15	-0.0 (1.4)	1.000 (0.039)	0.554	0.309
14	0.0 (1.4)	1.000 (0.039)	0.554	0.309
13	0.0 (1.5)	1.000 (0.040)	0.547	0.310
12	-0.0 (1.5)	1.000 (0.041)	0.538	0.313
11	-0.0 (1.5)	1.000 (0.041)	0.532	0.314
10	0.0 (1.5)	1.000 (0.042)	0.526	0.315
9	-0.0 (1.5)	1.000 (0.042)	0.524	0.315
8	-0.0 (1.5)	1.000 (0.042)	0.523	0.315
7	0.0 (1.7)	1.000 (0.046)	0.487	0.323
6	0.0 (1.8)	1.000 (0.049)	0.468	0.327
5	0.0 (1.8)	1.000 (0.049)	0.464	0.327
T0, T_{room}, T3, T1	0.0 (1.8)	1.000 (0.049)	0.460	0.327
T0, T_{room}, T3	0.0 (1.8)	1.000 (0.049)	0.456	0.324
T0, T_{room}	0.0 (1.8)	1.000 (0.050)	0.448	0.325
T0	0.0 (2.0)	1.000 (0.054)	0.419	0.330

Table O5: Linear regressions of observed vs. predicted core temperatures for several models. $T_{c,observed} = a + b.T_{c,predicted}$. The parameters included in the model are in order: *T0*, T_{room}, *T3*, *T9*, *T1*, *T5*, H_{room}, *Weight*, *T7*, *T11*, *Age*, *Height*, *BMI*, *Gender*, *Loc9C* and *Loc11C*. *Loc3C* was not included as it was proved to be not significant.

Model	Parameter	Value	Std. Error	Sig
1	(Constant)	31.68	0.26	0.000
	T0	0.140	0.008	0.000
2	(Constant)	32.24	0.27	0.000
	T0	0.108	0.009	0.000
	T_{room}	0.021	0.003	0.000
3	(Constant)	31.81	0.30	0.000
	T0	0.098	0.010	0.000
	T_{room}	0.015	0.004	0.000
	T3	0.028	0.008	0.000
4	(Constant)	31.88	0.31	0.000
	T0	0.099	0.010	0.000
	T_{room}	0.018	0.005	0.000
	T3	0.029	0.008	0.000
	T9	-0.007	0.007	**0.328**
5	(Constant)	31.54	0.35	0.000
	T0	0.096	0.010	0.000
	T_{room}	0.017	0.005	0.001
	T3	0.021	0.009	0.020
	T9	-0.006	0.007	**0.394**
	T1	0.020	0.010	0.042
6	(Constant)	31.45	0.35	0.000
	T0	0.096	0.010	0.000
	T_{room}	0.016	0.005	0.001
	T3	0.017	0.009	0.067
	T9	-0.005	0.007	**0.458**
	T1	0.010	0.011	**0.364**
	T5	0.018	0.007	0.012
7	(Constant)	32.19	0.37	0.000
	T0	0.087	0.010	0.000
	T_{room}	0.014	0.005	0.005
	T3	0.012	0.009	**0.174**
	T9	0.000	0.007	**0.993**
	T1	0.005	0.011	**0.652**
	T5	0.018	0.007	0.012
	H_{room}	-0.005	0.001	0.000
8	(Constant)	32.97	0.37	0.000
	T0	0.078	0.009	0.000
	T_{room}	0.016	0.005	0.001
	T3	0.023	0.009	0.009
	T9	0.008	0.007	**0.240**
	T1	0.001	0.010	**0.950**
	T5	0.000	0.007	**0.983**
	H_{room}	-0.004	0.001	0.000
	Weight	-0.006	0.001	0.000
9	(Constant)	32.94	0.37	0.000
	T0	0.078	0.009	0.000
	T_{room}	0.019	0.005	0.000
	T3	0.025	0.009	0.005
	T9	0.013	0.007	0.066
	T1	0.003	0.010	**0.800**
	T5	0.001	0.007	**0.915**
	H_{room}	-0.003	0.001	0.000
	Weight	-0.006	0.001	0.000
	T7	-0.013	0.007	0.047

Table O6: Coefficient values and significance of the parameters (sig <0.05) for several core temperature models

Location	Cohort where trend changes	Mean	SD	Valid range of skin temperature
T0	2	33.55	0.18	>= 33.4
T1	3	34.35	0,18	>= 34.2
T3	Covered -> 2 Exposed -> filtered out	32.50	0.25	>= 32.3 and location covered
T5	1	31.01	0.98	>= 30.0
T7	3	33.06	0.33	>= 32.7
T9	Covered -> 2 Exposed -> filtered out	28.66	0.48	>= 28.2 and location covered
T11	Covered -> 2 Covered -> 4 Exposed -> filtered out	31.54 32.84	0.20 0.16	[31.3, 33.0] and location covered

Table O7: Constrains to the model: local skin temperatures for which the new model applies. Values have been chosen to provide higher correlation.

Relax factor	N cases	N acum	%	R-value	SE estimate	Constant	Slope
0	171	171	11.5	0.806	0.201	0.0 (2.1)	1.000 (0.057)
1	374	545	36.7	0.675	0.266	-0.0 (1.7)	1.000 (0.047)
2	339	884	59.5	**0.641**	0.275	0.0 (1.5)	1.000 (0.040)
3	263	1147	77.2	0.605	0.295	-0.0 (1.4)	1.000 (0.039)
4	164	1311	88.2	0.599	0.300	0.0 (1.4)	1.000 (0.037)
5	101	1412	95.0	0.582	0.302	0.0 (1.4)	1.000 (0.037)
6	70	1482	99.7	0.570	0.304	0.0 (1.4)	1.000 (0.038)
7 (No constrains)	4	1486	100	0.561	0.307	0.0 (1.4)	1.000 (0.038)

Table O8: Performance description of 16-parameters models of core temperature for different relax factors. Calculations based on 1207 measurements with complete local skin temperature data.

Parameter	Correlation with Tc	Significance level
T_{room}	0.462	0.01
H_{room}	-0.351	0.01
T0	0.470	0.01
T1	0.405	0.01
T3	0.453	0.01
T5	0.269	0.01
T7	0.297	0.01
T9	0.271	0.01
T11	0.262	0.01
Weight	-0.205	0.01
Height	-0.081	0.05
Age	-0.276	0.01
BMI	-0.153	0.01
Gender	0.029	---
Loc3C	0.059	---
Loc9C	-0.094	0.05
Loc11C	-0.094	0.05

Table O9: Correlation values between core temperature and each individual potential factor when constraints in local skin temperature ranges are applied under relax factor 2.

Model parameters	Relax factor	Constant (ºC)	Slope	R-value	Std. error estimate	N (%)
15	2	0.0 (1.6)	1.000 (0.044)	0.612	0.283	54.7%
14	2	0.0 (1.6)	1.000 (0.045)	0.603	0.286	54.7%
13	2	0.0 (1.6)	1.000 (0.045)	0.603	0.286	54.7%
12	2	-0.0 (1.6)	1.000 (0.045)	0.600	0.286	54.7%
11	2	0.0 (1.6)	1.000 (0.045)	0.600	0.286	54.7%
10	2	0.0 (1.7)	1.000 (0.046)	0.595	0.288	54.7%
9	2	0.0 (1.7)	1.000 (0.045)	0.573	0.296	62.6%
8	2	-0.0 (1.7)	1.000 (0.045)	0.569	0.298	63.8%
7	2	0.0 (1.6)	1.000 (0.044)	0.547	0.298	74.5%
6	2	-0.0 (1.6)	1.000 (0.044)	0.545	0.299	74.8%
T0, T3, T_{room}, T1, H_{room}	2	0.0 (1.8)	1.000 (0.048)	0.481	0.316	88.9%
T0, T3, T_{room}, T1	2	0.0 (1.8)	1.000 (0.050)	0.466	0.319	88.9%
T0, T3, T_{room}	2	0.0 (1.8)	1.000 (0.049)	0.456	0.324	97.7%
T0, T3	2	0.0 (1.8)	1.000 (0.050)	0.448	0.325	99.3%
T0	2	0.0 (2.0)	1.000 (0.054)	0.419	0.330	99.3%
6	1	-0.0 (1.8)	1.000 (0.050)	0.553	0.290	55.4%
T0, T3, T_{room}, T1, H_{room}	1	-0.0 (1.8)	1.000 (0.050)	0.512	0.300	69.1%
T0, T3, T_{room}, T1	1	0.0 (1.9)	1.000 (0.052)	0.502	0.302	69.1%
T0, T3, T_{room}	1	0.0 (1.9)	1.000 (0.051)	0.466	0.319	86.2%
T0, T3	1	0.0 (1.8)	1.000 (0.050)	0.448	0.325	99.3%
T0	1	0.0 (2.0)	1.000 (0.054)	0.419	0.330	99.3%
6	0	-0.0 (2.3)	1.000 (0.062)	0.587	0.269	30.8%
T0, T3, T_{room}, T1, H_{room}	0	-0.0 (2.0)	1.000 (0.054)	0.596	0.286	38.2%
T0, T3, T_{room}, T1	0	0.0 (2.0)	1.000 (0.055)	0.594	0.286	38.2%
T0, T3, T_{romp}	0	0.0 (1.8)	1.000 (0.050)	0.563	0.294	53.7%
T0, T3	0	0.0 (1.9)	1.000 (0.053)	0.474	0.313	77.5%
T0	0	0.0 (1.9)	1.000 (0.053)	0.470	0.314	77.5%

Table O10: Linear regressions of observed values vs. predicted core temperatures for several models ($T_{c,observed} = a + b.T_{c,predicted}$).

The parameters included in the model are in order: *T0*, T_{room}, *T3*, *T1*, H_{room}, *T7*, *age*, *T9*, *T5*, T11, *weight*, *BMI*, *Loc9C*, *Loc11C* and *height*. *Gender* and *Loc3C* were not considered as they are not significant. Percentages were calculated based on the 1611 collected measurements sets.

Model parameters	Relax factor	Constant (ºC)	Slope	R-value	Std. error estimate	N (%)
T_{room}, H_{room}, T0, T3	2	-0.0 (1.7)	1.000 (0.047)	0.474	0.321	97.4
T_{room}, H_{room}, T0, T3, T7	2	-0.0 (1.7)	1.000 (0.046)	0.498	0.314	88.5
T_{room}, H_{room}, T0, T7	2	0.0 (1.7)	1.000 (0.047)	0.471	0.320	98.9
T_{room}, H_{room}, T0	1	0.0 (2.5)	1.000 (0.067)	0.466	0.321	99.0
T_{room}, H_{room}, T0, T3	1	-0.0 (1.8)	1.000 (0.049)	0.482	0.316	86.0
T_{room}, H_{room}, T0, T3, T7	1	0.0 (1.7)	1.000 (0.047)	0.547	0.297	66.1
T_{room}, H_{room}, T0, T7	1	-0.0 (1.7)	1.000 (0.048)	0.497	0.313	83.4
T_{room}, H_{room}, T7	1	-0.0 (2.1)	1.000 (0.056)	0.406	0.332	99.1
T_{room}, H_{room}, T1	1	-0.0 (2.0)	1.000 (0.054)	0.423	0.329	99.1
T_{room}, H_{room}, T0	0	-0.0 (2.7)	1.000 (0.073)	0.480	0.312	77.3
T_{room}, H_{room}, T0, T3	0	0.0 (1.8)	1.000 (0.049)	0.569	0.292	53.6
T_{room}, H_{room}, T0, T3, T7	0	-0.0 (1.9)	1.000 (0.052)	0.604	0.274	40.3
T_{room}, H_{room}, T0, T7	0	-0.0 (1.9)	1.000 (0.051)	0.571	0.279	50.3
T_{room}, H_{room}, T7	0	0.0 (2.1)	1.000 (0.057)	0.505	0.305	56.6
T_{room}, H_{room}, T1	0	0.0 (2.1)	1.000 (0.056)	0.504	0.305	57.1

Table O11: Linear regressions of observed values vs. predicted core temperatures for several models ($T_{c,observed} = a + b.T_{c,predicted}$).

The parameters included in the model were selected for their convenience and measurement practicability. Percentages were calculated based on the 1612 collected measurements sets.

Appendix P: Core temperature estimation based on IR images

Parameter		T_{room}	T_{max}	$T_{average}$	T_{max} - T_c	$T_{average}$ - T_c	T_{max} – T_{room}	$T_{average}$ - T_{room}
T_c	p	0.183*	0.396**	0.326**	-0.325**	-0.211*	-0.128	-0.128
	sig	0.035	0.000	0.000	0.000	0.014	0.142	0.140
T_{room}	p		0.405**	0.597**	0.284**	0.517**	-0.989**	-0.982**
	sig		0.000	0.000	0.001	0.000	0.000	0.000
T_{max}	p			0.904**	0.740**	0.718**	-0.263**	-0.243**
	sig			0.000	0.000	0.000	0.002	0.005
$T_{average}$	p				0.692**	0.855**	-0.481**	-0.435**
	sig				0.000	0.000	0.000	0.000
T_{max} - T_c	p					0.893**	-0.177*	-0.156
	sig					0.000	0.040	0.072
$T_{average}$ - T_c	p						-0.428**	-0.380**
	sig						0.000	0.000
T_{max} – T_{room}	p							0.996**
	sig							0.000

Table P1: Correlation between T_c measured by a standard method, the extracted temperature values from the IR images and other computed parameters. (*) Correlation is significant at the 0.05 level (2-tailed). (**) Correlation is significant at the 0.01 level (2-tailed).

Model parameters	Constant (ºC)	Slope	R-value	Std. error estimate	AIC w_i
Tmax, Tavg, T_{room}	0.0 (7.0)	1.00 (0.19)	0.411	0.268	0.2595
Tmax, Tavg	0.0 (7.2)	1.00 (0.20)	0.402	0.269	0.2752
Tmax	-0.0 (7.4)	1.00 (0.20)	0.396	0.270	0.2888
Tavg	0.0 (9.2)	1.00 (0.25)	0.326	0.278	0.0058
T_{room}	0 (17)	1.00 (0.47)	0.183	0.289	0.0000
Tavg, T_{room}	-0.0 (9.2)	1.00 (0.25)	0.327	0.278	0.0033
Tmax, T_{room}	-0.0 (7.3)	1.00 (0.20)	0.396	0.270	0.1674

Table P2: Linear regressions of observed vs. predicted core temperatures ($T_{c,observed} = a + b.T_{c,predicted}$) for several multi-linear models where T_{room}, T_{max} and $T_{average}$ are used as parameters. Both T_{max} and $T_{average}$ have been extracted from IR images.

Appendix Q: Effect of long periods of inactivity

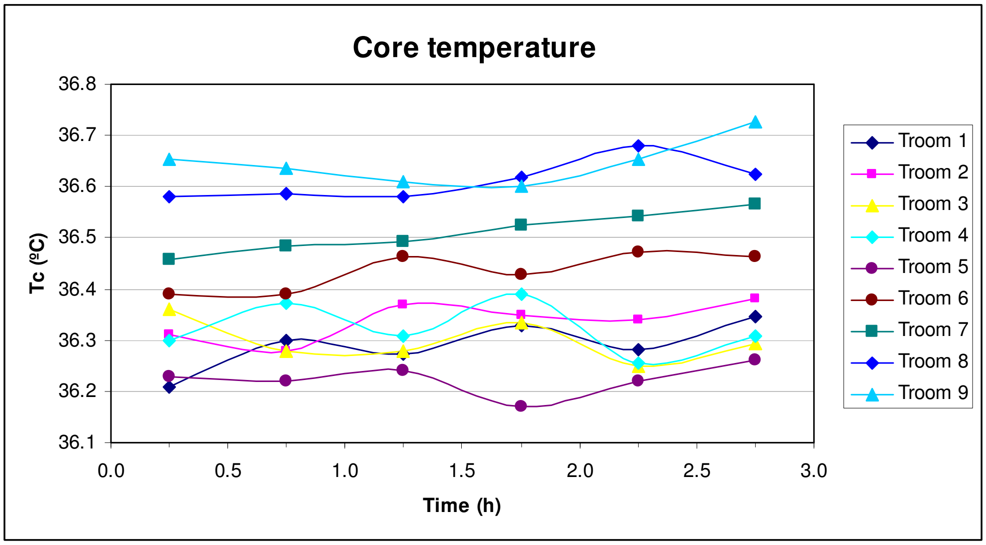
Variation of core temperature and local skin temperatures in prolonged periods of inactivity, investigated in Chapter 7. Graphs presented by location. Definition of each T_{room} categories is given in **table Q1**.

	T_{room} (ºC)	H_{room} (%)	Age (y)	BMI (W/m2)	Tc (ºC)
Mean	24.1	41.1	30.1	24.5	36.42
Std. Dev.	2.9	9.4	11.0	4.4	0.33
Minimum	19.5	21.6	19.0	13.9	35.4
Maximum	29.8	59.2	72.0	42.5	37.1

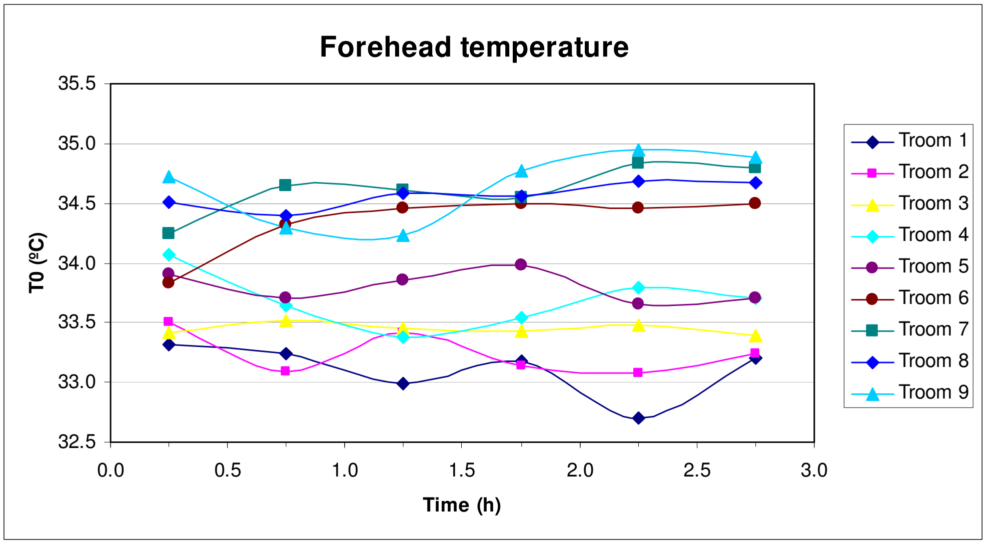
Table Q1: Description of experimental data based on 106 volunteers, 52 males and 54 females.

T_{room} Group	Range	Average	SD	Nº volunteers
1	[19.5, 20.5]	19.88	0.20	11
2	(20.5, 21.2]	20.91	0.17	10
3	(21.2, 21.9]	21.57	0.14	14
4	(21.9, 23.0]	22.41	0.33	11
5	(23.0, 24.1]	23.57	0.29	10
6	(24.1, 26.0]	24.81	0.51	11
7	(26.0, 26.9]	26.50	0.21	12
8	(26.9, 28.0]	27.22	0.30	16
9	(28.0, 29.8]	28.82	0.53	11

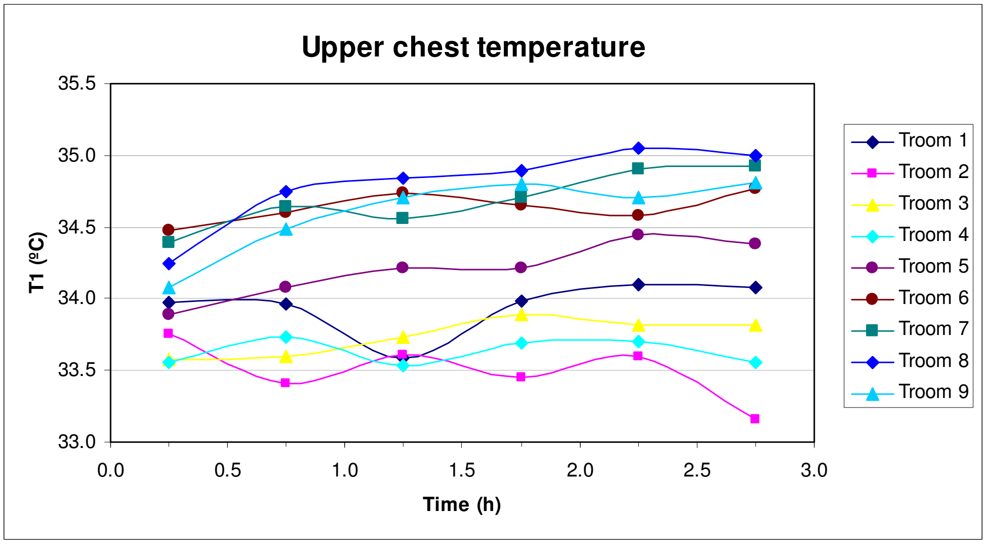
Table Q2: Cohorts based on room temperature



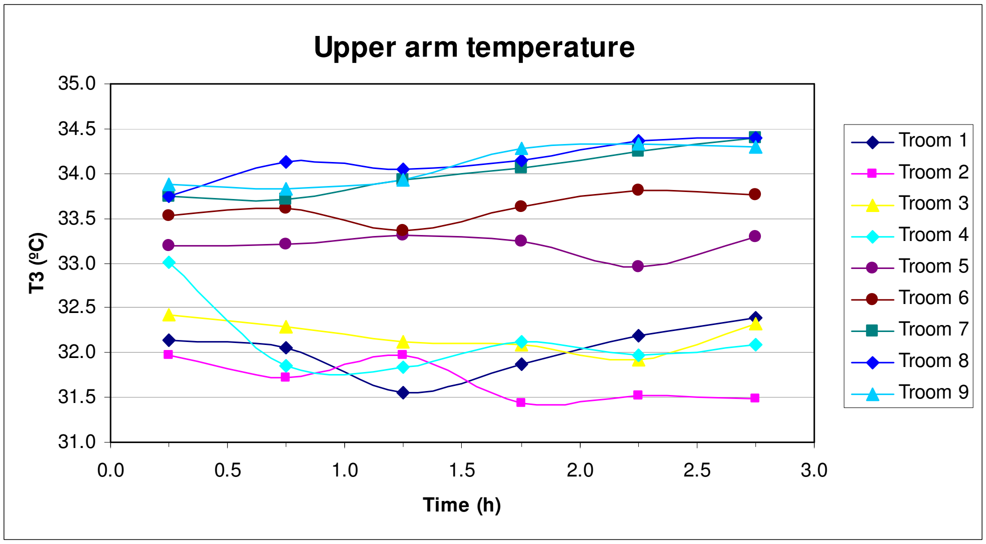
(a)


Forehead temperature
T0 (ºC)
35.5
35.0
34.5
34.0
33.5
33.0
32.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Time (h)
Troom 1
Troom 2
Troom 3
Troom 4
Troom 5
Troom 6
Troom 7
Troom 8
Troom 9

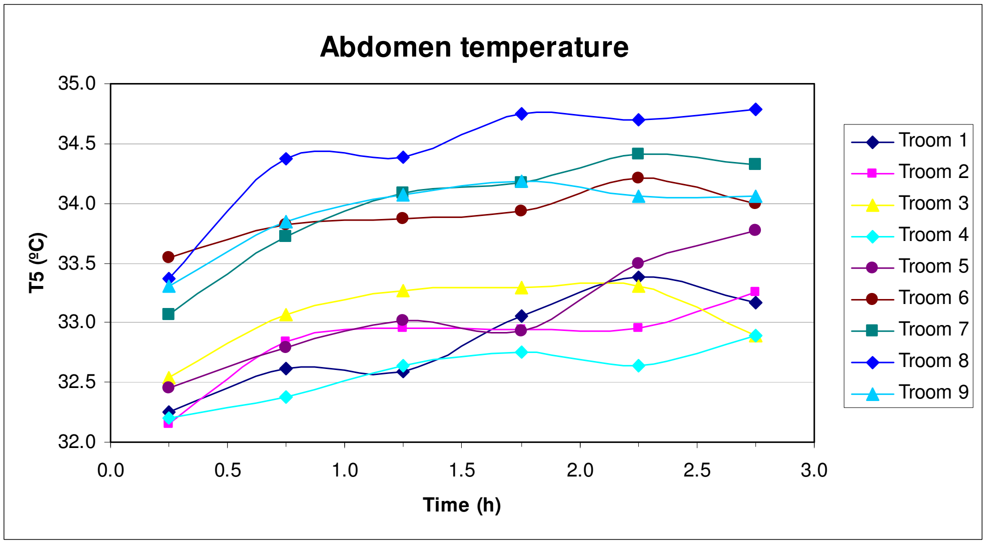
(b)


Upper chest temperature
T1 (ºC)
35.5
35.0
34.5
34.0
33.5
33.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Time (h)
Troom 1
Troom 2
Troom 3
Troom 4
Troom 5
Troom 6
Troom 7
Troom 8
Troom 9

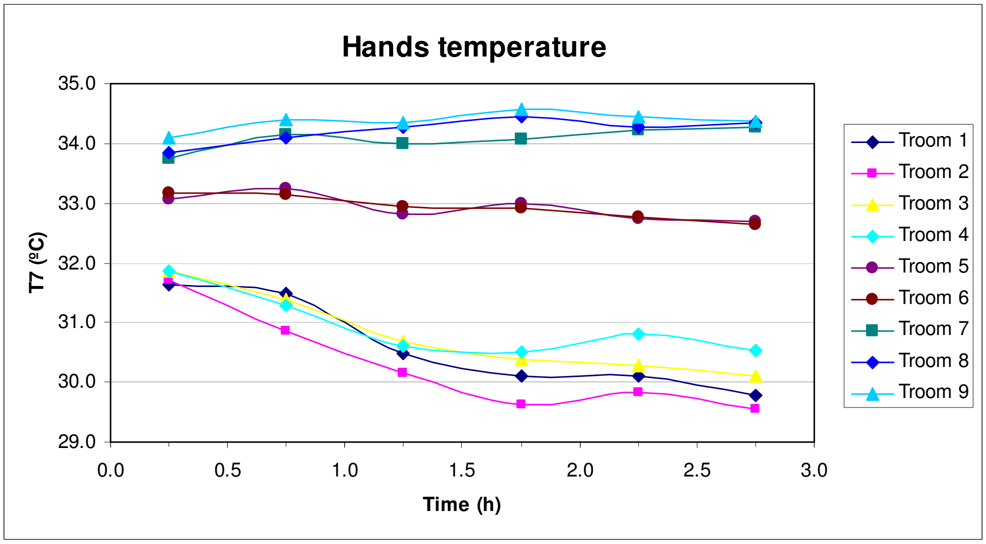
(c)


Upper arm temperature
T3 (ºC)
35.0
34.5
34.0
33.5
33.0
32.5
32.0
31.5
31.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Time (h)
Troom 1
Troom 2
Troom 3
Troom 4
Troom 5
Troom 6
Troom 7
Troom 8
Troom 9

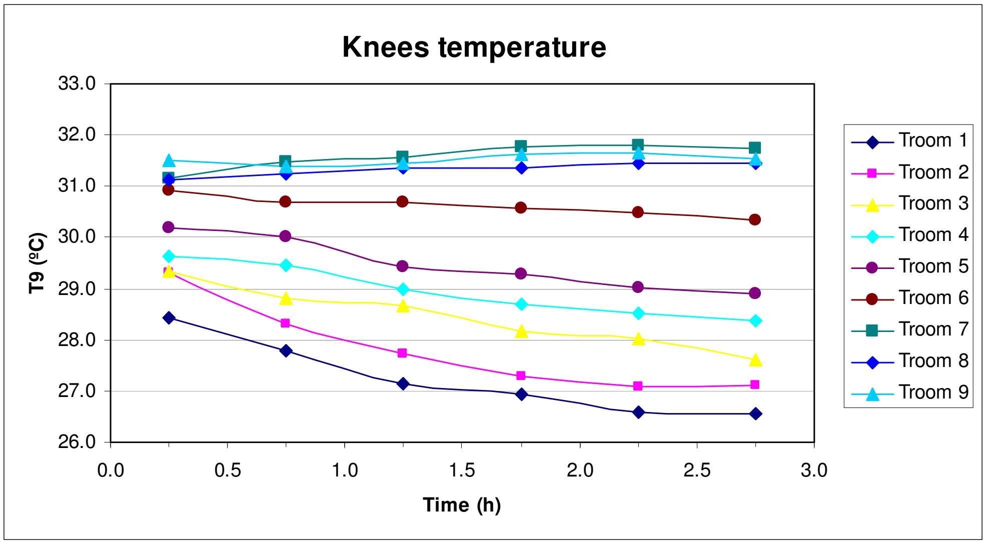
(d)


Abdomen temperature
T5 (ºC)
35.0
34.5
34.0
33.5
33.0
32.5
32.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Time (h)
Troom 1
Troom 2
Troom 3
Troom 4
Troom 5
Troom 6
Troom 7
Troom 8
Troom 9

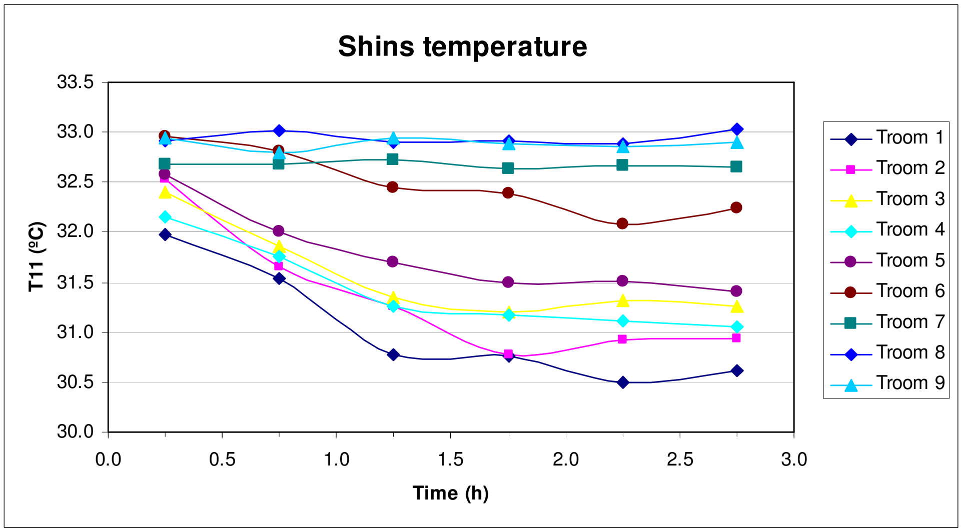
(e)


Hands temperature
T7 (ºC)
35.0
34.0
33.0
32.0
31.0
30.0
29.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Time (h)
Troom 1
Troom 2
Troom 3
Troom 4
Troom 5
Troom 6
Troom 7
Troom 8
Troom 9

(f)

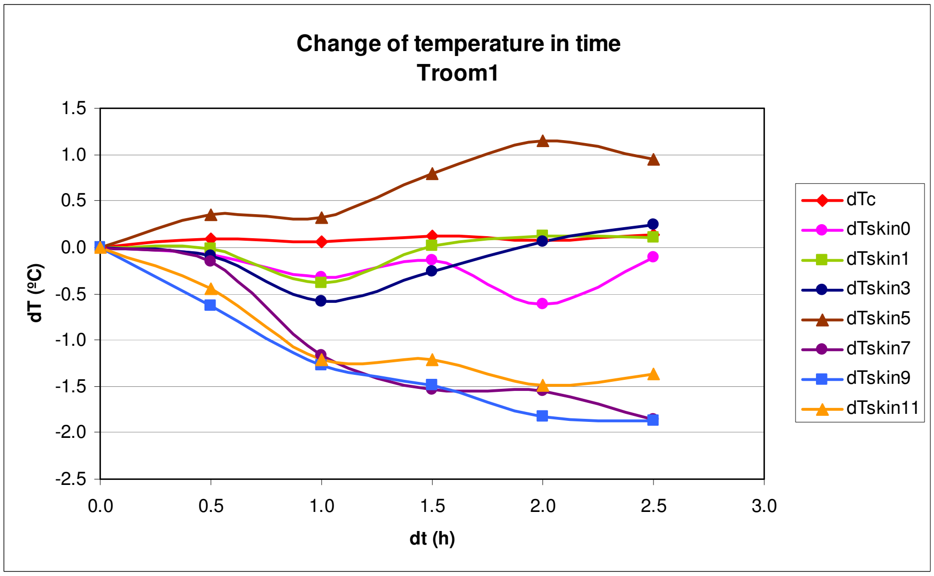

Knees temperature
T9 (ºC)
33.0
32.0
31.0
30.0
29.0
28.0
27.0
26.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Time (h)
Troom 1
Troom 2
Troom 3
Troom 4
Troom 5
Troom 6
Troom 7
Troom 8
Troom 9

(g)

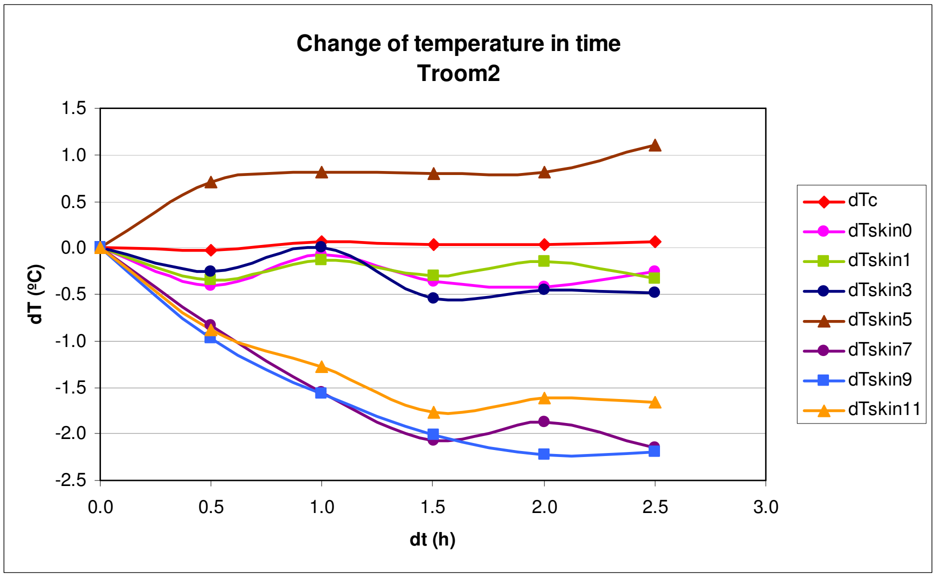


(h)

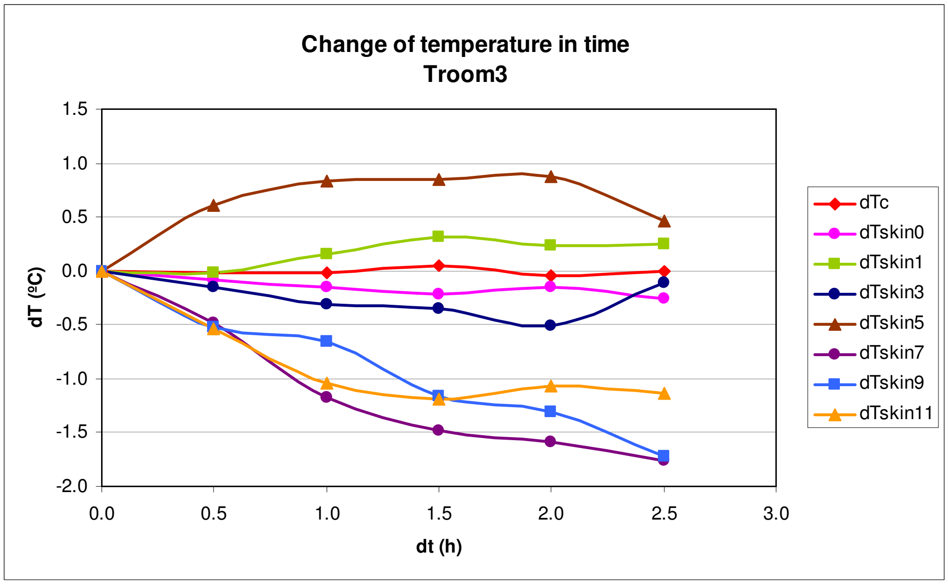
Figure Q1: Core and local skin temperatures versus time in prolonged periods of inactivity for different T_{room} categories, defined according to **Table Q2**.



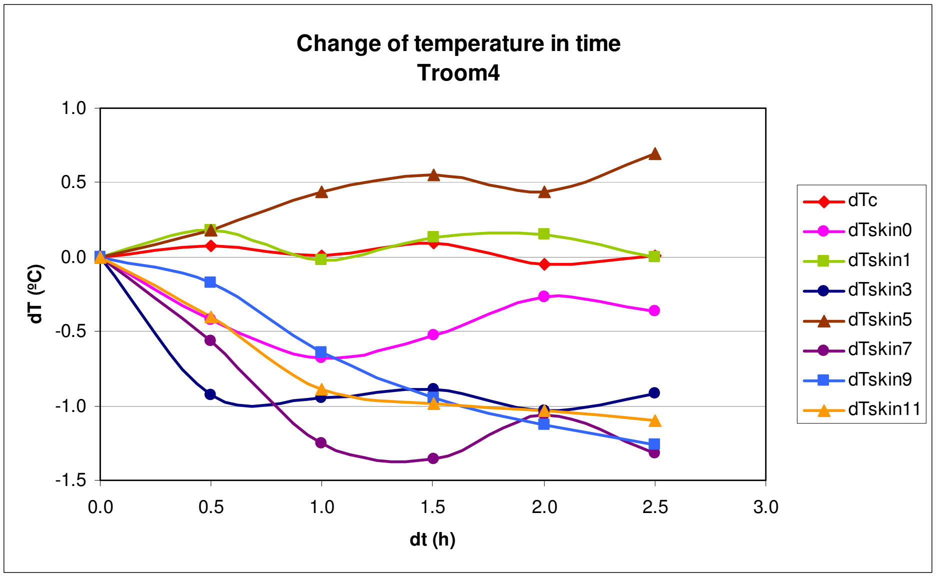
(a)



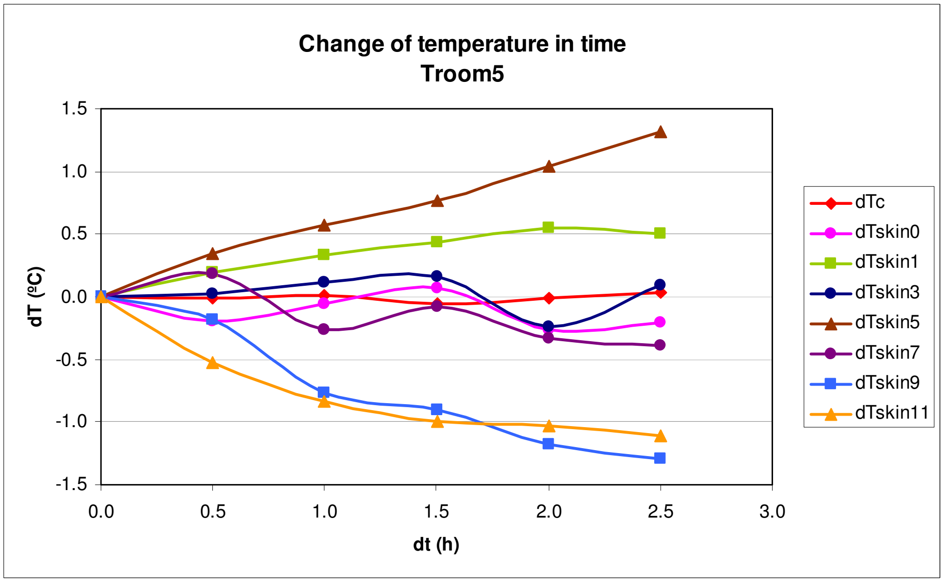
(b)


Change of temperature in time
Troom3
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
dT (ºC)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
dt (h)
dTc
dTskin0
dTskin1
dTskin3
dTskin5
dTskin7
dTskin9
dTskin11

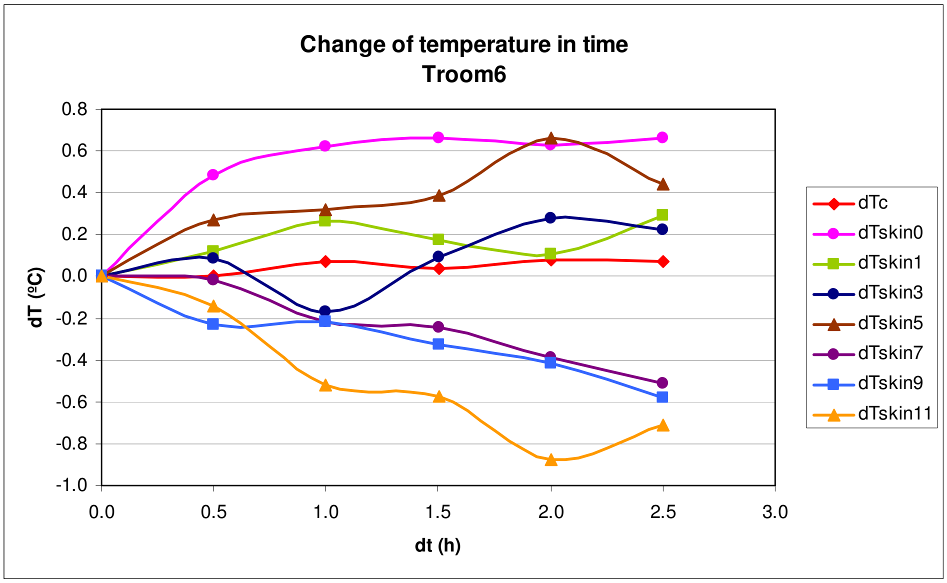
(c)


Change of temperature in time
Troom4
1.0
0.5
0.0
-0.5
-1.0
-1.5
dT (ºC)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
dt (h)
dTc
dTskin0
dTskin1
dTskin3
dTskin5
dTskin7
dTskin9
dTskin11

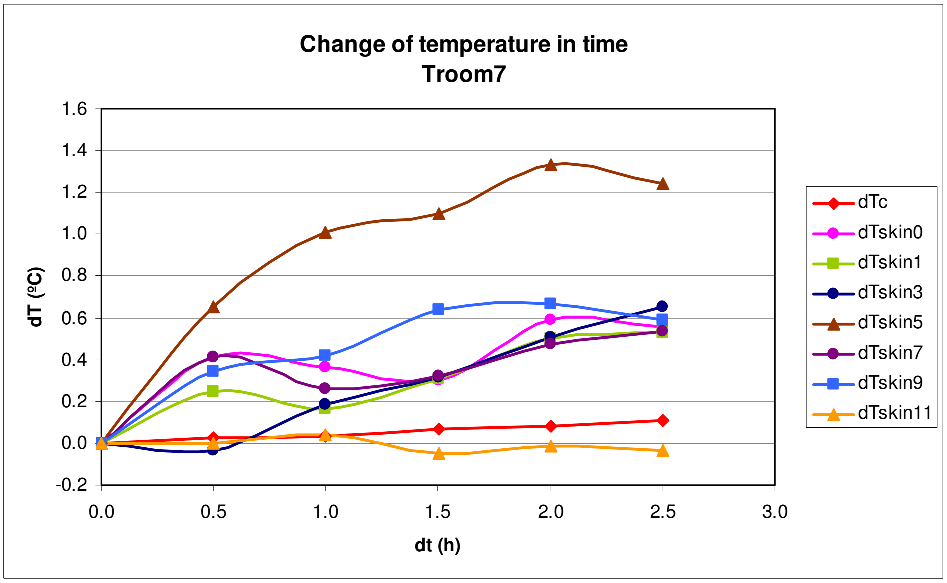
(d)


Change of temperature in time
Troom5
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
dT (ºC)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
dt (h)
dTc
dTskin0
dTskin1
dTskin3
dTskin5
dTskin7
dTskin9
dTskin11

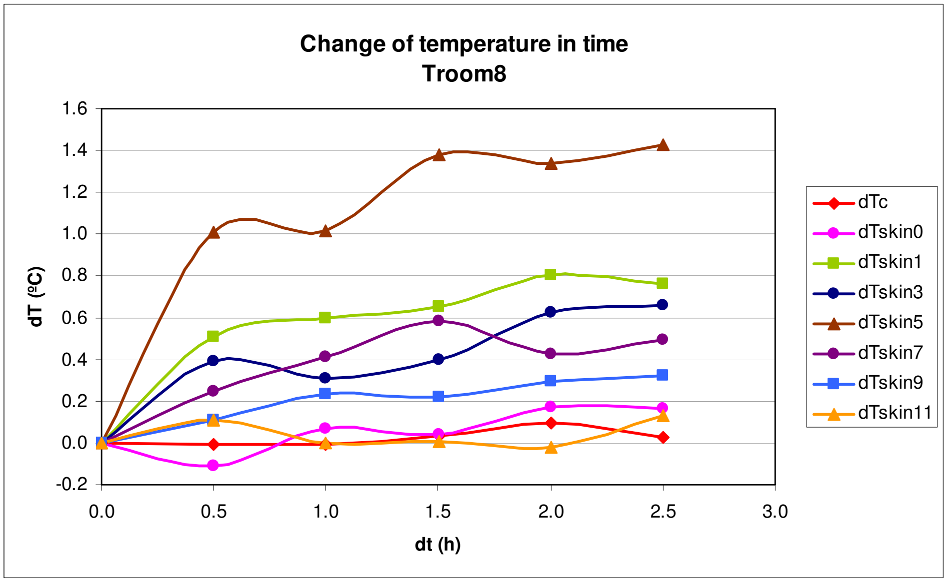
(e)


Change of temperature in time
Troom6
dT (ºC)
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
dt (h)
dTc
dTskin0
dTskin1
dTskin3
dTskin5
dTskin7
dTskin9
dTskin11

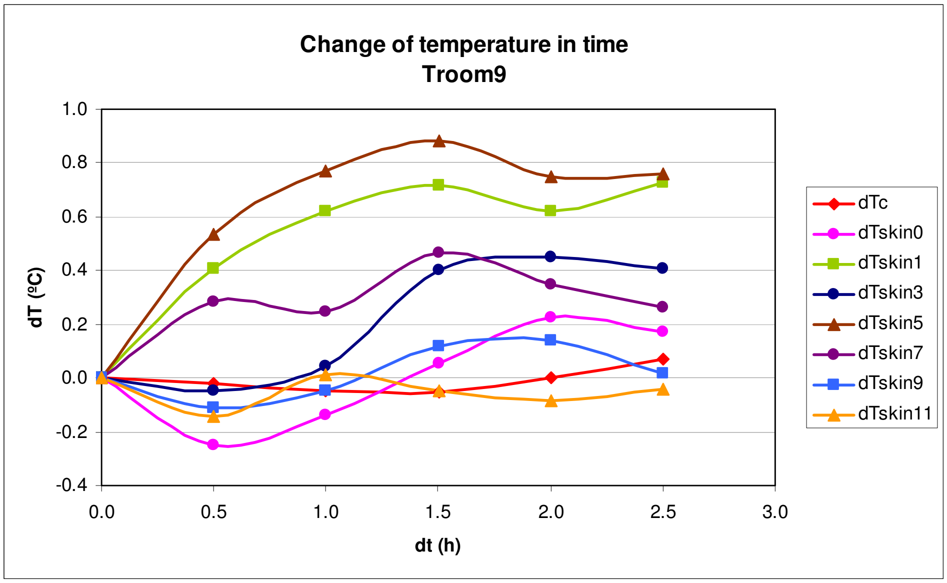
(f)


Change of temperature in time
Troom7
dT (ºC)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
0.0
0.5
1.0
1.5
2.0
2.5
3.0
dt (h)
dTc
dTskin0
dTskin1
dTskin3
dTskin5
dTskin7
dTskin9
dTskin11

(g)

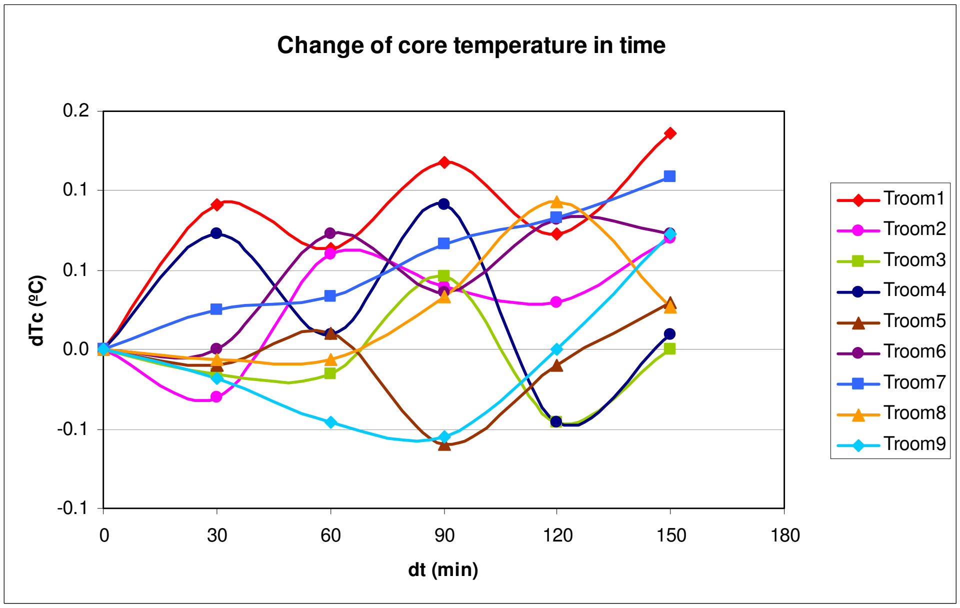

Change of temperature in time
Troom8
dT (ºC)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
0.0
0.5
1.0
1.5
2.0
2.5
3.0
dt (h)
dTc
dTskin0
dTskin1
dTskin3
dTskin5
dTskin7
dTskin9
dTskin11

(h)

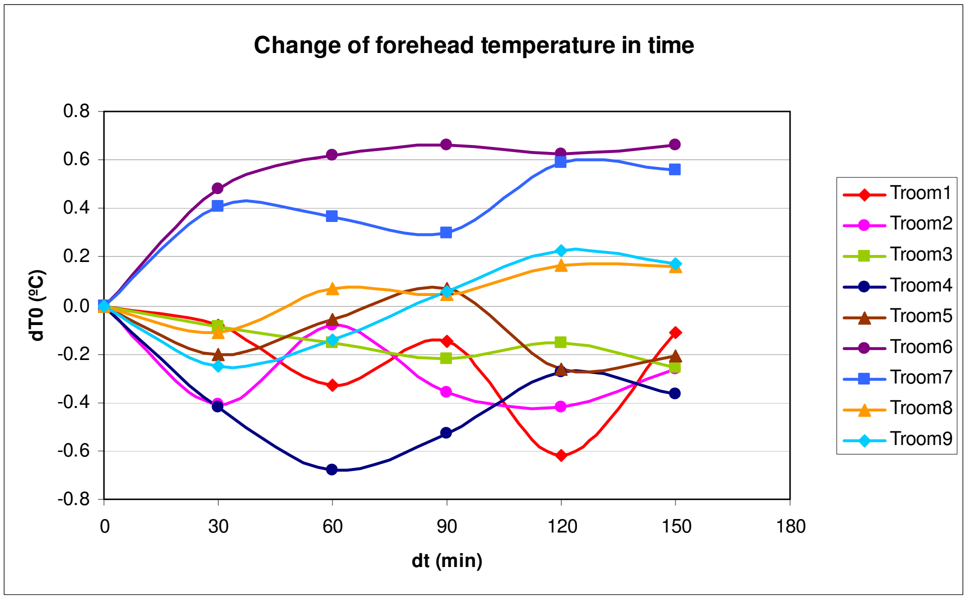


(i)

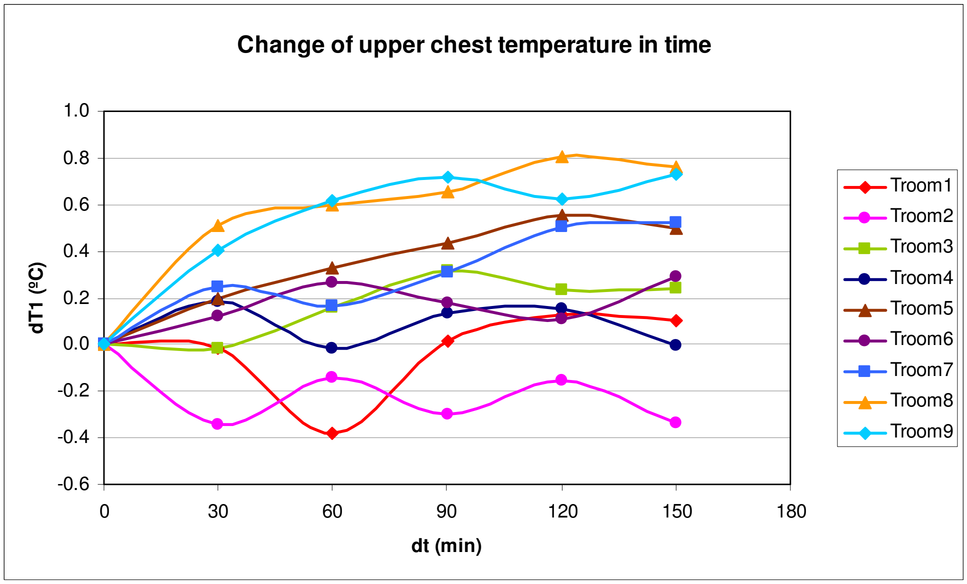
Figure Q2: Variation of core temperature and local skin temperatures in prolonged periods of inactivity. Same graphs but presented by location are given in **appendix Q3**. Indices for skin temperature in the legend stand for forehead (0), upper chest (1), upper arm (3), abdomen (5), hand (7), knee (9) and shin (11).



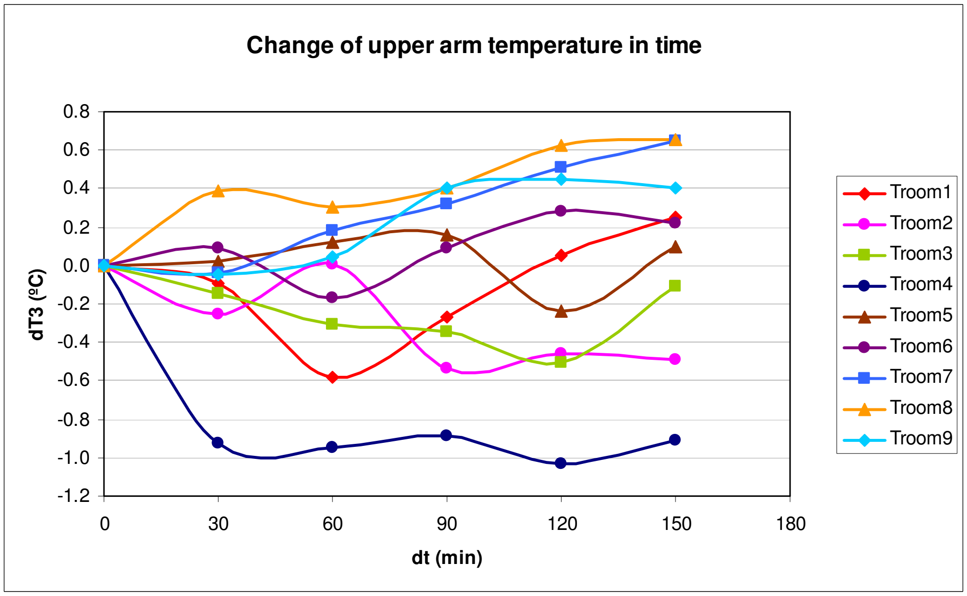
(a)


Change of forehead temperature in time
dT0 (ºC)
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0
30
60
90
120
150
180
dt (min)
Troom1
Troom2
Troom3
Troom4
Troom5
Troom6
Troom7
Troom8
Troom9

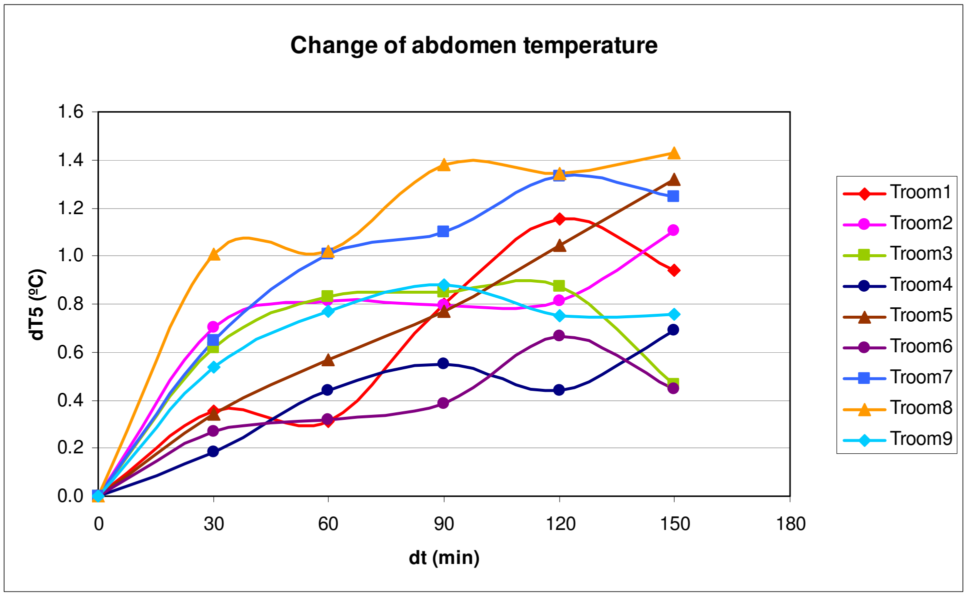
(b)


Change of upper chest temperature in time
dT1 (ºC)
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
0
30
60
90
120
150
180
dt (min)
Troom1
Troom2
Troom3
Troom4
Troom5
Troom6
Troom7
Troom8
Troom9

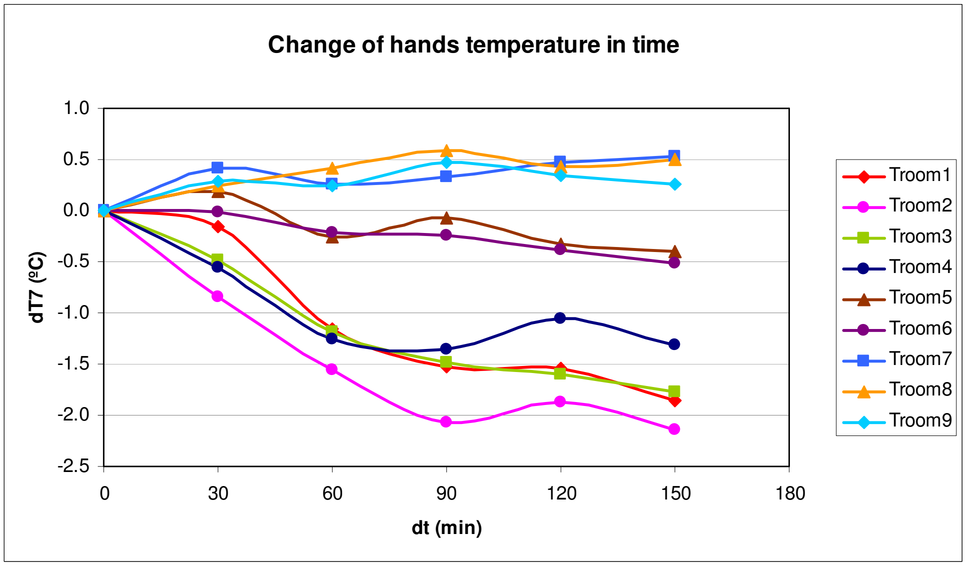
(c)


Change of upper arm temperature in time
dT3 (ºC)
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
0
30
60
90
120
150
180
dt (min)
Troom1
Troom2
Troom3
Troom4
Troom5
Troom6
Troom7
Troom8
Troom9

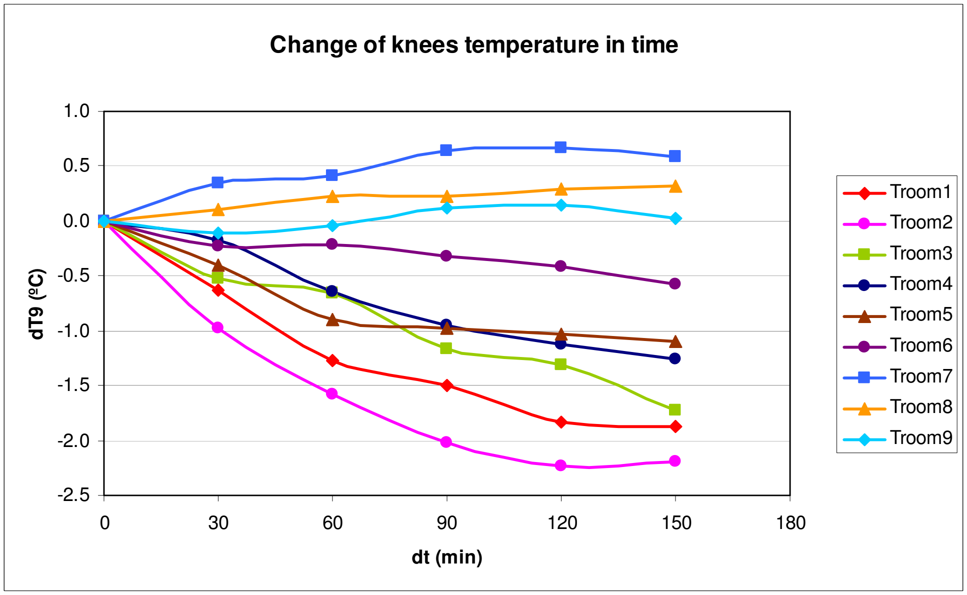
(d)


Change of abdomen temperature
dT5 (ºC)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
30
60
90
120
150
180
dt (min)
Troom1
Troom2
Troom3
Troom4
Troom5
Troom6
Troom7
Troom8
Troom9

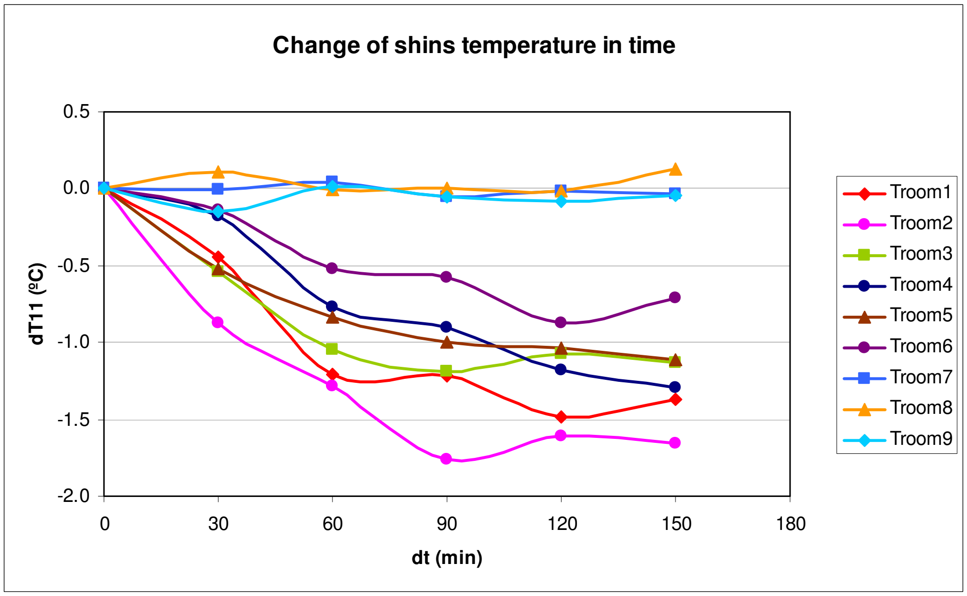
(e)


Change of hands temperature in time
dT7 (ºC)
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
0
30
60
90
120
150
180
dt (min)
Troom1
Troom2
Troom3
Troom4
Troom5
Troom6
Troom7
Troom8
Troom9

(f)


Change of knees temperature in time
dT9 (ºC)
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
0
30
60
90
120
150
180
dt (min)
Troom1
Troom2
Troom3
Troom4
Troom5
Troom6
Troom7
Troom8
Troom9

(g)



(h)

Figure Q3: Variation of core temperature and local skin temperatures in prolonged periods of inactivity. Graphs presented by location. Indices for skin temperature stand for forehead (0), upper chest (1), upper arm (3), abdomen (5), hand (7), knee (9) and shin (11).

	m_{TS}	m_{CL}	m_c	m_0	m_1	m_3	m_5	m_7	m_9	m_{11}
T_{room}	**0.393****	-0.186	-0.027	**0.292****	**0.311****	**0.324****	0.101	**0.605****	**0.687****	**0.522****
H_{room}	-0.167	**-0.263****	-0.073	0.063	0.031	0.017	0.047	-0.031	**-0.212****	-0.026
Tc	0.201*	0.056	0.016	-0.053	0.022	0.053	0.033	**0.226****	**0.344****	0.143*
age	-0.189	-0.031	-0.033	-0.159*	-0.015	-0.132	-0.147*	-0.092	-0.166*	-0.122
BMI	0.071	-0.115	0.044	0.012	**0.267****	**0.199****	**0.359****	0.147*	0.042	**0.201****
gender	-0.091	**0.303****	0.047	**-0.256****	-0.166*	-0.078	**-0.195****	-0.145*	-0.141*	**-0.329****
Loc3C	-0.040	-0.002	0.069	-0.042	0.088	0.052	0.128	-0.105	-0.088	0.095
Loc9C	0.042	0.088	0.070	0.028	***-0.204*****	-0.093	-0.131	-0.008	-0.075	-0.099
Loc11C	0.059	0.091	0.088	0.013	-0.178*	-0.091	-0.163*	0.029	-0.048	-0.118

Table Q3: Pearson correlation values. *m* represents $\Delta Tskin/\Delta t$

* Correlation is significant at the 0.05 level (2-tailed)

** Correlation is significant at the 0.01 level (2-tailed)

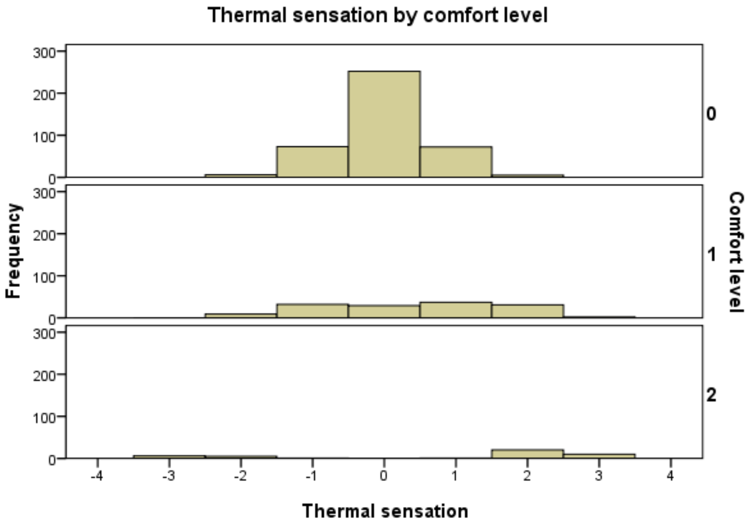
Appendix R: Thermal comfort model

Model parameters	TS	CL	CL*
TS	1.000	0.260**	**0.767****
CL	0.260**	1.000	0.352**
CL*	**0.767****	0.352**	1.000
Troom	**0.570****	0.235**	**0.477****
Hroom	-0.040	-0.098*	-0.033
Time	-0.104*	0.091*	-0.058
Tc	0.238**	0.178**	0.193**
T0	0.357**	0.042	0.230**
T1	0.175**	-0.002	0.114**
T3	**0.455****	0.052	0.322**
T5	0.260**	0.028	0.144**
T7	**0.529****	0.130**	**0.453****
T9	**0.523****	0.114**	**0.425****
T11	0.409**	0.002	0.297**
Gender	-0.132**	-0.028	-0.220**
BMI	0.138**	0.127**	0.183**
Age	-0.162**	-0.087*	-0.129**
Loc3C	-0.016	-0.025	-0.025
Loc9C	-0.078	-0.117**	-0.051
Loc11C	-0.080	-0.097*	-0.043

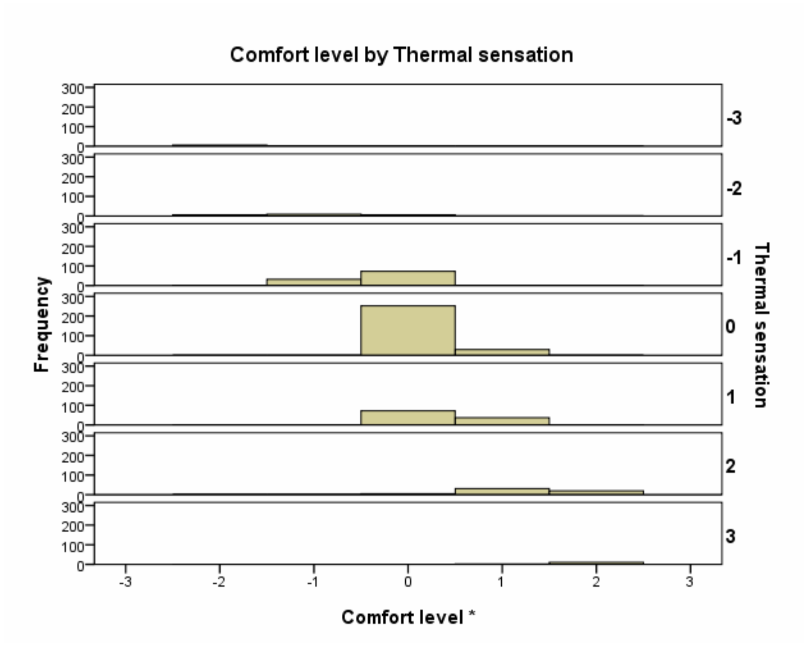
Table R1: Pearson correlation values. m represents ΔTskin/Δdt

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).



(a)



(b)

Figure R1: Relation between thermal sensation and comfort level

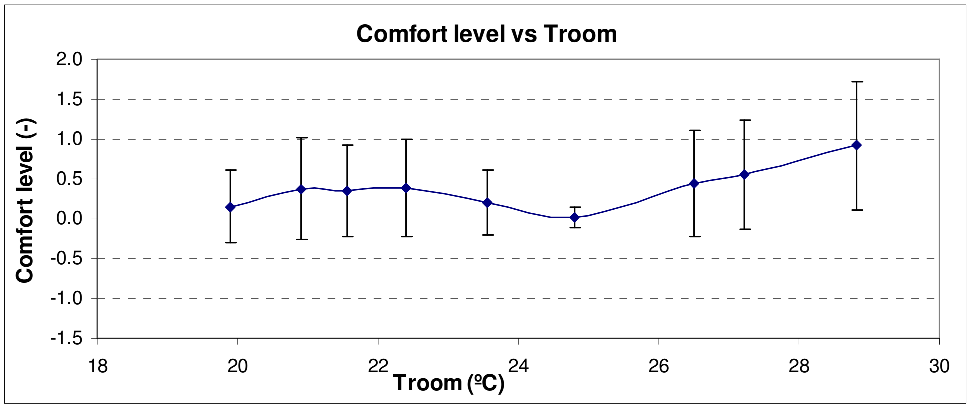


Figure R2: Thermal sensation and comfort level versus room temperature

Model coeff.	TS	CL*
a	-11.2 (3.0)	-8.1 (2.0)
b	0.072 (0.018)	0.078 (0.014)
c	0.137 (0.083)	0.200 (0.057)
d0	-0.009 (0.033)	-0.070 (0.027)
d1	-0.058 (0.025)	-0.026 (0.021)
d3	0.084 (0.029)	0.026 (0.023)
d5	0.045 (0.024)	-0.011 (0.021)
d7	0.102 (0.021)	0.082 (0.015)
d9	-0.010 (0.027)	0.002 (0.020)
d11	-0.012 (0.033)	-0.020 (0.023)
e	-0.0058 (0.0023)	-0.0056 (0.0019)
f	0.0122 (0.0057)	0.0103 (0.0047)
g	0.054 (0.053)	-0.140 (0.040)
k	0.78 (0.12)	0.019 (0.022)
R-value	0.649	0.545
Estimated error	0.829	0.622

Table R2: Coefficient values for the TS and CL* models with all significant parameters

Coeff. Model	a	b	c	d0	d7	g	k	R^2-value	Estimated error
TS-M1	-9.7 (2.7)	0.087 (0.014)	0.112 (0.076)	0.023 (0.028)	0.095 (0.018)	-	0.74 (0.11)	0.383	0.846
TS-M2	**-5.99** **(0.91)**	**0.090** **(0.014)**	**-**	**0.034** **(0.027)**	**0.092** **(0.017)**	**-**	**0.75** **(0.11)**	**0.382**	**0.844**
TS-M3	-5.04 (0.53)	0.095 (0.013)	-	-	0.095 (0.018)	-	0.75 (0.11)	0.381	0.845
TS-M4	-4.34 (0.80)	0.120 (0.013)	-	0.053 (0.026)	-	-	0.90 (0.11)	0.366	0.855
TS-M5	-6.79 (0.78)	0.194 (0.011)	-	0.067 (0.026)	-	-	-	0.328	0.880
TS-M6	-7.37 (0.43)	0.143 (0.012)			0.126 (0.017)			0.356	0.861
CL*-M1	-7.4 (1.8)	0.0848 (0.0099)	0.154 (0.054)	-0.065 (0.024)	0.073 (0.013)	-0.154 (0.038)	0.029 (0.020)	0.272	0.627
CL*-M2	**-2.40** **(0.68)**	**0.0896** **(0.0096)**	**-**	**-0.048** **(0.022)**	**0.070** **(0.013)**	**-0.140** **(0.036)**	**0.027** **(0.020)**	**0.266**	**0.624**
CL*-M3	-3.71 (0.34)	0.0822 (0.0094)	-	-	0.066 (0.013)	-0.139 (0.037)	0.028 (0.021)	0.263	0.626
CL*-M4	-1.33 (0.68)	0.1223 (0.0087)	-	-0.033 (0.022)	-	-0.193 (0.038)	0.042 (0.020)	0.247	0.632
CL*-M5	-1.85 (0.68)	0.1236 (0.0084)	-	-0.029 (0.022)	-	-	-	0.229	0.640
CL*-M6	-4.26 (0.34)	0.0775 (0.0088)			0.076 (0.013)			0.254	0.629

Table R3: Coefficient values for the simplified models of TS and CL* with practical parameters

Case	Reliability BTC module	Reliability PT module	R^2 of combination
1	1	2-4	0.3393
2	2	2-4	0.3531
3	2	1-3	0.3644

Table R4: Accuracy of thermal sensation model based on the combination of *BTC module* and *PT module* with different reliability values per module

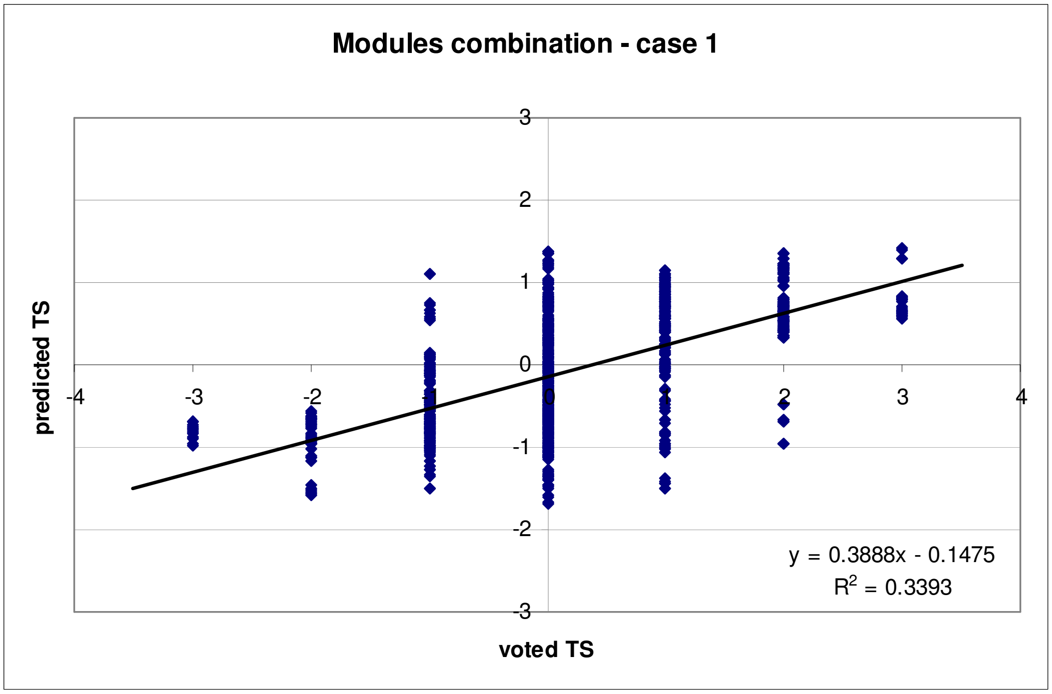


Figure R3: Accuracy of *TS* prediction when combining *basic thermal comfort model* and *personal temperature model* (combination 1)

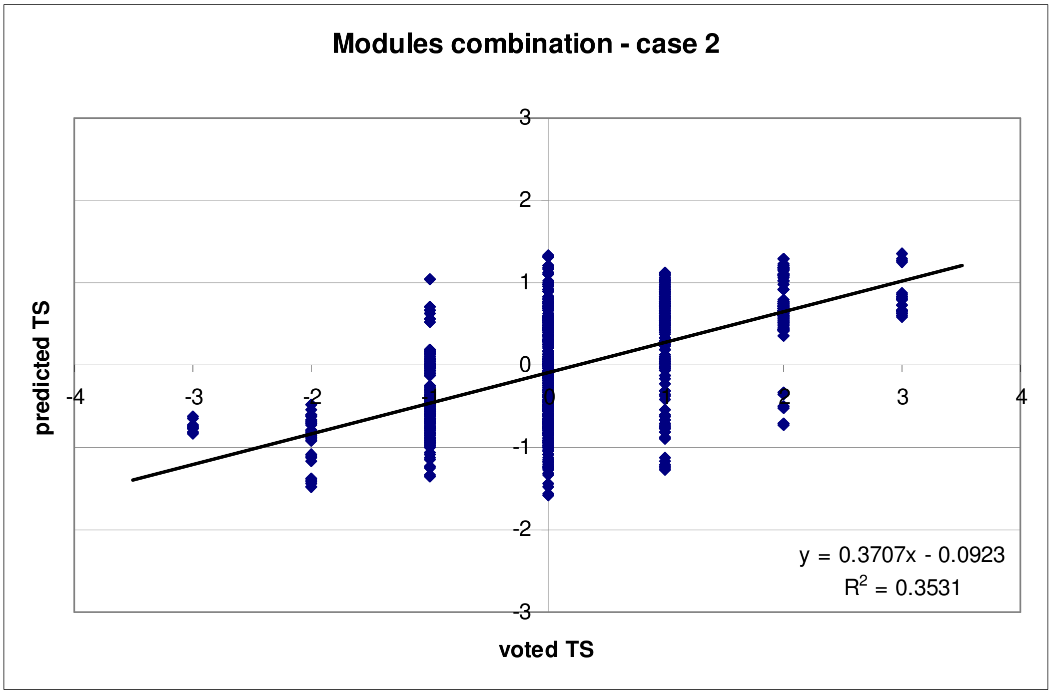


Figure R4: Accuracy of *TS* prediction when combining *basic thermal comfort model* and *personal temperature model* (combination 2)