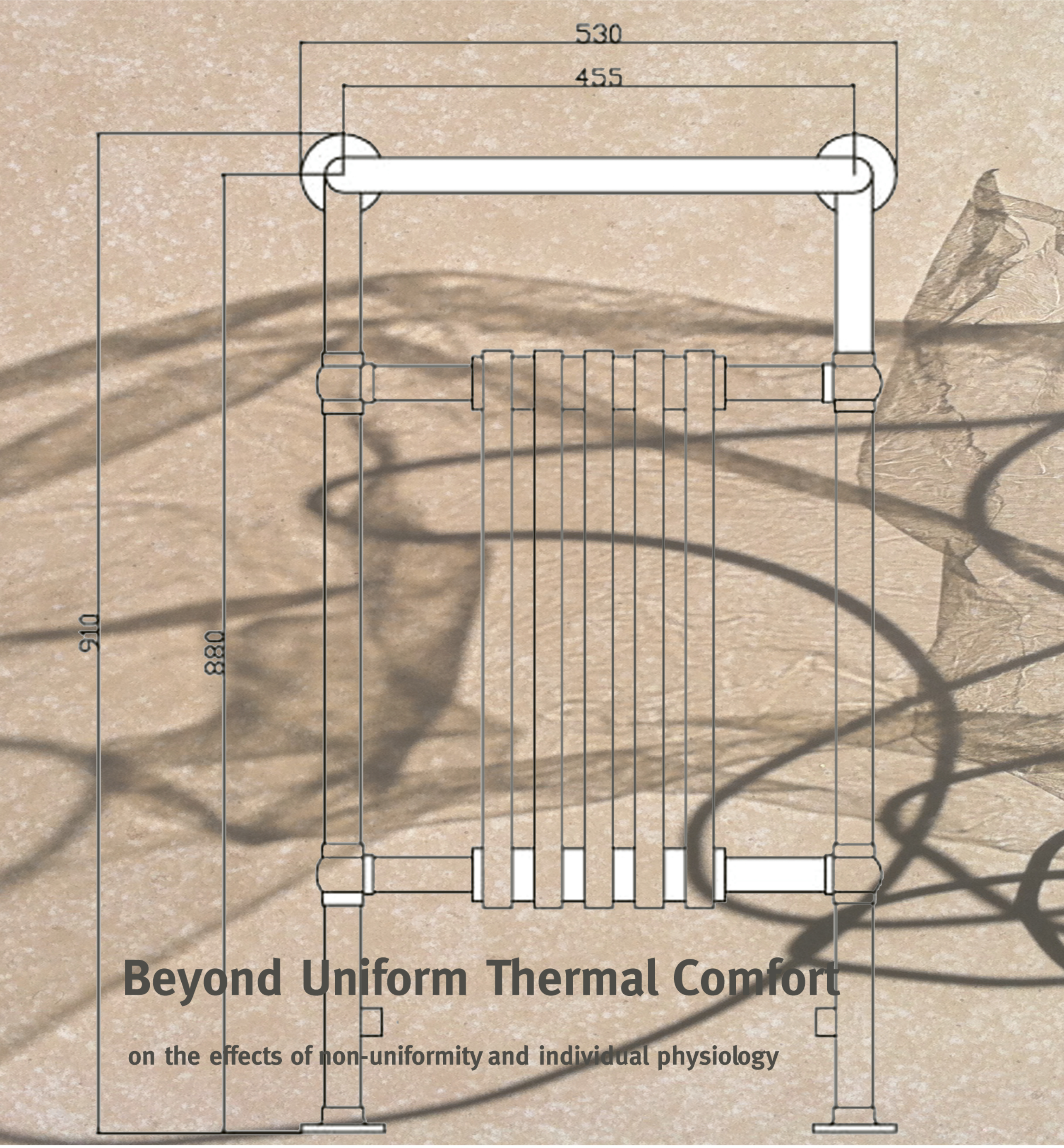
Beyond uniform thermal comfort : on the effects of non-uniformity and individual physiology



Beyond Uniform Thermal Comfort

on the effects of non-uniformity and individual physiology

Lisje Schellen

/ Department of the Built Environment

bouwstenen 165

Beyond Uniform Thermal Comfort

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PROEFSCHRIFT

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door

Lisje Schellen

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prof.dr.ir. M.H. de Wit

Copromotoren:
dr.ir. M.G.L.C. Loomans
en
dr. W.D. van Marken Lichtenbelt

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Oorsprong, compleet,
exclusief en puur
volledig geregeld door de natuur
Nu, open, werelds,
niet meer uniek
afhankelijk geworden van techniek
(Bas Schellen)

Origin, complete,
exclusive and pure
fully controlled by nature
Now, open, worldly,
not unique anymore
became dependent on technology
(Bas Schellen)

Samenstelling promotiecommissie:

prof.ir. E.S.M. Nelissen, Eindhoven University of Technology (voorzitter)
prof.dr.ir. M.H. de Wit, Eindhoven University of Technology (promotor)
dr.ir. M.G.L.C. Loomans, Eindhoven University of Technology (co-promotor)
dr. W.D. van Marken Lichtenbelt, Maastricht University (co-promotor)
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dr.ir. A.J.H. Frijns, Eindhoven University of Technology
prof.dr. B.W. Olesen, Technical University of Denmark
prof.dr.–ing. D. Müller, RWTH Aachen University

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VOORWOORD

Dinsdag 18 september 2012 is om verschillende redenen een memorabele dag: op die dag is het namelijk 68 jaar geleden dat Eindhoven bevrijd is; daarnaast is het Prinsjesdag 2012; maar voor mij persoonlijk is het om hele andere redenen een bijzondere dag. Op deze dag sluit ik een periode van 10 jaar TU/e af. En een proefschrift is geen proefschrift zonder een uitgebreid woord van dank, en terecht. Gedurende mijn promotie heb ik me erop verheugd om dit als laatste afronding te mogen schrijven. Eindelijk kan ik recht doen aan alle mensen die mij gesteund en geholpen hebben op welke manier dan ook. Ik weet inmiddels hoe belangrijk comfort is. In dit proefschrift behandel ik voornamelijk thermisch comfort. Echter, algemeen comfort komt tot stand door vele aspecten, en voor mij is mijn omgeving, gevormd door de mensen om mij heen, een belangrijk aspect.

Allereerst wil ik graag mijn kerncommissie bedanken. Beste Martin, ik vond het een grote eer toen u tijdens mijn afstuderen vroeg of ik er iets in zag om het onderwerp waar ik op afstudeerde te continueren in een promotie. Ik vind het erg fijn dat u hierbij mijn eerste promotor wilde zijn. De vrijheid die u aan mij, Marcel en Wouter gaf om het project verdere invulling te geven, wekte vertrouwen. Met veel plezier denk ik terug aan de gesprekken en discussies die we hebben gehad, waarbij vaak afgedwaald werd naar uw eigen ervaringen met verbouwen, koude voeten etc.
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Samenvatting

SAMENVATTING

De gebouwde omgeving is verantwoordelijk voor een derde van het totale primaire energiegebruik in Westerse landen. Deze energie wordt voornamelijk gebruikt voor het verwarmen, koelen, ventileren en verlichten van onze gebouwen. Voor een duurzame ontwikkeling van de gebouwde omgeving zal niet alleen het energiegebruik verminderd moeten worden, maar ook de inzet van hoogwaardige fossiele energiebronnen. Dit laatste kan door de toepassing van laag-exergetische systemen. Een kenmerk van die systemen is dat het verschil tussen de temperatuur waarmee verwarmd of gekoeld wordt en de gewenste ruimtetemperatuur veel kleiner is dan tot nu toe gebruikelijk. Bij de toepassing van deze systemen in ruimten met een zeer lage energievraag kunnen niet-uniforme en dynamische omgevingscondities ontstaan. Deze condities kunnen leiden tot lokaal en algemeen discomfort. Voor het succesvol toepassen van laag energetische en exergetische gebouwsystemen is de tevredenheid met betrekking tot het thermisch comfort van de gebruikers een belangrijke randvoorwaarde. Meer kennis over de interactie tussen het gebouwsysteem, binnenklimaat en menselijke fysiologie is benodigd voor het ontwerpen van toekomstige energiezuinige en comfortabele binnenklimaatcondities.

Thermisch comfort is een complex fenomeen, het wordt behalve door de omgeving ook door persoonsgebonden factoren bepaald. Het is lastig om alle personen in eenzelfde ruimte tevreden te stellen wanneer er geen individuele regelmogelijkheden aanwezig zijn. Dit wordt veroorzaakt door de grote verschillen tussen individuele personen, zowel op psychisch als op fysiologisch vlak. In de huidige bouwpraktijk wordt tijdens de ontwerpfase vaak het PMV (predicted mean vote) model gebruikt voor het voorspellen van het thermisch comfort van de toekomstige gebruiker. Dit model voorspelt het gemiddelde thermisch comfort aan de hand van de gegeven klimaatrandvoorwaarden en gebruikerkarakteristieken (activiteitenniveau en kledingsisolatie). Het PMV model is opgenomen in verschillende nationale en internationale normen ten aanzien van het thermisch comfort van gebruikers. Echter, aan de hand van literatuur blijkt dat het daadwerkelijke thermisch comfort van individuele gebouwgebruikers significant kan afwijken van het gemiddelde thermisch comfort dat vooraf voorspeld werd. Als gevolg hiervan voelen de gebruikers zich oncomfortabeler en ontevredener dan vooraf voorspeld werd, hetgeen ook de productiviteit kan beïnvloeden. De verschillen tussen het vooraf voorspelde comfort en het gerealiseerde comfort worden ondermeer veroorzaakt door geslacht- en leeftijdseffecten.

In deze studie wordt het thermisch comfort onderzocht onder niet-uniforme condities. Deze niet-uniformiteit wordt vanuit twee verschillende standpunten onderzocht: aan de hand van (-) de omgeving (niet-uniforme en dynamische thermische omgevingscondities) en (-) de mens (verschillende subpopulaties; mannen vs. vrouwen en jong volwassenen vs. ouderen).

Het eerste gedeelte van het proefschrift (Hoofdstuk 2 en 3) gaat over de toepassing van een dynamisch temperatuurverloop en de verschillen in thermisch comfort tussen jong volwassenen en ouderen. De resultaten laten zien dat een temperatuurverloop tot ±2 K/u in een temperatuurbereik van 17–25°C als acceptabel beoordeeld wordt en niet leidt tot onacceptabele condities ten aanzien van het thermisch comfort. Op subpopulatie niveau blijkt dat de ouderen in het algemeen een thermische sensatie beleven die 0,5 punten (op de 7-punts thermische sensatieschaal van ASHRAE) lager ligt (lichtelijk koel versus neutraal bij de jongeren) dan de thermische sensatie van jongeren onder dezelfde thermische omstandigheden. Ten gevolge hiervan geven ouderen de voorkeur aan een hogere omgevingstemperatuur in vergelijking met jong volwassenen.
Ondanks dat de thermische condities niet tot onacceptabele situaties leiden, resulteren ze wel in significante fysiologische responsies. Uit literatuur blijkt dat milde koude blootstellingen (20°C bij 0,04 clo) kunnen leiden tot een verhoogde systolische bloeddruk bij ouderen. Daarom is het verstandig om ouderen te beschermen tegen thermische schommelingen, ook al zijn deze gering van aard. In tegenstelling tot ouderen, kunnen jong volwassenen baat hebben bij dynamisch thermische condities.
In Hoofdstuk 3 wordt een nieuwe aanpak gepresenteerd voor het voorspellen van de thermische sensatie onder dynamische omstandigheden, gebaseerd op de neurofysiologie van de thermische perceptie. Het model werd ontwikkeld aan de hand van twee onafhankelijke datasets. Met behulp van het ontwikkelde model was het mogelijk om 89% van de variatie in thermische sensatie te verklaren.

In het tweede gedeelte van het proefschrift (Hoofdstuk 4 tot en met 6) worden de effecten van niet-uniforme omgevingscondities en de verschillen in thermische comfortbeleving tussen mannen en vrouwen bestudeerd. Onder niet-uniforme omgevingscondities hebben lokale effecten, zoals de lokale huidtemperaturen, een significante invloed op de algehele thermische sensatie en het algehele thermisch comfort. Voornamelijk de huidtemperaturen en de gekoppelde thermische sensaties van de extremiteiten (handen en armen) zijn van belang voor de algehele thermische comfortbeleving. Dit geldt met name voor vrouwen (Hoofdstuk 4). De operatieve temperatuur alleen is daarom niet voldoende voor het voorspellen van de thermische sensatie. Voor het grootste gedeelte van de experimentele cases week de daadwerkelijke thermische sensatie significant af van de vooraf voorspelde PMV (Hoofdstuk 4 en 5). Deze afwijkingen werden met name veroorzaakt door de lokale effecten en de aanwezigheid van gecombineerde lokale discomfort factoren, ook al waren deze individueel binnen de gestelde limieten (voorspelde aantal ontevreden < 10%).
De resultaten laten zien dat de vrouwen zich in het algemeen oncomfortabeler en ontevredener voelen in vergelijking tot de mannen onder dezelfde thermische omstandigheden. Wanneer er gekoeld dient te worden, dan dient de omgevingstemperatuur voor vrouwen hoger te zijn om de tevredenheid met de thermische

omgeving te verhogen. Daarnaast dient, om algeheel thermisch comfort te bewerkstelligen, de nadruk te liggen op lokale effecten.
In Hoofdstuk 6 wordt het thermisch comfort bestudeerd voor een niet-uniforme verwarmingssituatie. De focus ligt hierbij op de validiteit van een vuistregel, om koudeval veroorzaakt door een groot glasvlak, te beoordelen. Het risico op koudeval wordt met deze vuistregel beoordeeld aan de hand van de U-waarde van het glas en de hoogte van het glasvlak. Zowel de experimentele als numerieke resultaten laten zien dat de huidige vuistregel conservatief lijkt te zijn met betrekking tot het voorspellen van (hinderlijke) koudeval. Bovendien laten de numerieke resultaten zien dat een verhoogde vloertemperatuur, wat dikwijls wordt gezien als maatregel om koudeval te voorkomen, kan resulteren in een verhoogd risico op koudeval. Daarom wordt aanbevolen om de vuistregel aan te passen door de vloertemperatuur hierin op te nemen.

Aan de hand van de resultaten kan geconcludeerd worden dat, zelfs onder milde condities, er significante verschillen bestaan in de thermische comfortbeleving tussen subpopulaties. Daarnaast blijken de bestaande normen niet geschikt te zijn voor het voorspellen van thermisch comfort onder niet-uniforme omgevingscondities. Lokale effecten spelen een belangrijke rol in de algehele thermische comfortbeleving. Voor het verbeteren van de thermische comfortvoorspelling kan het zinvol zijn om de fysiologie, die ten grondslag ligt aan de thermische perceptie, mee te nemen. Door gebruik te maken van een thermofysiologisch model is het mogelijk om (lokale) thermoregulatorische responsies te modelleren. De koppeling tussen de fysiologische responsies en het thermisch comfort is een belangrijk aandachtspunt voor onderzoek.
In het laatste gedeelte van het proefschrift (Hoofdstuk 7) wordt de toegevoegde waarde van het gebruik van een thermofysiologisch model (ThermoSEM) voor het voorspellen van het thermisch comfort in de gebouwde omgeving bediscussieerd. Tevens wordt het gebruik van Computational Fluid Dynamics (CFD) voor het voorspellen van de randvoorwaarden, benodigd voor het thermofysiologisch model, bediscussieerd. Aan de hand van de resultaten blijkt dat het detailniveau van het numerieke model beperkt mag zijn ten aanzien van het voorspellen van de randvoorwaarden (CFD) voor het thermofysiologisch model. Daarnaast laten de resultaten zien dat het gebruik van ThermoSEM in combinatie met de ISO 14505 norm veelbelovend lijkt te zijn voor het voorspellen van het lokale en algehele thermische comfort onder constante niet-uniforme omgevingscondities tijdens de ontwerpfase.

Summary

Approximately one-third of the primary energy used in developed countries is consumed in the built environment. As heating, ventilating, air conditioning and lighting in residential, commercial and public buildings take a large part in that use, a need to reduce the energy demand of buildings exists. For a sustainable development of the built environment, it is not only important to reduce the energy consumption, but it is also important to reduce the use of high quality energy sources. The latter can be realized by the application of low exergy HVAC systems. One of the characteristics of these systems is that the temperature difference between the supply temperature needed for heating or cooling and the room temperature is smaller than we are used to. However, non-uniform and transient thermal conditions, which may occur due to application of low energy and exergy HVAC systems, can be responsible for whole-body and local thermal discomfort.
Yet, satisfaction of the occupants with their thermal environment is one of the most important parameters to successfully apply these systems. To adequately design optimal environmental conditions in the future, both in an energy-friendly and comfortable way, more knowledge on the interaction between the system, indoor climate and human physiology is indispensable.

Thermal comfort is a complex phenomenon and it is therefore difficult to satisfy everyone in the same room if no individual correction measures can be taken. This is due to the large differences between persons, both psychological and physiological. In current building practice, often the predicted mean vote model (PMV) as developed by Fanger is used during the design phase to predict the thermal comfort of the occupants under given thermal boundary conditions and personal characteristics (metabolism, clothing). The PMV-model is included in several standards regarding the assessment of thermal comfort. However, evidence exists that actual mean thermal sensation votes can significantly differ from the PMV. Consequently, occupants are less comfortable and more dissatisfied than predicted, which may influence their productivity as well. The differences, among others, are partly caused by gender and age.

In this study thermal comfort is studied *beyond uniform* conditions from two perspectives; (-) the environment, i.e. non-uniform and transient thermal environmental conditions and (-) the human being, i.e. different subpopulations (males vs. females and young adults vs. elderly).

The first part of the thesis (Chapter 2 and 3) focuses on the application of temperature drifts in the built environment and the differences in thermal perception between young adults and elderly. The results of the studied moderate temperature drift show that a temperature drift up to ±2 K/h in the range of 17–25°C is assessed as applicable and will not lead to unacceptable conditions with respect to thermal comfort. On subpopulation level, the thermal sensation of the elderly is in general 0.5 scale units (on the 7-point ASHRAE

thermal sensation scale) lower in comparison to the younger adults under the same thermal conditions (the elderly are feeling slightly cool while the young adults are feeling neutral). Consequently, the elderly prefer higher ambient temperature levels.
Although, the thermal conditions do not result in an unacceptable situation, mild thermal challenges can cause significant physiological responses. From literature we know that mild cold temperature exposures can result in increased systolic blood pressure levels in the elderly. Therefore, it is advisable to protect our elderly from even mild thermal disturbances. On the contrary, younger adults may benefit from moderate temperature drifts.
In Chapter 3, a novel approach based on the neurophysiology of thermal reception is presented to predict thermal sensation under transient thermal environments. The developed model, using two independent datasets, explained 89% of the variance in thermal sensation.

The second part of the thesis (Chapter 4 through 6) deals with non-uniform thermal conditions and the differences in thermal perception between males and females. Under non-uniform conditions local effects, such as local skin temperatures and local thermal sensations, significantly influence whole-body thermal sensation and thermal comfort. Mainly the skin temperatures and coupled thermal sensations of the extremities (i.e. hands and arms) are important for whole body thermal sensation and thermal comfort; this applies especially for the females (Chapter 4). Therefore, operative temperature alone is not sufficient for the prediction of thermal sensation. For the majority of the experimental cases the actual mean votes (AMV, whole-body thermal sensation) significantly differed from the PMV (Chapter 4 and 5). The differences are mainly caused by the presence of the local effects and combined local discomfort factors, even if the individual discomfort factors are within their limits (predicted percentage dissatisfied < 10%) according to the thermal comfort standards.
The results show that females are more uncomfortable and dissatisfied under the same environmental conditions compared to males. In terms of cooling, the ambient temperatures for females need to be increased to improve satisfaction with the thermal environment and focus should be on local effects to achieve whole-body thermal comfort.
In Chapter 6, thermal comfort is discussed for a non-uniform heating condition. The focus is on the validity of a rule of thumb to assess the downdraught risk near glazed façades. According to the rule of thumb, the downdraught risk is assessed based on the U-value and height of the glass. Both the experimental and numerical modelling results reveal that the existing rule of thumb seems to be conservative regarding the downdraught risk. Furthermore, the numerical modeling results reveal that an increased floor temperature (i.e. floor heating), which is often regarded as a measure to prevent downdraught, can increase the downdraught risk. Therefore, it is recommended to modify the rule of thumb by implementing the floor temperature as a parameter.

From the results presented in this thesis we can conclude that significant differences in thermal comfort exist on subpopulation level. Furthermore, existing thermal comfort standards are not suitable for application under non-uniform thermal environments for the assessment of thermal comfort. Local effects, as local skin temperatures, play an important role in the whole body thermal assessment. Therefore, the thermal comfort assessment may benefit from incorporating the physiology behind thermal perception. By using a thermophysiological model it is possible to model (local) thermoregulatory responses. However, the coupling between these responses and thermal comfort remains an important research issue.
In the last part of the thesis (Chapter 7), the added value of a thermophysiological model (ThermoSEM) in the built environment to assess thermal comfort is discussed. Furthermore, the use of Computational Fluid Dynamics (CFD) to predict the boundary conditions, necessary for the thermophysiological model, is discussed. The results show that the level of detail which is necessary to predict the boundary conditions using CFD may be limited with respect to the use as input for a thermophysiological model. Furthermore, the results indicate that the use of ThermoSEM in combination with the ISO 14505 standard seems to be very promising regarding the prediction of thermal sensation of local body parts and overall thermal comfort under steady-state non-uniform environments during the building design phase.

Chapter

1

General introduction

1.1 Thermal comfort

Thermal comfort is defined by the American Society of Heating, Refrigerating an Air-Conditioning Engineers[1] (ASHRAE) as 'that expression of mind which expresses satisfaction with the thermal environment'. From the time we were able to actively provide heating (late 18th century), cooling (early 20th century) and ventilation for our buildings, the need for design temperatures arose[2]. Due to the differences between persons, both psychological and physiological, it is difficult to satisfy everyone in the same room. The environmental conditions which are required for thermal comfort are not equal for every person. In the past many researchers carried out laboratory and field studies to investigate the parameters which affect thermal comfort.

In the building design phase it is necessary to predict thermal comfort of the occupants, since thermal comfort is an important building performance indicator[3]. One of the first studies regarding the required environmental conditions to achieve thermal comfort for a major part of the occupants was conducted by ASHVE (currently ASHRAE) in 1925, this research resulted in an index for the effective temperature (ET)[4]. The ET is the operative temperature of a standard environment at a relative humidity of 50%, which realizes the same heat exchange with a human body, both latent and sensible, as the actual environment; i.e. the ET is the temperature of a standard environment which produces the same thermal sensation as the actual environment. In another study conducted by Vernon and Warner[5], the corrective effective temperature (CET) was developed. The purpose of that study was to take the effect of radiation into account. Both methods are used worldwide as an index for thermal comfort.

The most well-known and probably most referred research in the field of thermal comfort was carried out by Fanger[6]. He developed a model which is capable of predicting thermal sensation for a larger group of occupants and the coupled predicted percentage of dissatisfied due to the thermal environment; the Predicted Mean Vote and Predicted Percentage Dissatisfied index (PMV/PPD-index)[6]. This model was based on regression equations which were derived from subjective responses. Within this study a scale was developed where the subjective responses regarding thermal sensation could be marked. This comfort scale consists of a range from -3 to +3, which corresponds with cold and hot respectively. In 1984 this scale was standardized in the EN-ISO standard 7730 and in 1992 in the ASHRAE Standard 55 as the 7-point thermal sensation scale. Currently this scale is widely accepted and used. The optimum condition according to Fanger[6], defined as the thermal neutral condition, is a condition wherein a person does not prefer either a colder or warmer environment (PMV ± 0.5). This thermal neutral condition can be achieved by establishing a heat balance between the human body and its environment based on six basic parameters: activity level (heat production within the human body), thermal insulation of the clothing (clo-value), air temperature, mean radiant temperature, relative air velocity and the water vapor pressure in the air. Furthermore, four conditions were defined which apply for a person in a thermal comfortable condition: the heat balance of the human body needs to be in equilibrium, the sweat secretion and mean skin temperature need to be within certain comfort limits and no thermal local discomfort should occur.

Many researchers showed limitations of the PMV/PPD model which is often used in the building design phase to predict thermal comfort of the occupants. Nevertheless, Fanger is still regarded as a pioneer in the thermal comfort research field.

According to de Dear[7], a paradigm shift in the notion of thermal comfort occurred during the last decade. Until then the 'thermal comfort mantra'[7], based on the research of Fanger, was 'cool, dry, still, indoor air to be maintained within static, isothermal indoor climates to which building occupants attained thermal steady-state with minimal expenditure of temperature regulatory effort'[7].

The optimal thermal condition is not necessarily equal to thermal neutrality since preferences for non-neutral thermal sensations are common[8-10]. Moreover, several studies indicate that optimum thermal conditions for the elderly differ from those of young adults[11-15]. As in the western world the number of people aged 60 or older will increase from 15.4% in 1996 to 25.3% in 2030[16], it is relevant to study possible differences in thermal comfort between young and elderly people.

Also gender plays a role in perceiving the indoor climate, in general females are more sensitive for cold conditions and deviations from the individual optimum conditions than males. Furthermore, females frequently prefer higher temperatures[4 17-19]. This, however, is contrary to results from studies reported in ASHRAE[20]. These reveal that the thermal conditions preferred by elderly and females do not differ from those preferred by younger adults and males.

The PMV/PPD model is not capable of predicting thermal comfort under non-uniform environmental parameters (i.e. vertical air temperature stratification cannot be modeled because air temperature is defined as mean air temperature). To solve this problem, standards have been developed regarding local discomfort caused by draught, asymmetrical radiation and/or vertical temperature differences. However, in some cases these standards might be conservative as the prevalence of local discomfort, for example draught under warm conditions, is not uncomfortable[21]. Furthermore, these standards focus at separate non-uniform conditions (e.g. only a vertical temperature gradient), however the combination of non-uniform conditions can result in discomfort while the individual conditions are within the comfort range. No research on this combined effect has been found in literature.

In general, based on the references summarized, the PMV/PPD model is regarded suitable in situations where the indoor climate conditions are uniform, close to neutral and where the individual occupants do not differ too much from each other (physiologically and anthropomorphically).

However, how should thermal comfort be assessed *beyond uniform* conditions such as transient, non-uniform (combined effects), and non-neutral conditions, or in buildings where the occupants significantly vary in age, gender or body composition?

1.2 Application of low-energy/exergy HVAC systems and thermal comfort

To arrive at comfortable conditions indoors, generally, energy is required. About one-third of the primary energy used in developed countries is currently consumed in the built environment, for a large share by heating, ventilating, air conditioning and lighting in residential, commercial and public buildings[22]. The energy use in buildings represents a major contributor to fossil fuel use and carbon dioxide production. This reveals a high importance to reduce the energy use in buildings. A low energy demand of buildings is a first step. The next step is the use of sustainable energy sources or a far more efficient use of high quality energy sources. When trying to improve the energy supply systems of buildings in current practice, energy analyses are applied. This results for example in well insulated dwellings equipped with a heat recovery system for ventilation air and a condensing boiler. However, energy analysis alone does not give enough insight to further improve our systems[23]. Often energy efficiencies reveal that there are no further improvements possible, since many systems (such as the boiler and the heat exchanger of the given example) already have an efficiency of almost 100%. But even though the energy efficiency can be high, the quality of the energy is always degraded to some extent. Exergy analysis can identify and quantify these losses and is therefore a method to support the development of further improved systems[23]. The consequence of a low-exergy (lowex) heating, ventilating and air conditioning (HVAC) system is that the room supply temperature used for heating, cooling and ventilating differs from the environment as little as possible.

Thermal comfort is one of the main requirements for successful application of lowex HVAC systems. The Annex 37 study revealed that an optimal energy/exergy use not always results in an increased comfort level[24]. In some cases it proved to be more difficult to achieve thermal comfort, for example to compensate the slow response of floor and/or wall heating and/or cooling by means of ventilation. Application of lowex systems can result in local and/or global discomfort, e.g. through unintended air flows in case of application of a natural ventilation system in combination with low temperature heating. Non-uniform thermal conditions, which may occur due to application of lowex systems, may be

responsible for discomfort. However, non-uniform environmental conditions can also result in higher thermal comfort levels compared to uniform conditions[25-27].
More knowledge on the interaction between the system, indoor climate and the human body is indispensable to optimize the design of systems in the future.

For a comparison between different design variants in the design process of a building it is important to know how the building will perform in real-life. One of the most relevant parameters is how satisfied the future occupants will be with the environmental conditions, of which thermal comfort is an important factor. Therefore, it is important to explore the thermal conditions which will result from the application of newly designed low energy and/or exergy systems, and how they will affect the thermal comfort of the future occupants.

1.3 Thermal comfort and health

Although thermal comfort and health are often considered as positively correlated, being continuously in thermal neutral conditions is not necessarily healthy[28]. In addition to the energy-saving potential of allowing environmental temperatures to drift inside buildings, it might be healthier to be exposed to temperatures outside the thermoneutral zone. The major part of people living in modern Western countries spend approximately 90% of their time inside buildings. While spending more time indoors under thermal comfortable conditions, the exposure to thermal challenges decreases. A causal relation may exist between the time spent indoors in the thermoneutral zone and an increased adiposity[29]. Mild temperature challenges could increase the energy expenditure, and subsequently reduce obesity[28].

Compared to a constant temperature, allowing the temperature to drift could be a means to reduce energy-use. In order to successfully apply drifting temperatures, the perceived thermal comfort level under these conditions is important and should be investigated further[30-32]. A significant parameter is the temperature range wherein a drift is acceptable.

1.4 Thermal comfort and productivity

The thermal environment has an influence on productivity. The productivity of office workers is important with respect to business output as salaries amount up to 90% of the total company costs[33]. Under extreme environmental conditions the physiological responses of the body can be extremely affected, and as a result vital functions are disabled. This may result in hypothermia, hyperthermia, loss of consciousness, confusion etc. In moderate thermal environments, productivity, as a result of reduced concentration and decreased motivation, is associated with temperature and thermal comfort[33 34]. The thermal state of the body seems to influence arousal and subsequently performance[34].

In literature contradictions are found with respect to the temperature ranges wherein productivity is influenced. For example, Seppänen and Fisk[35] found no influence of room temperature on productivity within the comfort zone (20-25°C), while Toftum found a significant negative effect for a temperature increase (2K) within the comfort zone[36]. Furthermore, another study indicates that temperature cycles can have a positive influence on productivity[32]. Studies conducted on the performance of school children in class rooms, indicate a significant relation between the thermal environment and performance as well[37-39].

Following the above, it is relevant to further elaborate on the effects of the thermal environment on productivity.

1.5 The prediction of thermal comfort

Since thermal comfort is regarded as one of the important building performance indicators, accurate models for predicting thermal comfort during the design phase of a building can be beneficial in avoiding malperformance in the operational phase. Many methods, ranging from simplified and less detailed to complex and very detailed, exist to predict the thermal comfort of the future occupants[4]. Most well-known, probably most referred, and the most often implemented method in building performance simulation programs, is the earlier mentioned PMV-index of Fanger[1 6 40]. However, as many studies showed the limitations for application under more complex daily encountered environments and for different subpopulations, a need exists for thermal comfort models which are better capable to cover these influences. Another approach for assessing thermal comfort is based on evaluating the thermophysiological responses caused by thermoregulation (i.e. skin temperatures and core temperature) rather than evaluating the heat balance between the human body and its thermal environment. These (dynamic) thermophysiological responses can be modeled by using a thermophysiological model. A thermophysiological model provides a mathematical description of physiological responses to thermal environments. Initially, these models were developed for application in extreme conditions (e.g. military and aerospace). Significant developments of these models and improved computer resources caused the attention for application under non-military conditions, including the thermal comfort area[4]. Currently, very detailed thermophysiological models (e.g. the Fiala (UTCI) model[41 42], the 65MN model[43], the UC Berkeley model[44], ThermoSEM[28 45 46]) are available for modeling the thermophysiological responses. However, the coupling of these responses to thermal comfort remains an important issue. During the last years emphasis was furthermore on the development of very accurate and detailed models for the prediction of the environmental conditions (e.g. Computational Fluid Dynamics [CFD]) and the coupling of CFD to thermophysiological models[47 48].

Application of these kinds of models during the design phase of a building is regarded as beneficial in case the thermal comfort of the future occupants has to be assessed for complex thermal environments. Though the high level of detail appears promising, the necessity and the appropriateness of highly detailed models remain unclear.

1.6 Outline of the thesis

This thesis aims to explore thermal comfort of occupants *beyond uniform conditions* with an emphasis on individual effects of different sub-populations (i.e. young/elderly and males/females) and application of realistic non-uniform thermal configurations. Within this thesis thermal comfort is studied according to different factors: the environment and the human being.

The first part of the thesis (i.e. Chapter 2 and 3) focuses on transient environments and the second part addresses the influences of steady-state non-uniform thermal environments (i.e. Chapter 4 through Chapter 6). In Chapter 2, the differences between young and elderly in response to a moderate drift are discussed. Focus is on the achieved thermal comfort, physiological responses and productivity. In Chapter 3, a novel approach is presented to model thermal sensation under transient conditions based on neurophysiology. Chapter 4 describes the differences in gender with respect to whole-body thermal sensation and comfort and the influence of local effects (i.e. local skin temperatures and thermal sensation). In Chapter 5, the application of several cooling techniques is investigated. Chapter 6 deals with the validity of a rule of thumb to assess downdraught in the design phase, furthermore a low energy/exergy system approach to prevent downdraught is discussed.

In Chapter 7, the added value of a thermophysiological model for the built environment to assess thermal sensation and comfort *beyond uniform* thermal sensation and comfort is discussed.

Finally, in Chapter 8 the results obtained in this thesis are discussed, techniques to gain knowledge on thermal comfort in relation complex thermal environments are reviewed, and implications for future research are presented.

Figure 1.1 provides a graphical overview of the research and the research issues addressed.

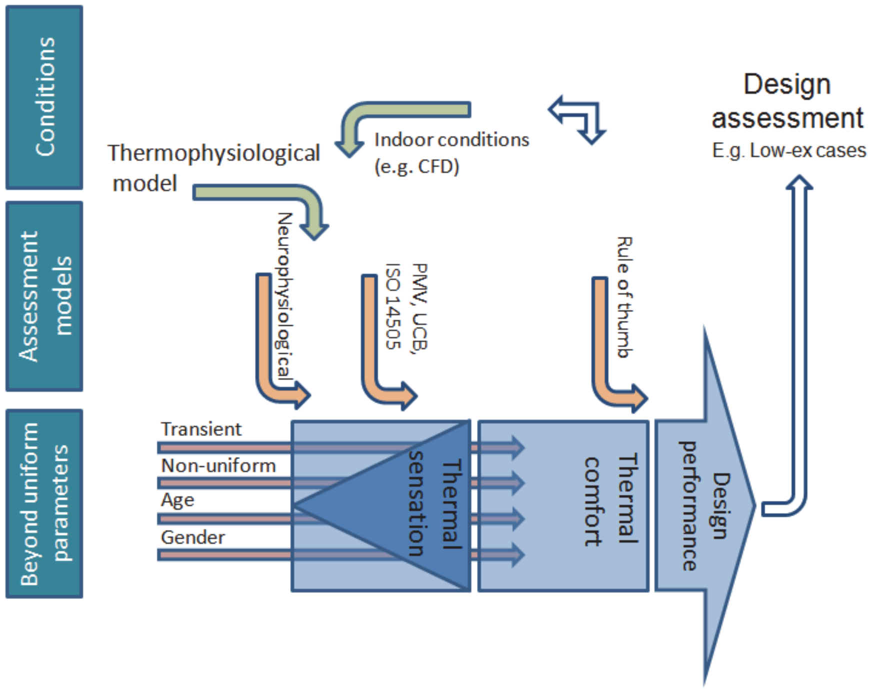

Figure 1.1 Graphical overview of the research and research issues addressed

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PART I

TRANSIENT ENVIRONMENTS

Chapter

2

Differences between young adults and elderly

in thermal comfort, productivity and thermal physiology in response to a moderate temperature drift and a steady-state condition

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The lay-out has been adjusted to fit the style of this thesis.

Abstract

Results from naturally ventilated buildings show that allowing the indoor temperature to drift does not necessarily result in thermal discomfort and may allow for a reduction in energy-use. However, for stationary conditions, several studies indicate that the thermal neutral temperature and optimum thermal conditions differ between young adults and elderly. There is a lack of studies that describe the effect of ageing on thermal comfort and productivity during a moderate temperature drift. In this study the effect of a moderate temperature drift on physiological responses, thermal comfort and productivity of 8 young adults (age 22-25yr) and 8 older subjects (age 67-73yr) was investigated. They were exposed to two different conditions: S1-a control condition; constant temperature of 21.5°C; duration: 8h and S2-a transient condition; temperature range: 17-25°C, duration: 8h, temperature drift: first 4h: +2K/h, last 4h: -2K/h.

The results indicate that thermal sensation (TS) of the elderly was, in general, 0.5 scale units lower in comparison to their younger counterparts. Furthermore, the elderly showed more distal vasoconstriction during both conditions. Nevertheless, TS of the elderly was related to air temperature only, while TS of the younger adults also was related to skin temperature. During the constant temperature session the elderly preferred a higher temperature in comparison to the young adults.

2.1 Introduction

Both thermal comfort and energy-use play an important role in the performance of a building. Approximately one-third of the primary energy used in developed countries is consumed by heating, ventilating and air conditioning in residential, commercial and public buildings[1]. Given these energy requirements, it is relevant to study how energy-savings can be achieved together with acceptable thermal comfort and performance.
Results from naturally ventilated buildings in practice revealed that satisfaction with the thermal environment does not mean that this environment has to be controlled at a constant indoor air temperature[2]. Compared to a constant temperature, allowing the temperature to drift could be a means to reduce energy-use.

In the past, several studies have been conducted to examine the influence of a temperature drift and a wider temperature range on thermal comfort and performance. These studies show that temperature drifts can be acceptable in air-conditioned buildings without self-control. The results of these studies show that slow temperature ramps up to 0.5 K/h have no effect on the width of the comfort zone as established under steady-state conditions; the environment is experienced as in steady-state conditions, i.e. slow temperature ramps (0.5K/h) were not significantly noticeable to the occupants[3-6]. Berglund and Gonzalez[4] also stated that at fast temperature changes (1.0K/h and 1.5K/h) the allowable deviation from the optimum thermal condition was larger in comparison to slow temperature changes (0.5K/h). Hensen[7] and Kolarik et al. [8] concluded from their reviews that for rates between 0.5K/h and 1.5 K/h there is no clear evidence of increased or decreased comfort zones due to temperature drifts, except from experiments with uncommon acceptability assessment procedures. From these studies it can be concluded that the knowledge regarding the effects of temperature drifts on human thermal comfort is still limited.
In a recent study by Kolarik et al.[9] different operative temperature ramps (±0.6 K/h, ±1.2 K/h, +2.4 K/h, +4.8 K/h; temperature ranges: 22-26.8°C and 17.8-25°C) were investigated to determine the influence of the slope. They found that a slow temperature drift (±0.6 K/h) was perceived by the subjects with 3-4 hours delay (depending on clothing level). During the first 3-4 hours of exposure subjects did not distinguish a slow temperature increase (+0.6K/h) from a constant temperature level (21.4°C and 24.4°C). These results are in agreement with earlier mentioned studies by Berglund and Gonzalez [4 5] and Rohles et al.[6].
The results also indicate that not the temperature ramp, but the combination of a temperature level above 24.4°C and the time of exposure affected the thermal sensation. Furthermore, a linear relation was found between mean thermal sensation and operative/air temperature for all the studied ramps.
In the building design phase it is useful to predict thermal comfort of the occupants; often the PMV/PPD model is used for this. However, Nicol and Humphreys[10] showed, based on

data of the ASHRAE RP-884 database[11], that the PMV model might not be applicable to predict thermal comfort for conditions that deviate much from thermal neutral conditions.
Although the PMV model was developed for steady-state conditions, the study by Kolarik et al.[9] indicates that the PMV model might also be applicable for transient conditions. For all slopes the relation between instantaneous mean thermal sensation and prediction by the PMV model[12] was in reasonably good agreement[9], which was found by Schellen et al.[13] as well. The same was found by Knudsen et al.[14]; they concluded that the PMV model possibly can be used for temperature ramps up to ±5 K/h.
Seppänen and Fisk[15] describe a literature review on the influence of temperature on performance. Several types of office tasks were analyzed, including text typing and the duration of telephone calls during call center work. According to their analyses, no influence of room temperature was found between 20°C and 25°C. Above 25°C, and below 20°C, a decrease of 2%/°C in performance was observed. These findings were confirmed in studies by Seppänen and Fisk[15] and Tanabe[16]. On the contrary, Toftum[17] discovered a significant negative effect on performance when increasing the temperature from 20-22°C to 22-24°C.
Studies concerning the effects of temperature drifts on performance and productivity were only found for studies comprising short cyclical temperature swings around the preferred ambient temperature. Kolarik et al.[8] concluded that small rapid swings (4K/8min) around the preferred temperature resulted in a decreased performance and work speed. Conversely, larger and slower swings (4K/32min) were related to a higher work speed in comparison to results achieved under steady-state conditions. The performance was equal to the performance achieved under steady-state conditions. According to these findings, temperature transients can have a positive influence on the work speed (productivity) and perhaps performance although thermal discomfort cannot be ruled out.
For both temperature and productivity no studies are available to determine the effects of ageing on thermal comfort and productivity during a moderate temperature drift. In this study this effect has been investigated.

The above mentioned studies reveal a challenge to explore if faster (>±0.5K/h) temperature drifts, both increasing and decreasing, are acceptable during a longer period of time in air-conditioned buildings. Moreover, there exists a need to study thermal preferences of elderly and resulting requirements[18 19].
ASHRAE[20] states, based on research by among others Rohles and Johnson[21], Fanger and Langkilde[22] and Fanger[23], that the thermal conditions preferred by elderly do not differ from those preferred by younger adults. This does not mean that the elderly and young adults are equally sensitive to cold or heat. On the contrary, several studies indicate that the thermal neutral temperature and optimum thermal condition of elderly differ from the thermal neutral temperature and optimum condition of young adults, mainly because of an on average lower activity level (which implies a lower metabolic heat production).

Therefore, elderly might require a higher ambient temperature to achieve thermal comfort in comparison to younger adults at equal clothing levels[18 24-30].
As, in the next 20 years, in the western world the number of people aged 60 or older will increase from 15.4% in 1996 to 25.3% in 2030[31], it is relevant to study possible differences in thermal comfort, physiological responses and performance between young and elderly people experiencing a moderate temperature drift.

Following the above, the objective of the present work was to study differences in thermal comfort, physiological responses and productivity between young and elderly people under a moderate temperature drift.

2.2 Methods

Design
The experiments were carried out in a climate room (4.5x3.7x2.3 m^3, LxWxH) at the laboratory of the unit Building Physics and Services at Eindhoven University of Technology (Figure 2.1 and 2.2), where air temperature and relative humidity could be controlled accurately. The climate room is situated in a laboratory with a controlled constant indoor climate. The room consists of well insulated walls with a low thermal mass, therefore the wall temperatures of the room followed the air temperature near instantly. The air, conditioned by an air handling unit (Fischback Luftungs- und Klimatechnik GmbH, type VNM) was supplied through a high inductive outlet vent. To further increase the mixing of the air, a ceiling fan was installed, resulting in a mean air velocity near the subject of 0.19±0.03 m/s. The temperature of the supplied air was controlled through a PID controller (Temperature controller, West type 1600). The relative humidity (RH) was controlled at a fixed level of nearly 40% (43.2 ± 2.3%).

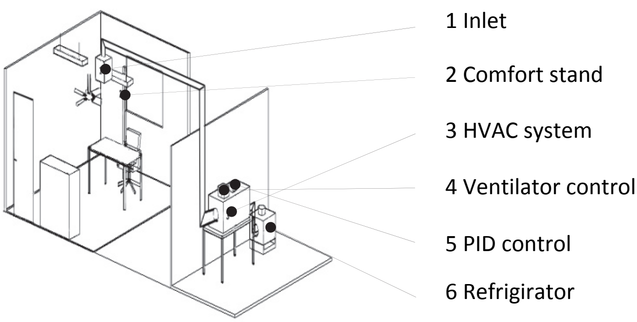


Figure 2.1 Schematic representation of climate room

Figure 2.2 Impression of test subjects in climate room

Sixteen subjects (8 young adults, age 22-25 and 8 older adults, age 67-73) were recruited to participate in the experiment. All subjects were male, healthy, normotensive and not taking any medications that might alter the cardiovascular or thermoregulatory responses to the temperature changes; subject characteristics per group are listed in Table 2.1.

Body fat percentage was determined by means of skinfold thickness, according the Siri equation[32]. Skin folds were measured at four sites: subscapular, suprailiacal and at the triceps and biceps[33].

Table 2.1 Subject characteristics per age group

	Age [yr]	Height* [m]	Weight* [kg]	BodyFat%* [%]
Jong adults	22-25	1.83±0.11	82.7±8.6	14.5±3.3
Older adults	67-73	1.76±0.06	77.8±7.2	18.7±5.3

*Mean ± SD

The subjects visited the climate room on two occasions (S1 and S2) that differed in indoor climate conditions. The order of the conditions was alternated (e.g. subject 1 started with S1 and ended with S2, subject 2 started with S2 and ended with S1, subject 3 started with S1, etc.).

S1: A steady temperature (21.5°C)

Session *S1* (duration 8h) was the control situation; with the results of this session possible time effects have been assessed. The temperature was fixed at 21.5°C (21.5±0.12°C), which corresponds to a neutral thermal sensation (PMV≈0).

S2: A transient condition

During session *S2* a moderate temperature ramp (duration: 8h; temperature range: 17-25°C; temperature drift: first 4h: +2K/h, last 4h: -2K/h) was imposed. Through this course both the effects of an increasing and decreasing ramp could be evaluated.

Most of the experiments done in the past focused on the effects of temperatures warmer than neutral. In this study temperatures colder than neutral will be studied as well. The minimum temperature of 17°C was set to avoid shivering, and therefore it is assumed that the condition will not be unacceptable cold[34]. The maximum temperature of 25°C fits within the comfort zone (PMV<0.5) according to ASHRAE[35] and EN-ISO 7730[12]. The imposed drift of 2K/h is within the comfort limit[12]. Furthermore this drift represents a building warming up during the beginning of the day, and cooling down during the second part of the day when the heating is turned off. It was assumed that cooling down the temperature in the second part of the day could perhaps positively influence the productivity due to 'freshness of mind'. The applied temperature course is represented in Figure 2.3. Mean deviation from the desired temperature course was 0.08±0.49°C.

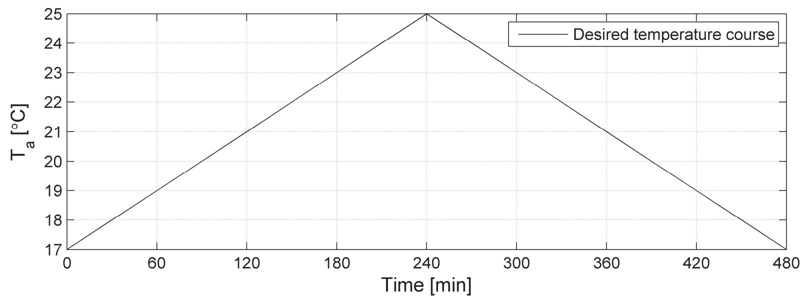


Figure 2.3 Designed temperature course condition S2

Prior to the measurements the subjects performed a light exercise until skin vasodilatation occurred to ensure all subjects entered the climate room in an equal thermal state. Vasodilatation was assessed by the skin temperature difference between forearm and top of the forefinger[36 37]. After entering the climate room the experiment started with an acclimatization period (30 minutes). During this period the skin temperature sensors were attached and their characteristics (height, weight and fat percentage) were determined. Furthermore they received an instruction regarding the use of the questionnaires. During the experiments the subjects wore standardized clothing, consisting of a cardigan, jogging pants, thin T-shirt, underpants, socks and shoes. The clo-values were determined according to EN-ISO 9920[38] and the databases of McCullough et al.[39 40]. The total heat resistance of the clothing ensemble, including desk chair, was approximately 1.0 clo.

The subjects continuously performed office tasks; their metabolic rate was estimated to be approximately 1.2 met[12]. The volunteers were given detailed information regarding the purpose and the methods used in the study, before written consent was obtained.

Measurements

During the experiments both physical and physiological measurements were carried out continuously. The measurements of the environmental parameters, air temperature (NTC Thermistor, type SC95), relative humidity (RH) (Humidity Sensors, Honeywell HIH-4000 series), air velocity (hot sphere anemometer, Dantec), mean radiant temperate (black bulb 0.15m), carbon dioxide (Carbon Dioxide Transmitter, Vaisala 0-2000 ppm) and illuminance (Lux meter, Hager model E2) were measured according to EN-ISO 7726[41]. Air temperature, RH and air velocity were measured on a comfort stand at 0.1, 0.6, 1.1 and 1.7m height.

The skin temperatures were measured according to EN-ISO 9886[42] by wireless iButtons[43] (Thermochron iButton® DS1291H, Dallas Maxim) at 17 locations. Mean skin temperature was calculated on the basis of the 14 point weighing as proposed by EN-ISO 9886[42]. The distal skin temperature was calculated as average of the finger tip, instep, hand and forehead skin temperature. To avoid a disproportional distribution, finger tip and hand temperature were averaged. The proximal skin temperature was calculated as an average of the scapula, paravertebral, upper chest and abdomen skin temperature. To obtain more insight into the extent of vasomotion (vasoconstriction and vasodilatation) three measurement sites were added: top of the middle right toe, left forearm and top of left forefinger. The core temperature was measured rectally at 10-15cm, deep in the young subjects (thermistor-probe, NTC Thermistor type SC95). In the elderly the core temperature was determined by measuring the intestinal temperature through an ingestible telemetry pill (CorTemp™, Ingestible Core Body Temperature Sensor, HT150002, HQ Inc., Palmetto, FL) which was ingested 30 minutes before entering the climate room.

Questionnaires

Two times per hour the test subjects filled in a questionnaire which included a continuous 7-point thermal sensation interval scale[12], scales to assess the acceptability of the thermal environment and Visual Analogue Scales (VAS) to assess adverse perceptions and the perceived indoor environment[44]. A questionnaire to assess self-estimated performance and a questionnaire to assess perceived stress were included as well. To assess the performance a 'Remote Performance Measurement' (RPM) method was used[17]. Within this method the performance was estimated by two simulated office tasks: text typing and addition. Both questionnaires and office tasks were presented in Dutch to the subjects through an Internet browser.

The differences in physiological responses, subjective responses and performance were studied by using ANOVA and a linear mixed effects model (LME) treating subject as a random factor; the experimental conditions were analyzed separately in the ANOVA model. To assess explaining variables for the thermal sensation and thermal comfort of the subject stepwise linear regression was used. Significant effects are reported for $p<0.05$. Two statistical software packages were used to analyze the data; for the LME analyses the free available R 2.9.2 (R Foundation for Statistical Computing, Vienna, Austria) software package was used, for all other analyses the commercially available software package SPSS 16.0 (SPSS Inc., Chicago, USA) was used.

2.3 Results

Physiological measurements

Mean, distal and proximal skin temperatures and core temperature of young (Y) and elderly (E) subjects for both sessions (S1 and S2) are given in Figure 2.4. For all three different skin temperatures the difference between young and elderly was significant ($p<0.01$). The majority of the local skin temperatures (forehead, neck, scapula, upper chest, upper arm, hand, abdomen, paravertebral, shin, calf and instep) of the elderly were significant lower than the skin temperature of the young adults. The temperature of the fingertip showed the largest difference, 29.1±1.90°C [S1] and 27.5±2.76°C [S2] for the young adults versus 24.8±2.73°C [S1] and 24.9±2.12°C [S2] for the elderly. However three measurement locations showed a deviation. At the underarm the difference was not significant, at the front and back of the upper leg (anterior and posterior thigh) the skin temperature of the elderly was for both sessions significant ($p<0.001$) higher than of the young adults, although this difference was relatively small (<0.8°C).

The mean core temperatures of the elderly (36.6±0.27°C [S1] and 36.5±0.33°C [S2]) were significant lower compared to their younger counterparts: 37.0±0.08°C [S1] and 36.9±0.09°C [S2]). Possibly this difference is caused by the difference in measuring technique for T_{core} between the groups.

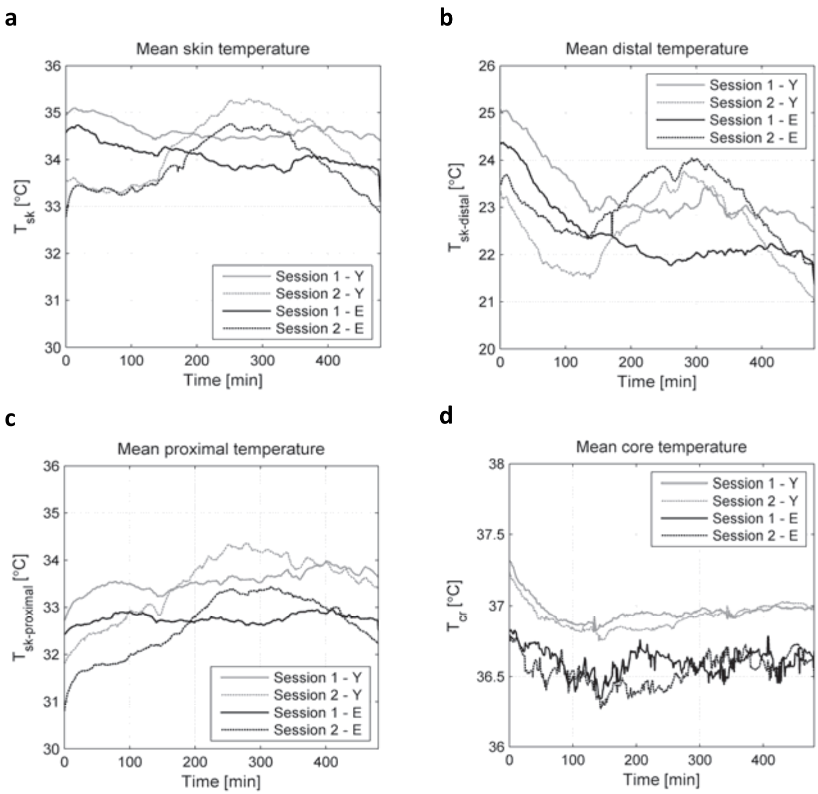


Figure 2.4 Mean (**a**), distal (**b**) and proximal (**c**) skin temperatures and core temperature (**d**) of young and elderly subjects during both experimental conditions

The difference (gradient) between fingertip and forearm temperature is given in Figure 2.5. Positive values indicate vasoconstriction (forearm temperature is higher than finger tip temperature), while negative values indicate vasodilatation. The fingertip–underarm gradient of the young adults is smaller during both sessions in comparison to the elderly, which is caused by the differences in vasoconstriction between the young adults and the elderly. Furthermore, the results of the young adults show a slightly negative difference (vasodilatation) as result of the high temperatures during session 2, in contrast to the elderly who maintained finger skin vasoconstriction.

The drop in distal skin temperatures during approximately the first 100 minutes of both conditions (S1 and S2) is most probably caused because the subjects started the experiment in vasodilatation state ($\Delta T_{(forearm\text{-}fingertip)} \approx 0$) which was maintained during the acclimatization period due to the slightly elevated activity level. After the start of the experiment (t=0), the subjects were completely sedentary which resulted in a slight decrease in core temperature (figure 2.4d) caused by a lowered internal heat production (metabolism). To maintain core temperature constant vasoconstriction was activated, indicated by the increase of forearm-fingertip gradient (Figure 2.5) and drop in distal temperatures (Figure 2.4b).

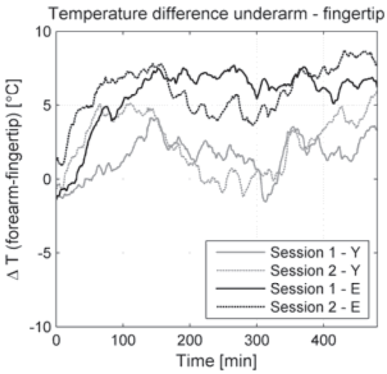


Figure 2.5 Mean difference between forearm and fingertip temperature of young and elderly subjects during both experimental conditions

Subjective responses

The results of the questionnaires have been analyzed separately for both experimental conditions (S1 and S2) and for both parts of the condition (1: first 4 hours, 2: last 4 hours), to be able to distinguish between a constant temperature and a temperature drift and to analyze time effects.

Thermal sensation (TS) of the young adults was significantly (ANOVA, $p<0.001$) affected by the two different conditions (Figure 2.6a). In the design of the experiment the temperature of session S1 was determined to be equal to a neutral thermal sensation according the PMV model (ISO 7730, 2005). Averaged TS for the young subjects was -0.18±0.56 during session S1 and -0.52±0.76 during session S2. TS of the elderly was -0.67±0.66 and -0.63±0.93 respectively.

TS during session S2 is not influenced by time. Differences (insignificant, $p>0.05$) between first and last part of session S2 are represented in Figure 2.6b.

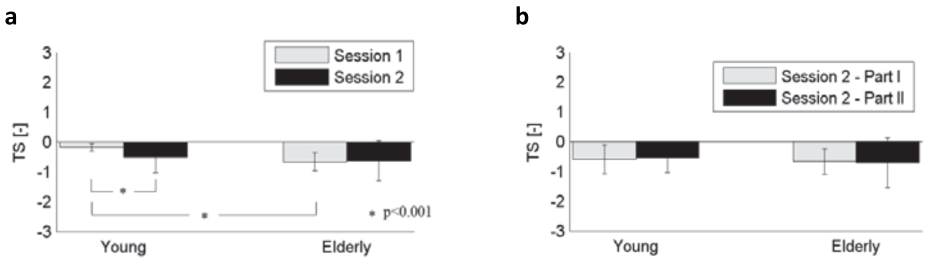


Figure 2.6 (**a)** Mean thermal sensation (TS) ± SD per measurement session (-3: Cold, -2: Cool, -1: Slightly Cool, 0: Neutral, 1: Slightly Warm, 2: Warm, 3 Hot) (**b**) Mean thermal sensation; Part 1: first 4 hours of session 2; Part 2: last 4 hours of session 2

In table 2.2a and 2.2b the results of stepwise multiple regression analysis are represented for thermal sensation as independent variable for the young adults and the elderly, respectively, only significant variables are listed. The following variables were taken into account as possible predictive variables: mean air temperature, mean, proximal and distal skin temperature, mean air velocity, fingertip-underarm gradient, core temperature and the change in mean skin temperature.

Table 2.2a Results from stepwise multiple regression model with $T_{a,}$ T_{core} and T_{skin} as predictive variables for young subjects and thermal sensation as the dependent variable

Independent variables	Slope	Significance (p)	R^2_{adj}
Air temperature (T_a)	0.215	0.000*	
Core temperature (T_{core})	0.646	0.000*	0.34
Mean skin temperature (T_{sk})	0.177	0.005*	

*significant (p<0.05)

Table 2.2b Results from multiple regression model with T_a, T_{core} and $\Delta T_{(forearm\text{-}finger\ tio)}$ as predictive variables for elderly subjects and thermal sensation as the dependent variable.

Independent variables	Slope	Significance (p)	R^2_{adj}
Air temperature (T_a)	0.221	0.000*	
Vasomotion ($\Delta T_{(forearm\text{-}finger\ tip)}$	-0.087	0.000*	0.40
Core temperature (T_{core})	-0.299	0.018*	

*significant (p<0.05)

In table 2.3 the significant (p<0.05) explaining variables per part (I and II) of the measurement session according to stepwise linear regression analyses are listed. No possible effects of time on TS could be observed.

Table 2.3 Explaining variables for thermal sensation as independent variable.

	Session 1		Session 2	
	Part I	Part II	Part I	Part II
Young adults	Core temperature (T_{cr}); Distal skin temperature ($T_{sk;dist}$); Proximal skin temperature ($T_{sk;prox}$); Extent of vasomotion ($\Delta T_{forearm\text{-}fingertip}$)	-	Air temperature (T_a); Core temperature (T_{cr}); Distal skin temperature ($T_{sk;dist}$)	Air temperature (T_a); Mean skin temperature (T_{sk})
Older adults	Proximal skin temperature ($T_{sk;prox}$)	Mean skin temperature (T_{sk}); Extent of vasomotion ($\Delta T_{forearm\text{-}fingertip}$); Core temperature ($T_{core}$)	Air temperature (T_a); Extent of vasomotion ($\Delta T_{forearm\text{-}fingertip}$);	Air temperature (T_a)

Linear regression analyses of TS as dependent variable and T_a as independent variable show the difference in TS between the young and older adults. Generally, TS of the older adults is approximately 0.5 lower than TS of the younger adults (Figure 2.7). However, only for session S1, the differences are significant (LMM, $p<0.05$). Comparing the subjective votes for TS and predicted votes according the PMV model, a similar trend can be detected; the general trend is in good agreement with the subjective votes. For the elderly, however, measured TS is 0.5 lower in comparison to PMV.

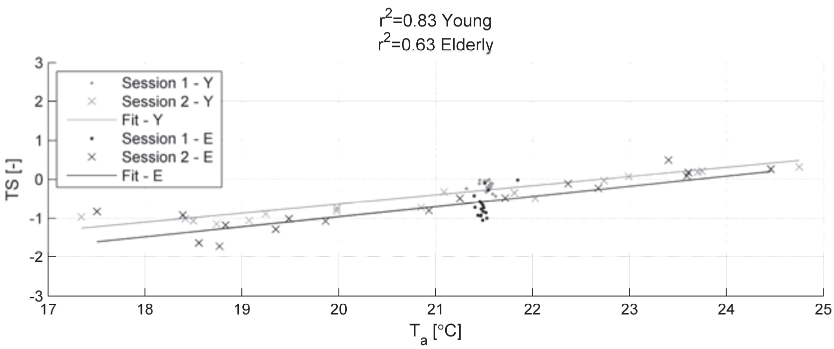


Figure 2.7 Linear regression analyses with TS as dependent variable and T_a as independent variable, for both sessions

The difference between young and elderly in thermal comfort (TC) is significant (LME, $p<0.001$); Figure 2.8. The elderly felt less comfortable during both sessions than the young adults, which is in agreement with TS. Since no significant differences can be detected between the parts of the session (Figure 2.8b), time effects are excluded for TC as well.
With respect to the preferred temperature, a significant difference (LME, $p<0.01$) was found for S1 (constant temperature); the elderly preferred a warmer temperature, while the young adults requested no change in temperature. For both young and elderly subjects, mainly skin temperature (mean skin temperature, distal and proximal skin temperature, extent of vasomotion) had a significant ($p<0.05$) effect on TC.

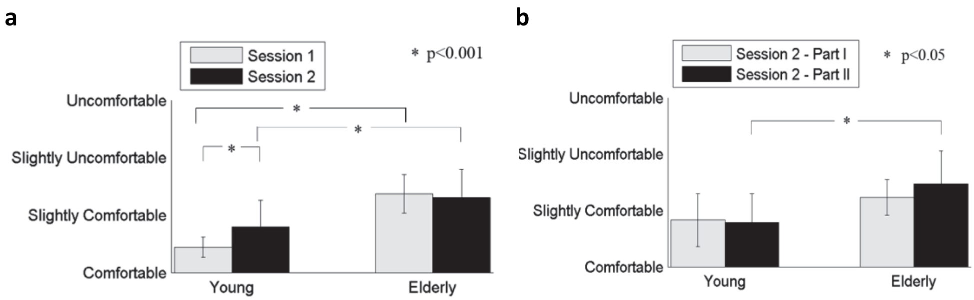
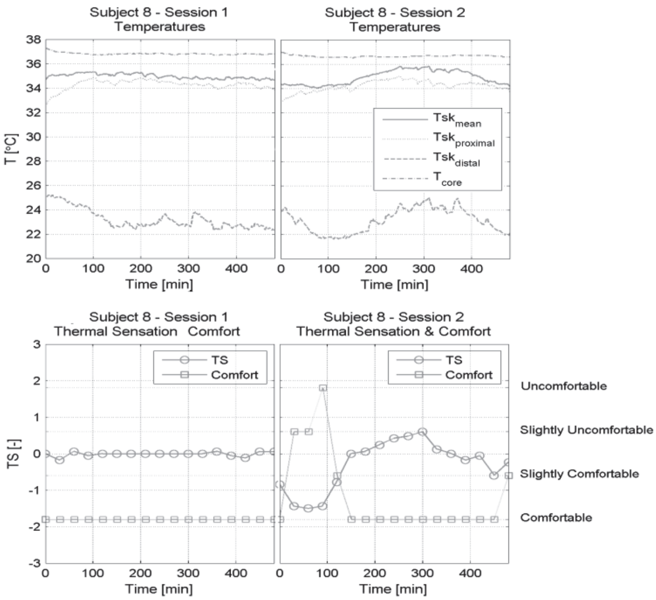


Figure 2.8 (a) Averaged thermal comfort votes ± SD per measurement session **(b)** Averaged thermal comfort votes; Part 1: first 4 hours of session 2; Part 2: last 4 hours of session 2

In figure 2.9a and 2.9b the results are represented for one typical young and one typical older adult respectively, of both experimental sessions (S1, left and S2, right). For both subjects mean and proximal skin temperatures are clear indicators for thermal sensation (TS). During S1 the older adult is more sensitive for distal skin temperature, which is reflected in TS. Furthermore, lower distal skin temperatures (i.e. vasoconstriction) are reflected in the comfort votes of both subjects, resulting in less comfortable votes. The sudden increase in mean and distal skin temperatures of the older adult during S2 at $t\approx200$ cannot be explained.

a



b

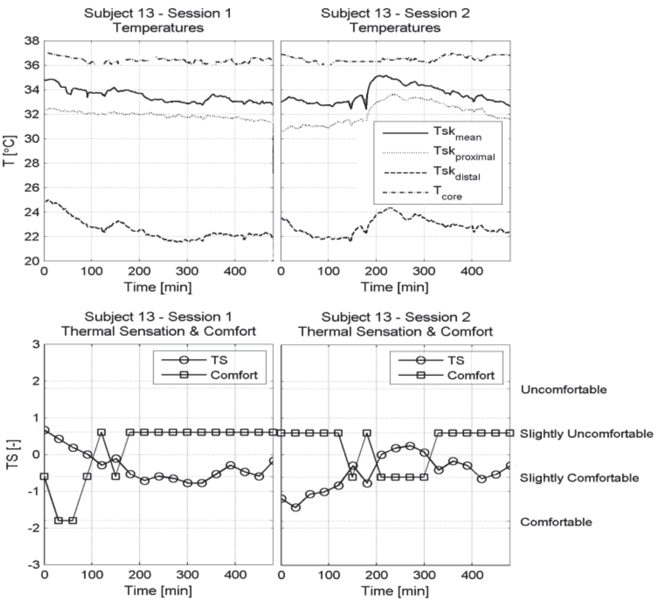


Figure 2.9 (a) Individual time plots typical **young subjec**t of mean distal and proximal skin temperatures, core temperature, thermal sensation vote and comfort vote for S1 (left) and S2 (right) **(b))** Individual time plots typical **older subject** of mean distal and proximal skin temperatures, core temperature, thermal sensation vote and comfort vote for S1 (left) and S2 (right)

To determine the effects of ageing on performance, the data of simulated office tasks were normalized; the maximum score of each subject was equal to 100% and all other scores of the subject were related to this score. After normalizing the data, the results of the simulated office tasks indicate a significant (LMM, p<0.05) effect of ageing on the number of completed additions (figure 2.10, left) and the number of correct additions (Figure 2.10, right). In general, the percentage of completed additions was approximately 15-20% higher for the young adults in comparison to the elderly; the percentage of correct additions was approximately 5% higher for the young subjects. Within the groups no significant differences of the temperature changes were observed. In addition, no significant differences were found between the parts of the measurement session; time-effects or the type of slope (increasing or decreasing) did not had a significant influence (Figure 2.11).

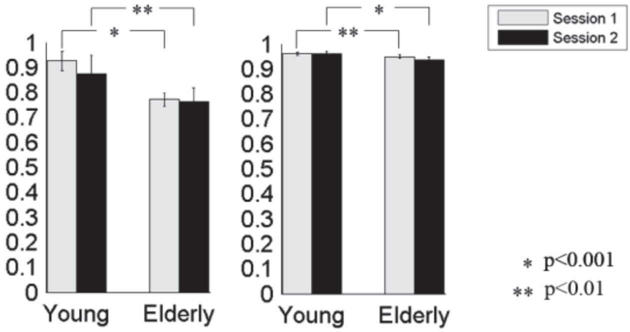


Figure 2.10 (left) Average normalized completed additions ± SD per measurement session **(right)** Average normalized **c**orrect additions ± SD per measurement session

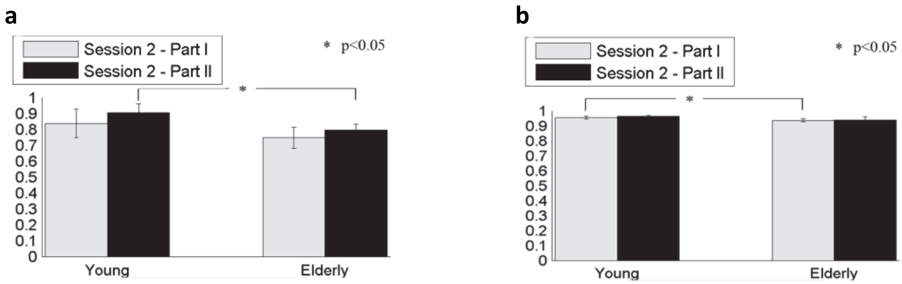


Figure 2.11 (a) Average normalized completed additions ± SD; Part 1: first 4 hours of session 2; Part 2: last 4 hours of session 2 **(b)** Average normalized **c**orrect additions ± SD; Part 1: first 4 hours of session 2; Part 2: last 4 hours of session 2

2.4 Discussion

Based on the experimental results for the control situation it was possible to distinguish between effects of a constant room temperature and transient conditions. The temperature drifts were significant noticeable for the young subjects (significant differences between session 1 and 2; Figure 2.6a and 2.8a). Based on results of the questionnaire, the studied moderate temperature drifts did not result in unacceptable thermal conditions. Furthermore, the results of the individual parts (I and II) show that thermal sensation (TS) and thermal comfort (TC) were not affected by time. No significant differences in thermal sensation and thermal comfort were observed between the increasing (part I) and decreasing ramp (part II) for both the elderly and younger adults; subjects perceived both ramps equally. During the stable temperature condition S1 thermal sensation was both for the elderly and young adults related to skin temperature. However, during the moderate temperature drift (S2) TS of the elderly was mainly related to air temperature, while TS of the younger adults was related to skin and air temperature. Thermal comfort was for both conditions (S1 and S2) related to skin temperature.

Fiala[45] derived a relation between thermal sensation, mean skin temperature, core temperature and the change in mean skin temperature. In this study, for the elderly subjects a significant relation was found between air temperature, the extent of vasomotion and core temperature. For the young adults a significant relation was found between air temperature, core temperature and mean skin temperature. The experiments which Fiala used to derive the relation between physiological parameters and thermal sensation were conducted with young subjects (college-age students). Therefore, the results can be compared only with results of the young adults in this study. In this study no influence of the rate of change in mean skin temperature on thermal sensation of the young adults was observed. Fiala originally included this term to account for rapid (e.g. step-wise) changes in ambient temperature. However, in this study the temperature changes can be considered as relative slow changes in ambient temperature which did not caused an immediate change in skin temperature.

Predictions of the thermal sensation obtained with the PMV model showed good agreement with the measurement results for the young adults. For the elderly, conversely, a difference of 0.5 scale units was found between predicted and measured TS. The trends, however, were in good agreement.

The results of the simulated office tasks revealed that ageing had a significant negative effect on performance; the average normalized performance was 5-20% lower for the elderly in comparison to the young adults. Office work normally covers a wide range of different tasks involving a complex set of component skills. Typical tasks include text typing and different types of arithmetical calculations. If these tasks are affected by changes in the indoor environment, it is reasonable to assume that office work in general will be affected similarly. Importantly, the temperature changes did not affect the productivity, which is in line with results from Seppänen and Fisk[15] and Tanabe[16].

The results of the subjective responses, obtained from the experiments carried out within this study, support that the optimum conditions for elderly differ from those of their younger counterparts, which is contrary to ASHRAE[20]. However, more recent studies by, among others, Collins et al.[25], Hashiguchi et al.[29], and DeGroot and Kenny[30], also revealed that the optimum conditions for elderly do differ from the optimum conditions of young adults. Elderly are more vulnerable, compared to young adults, in conditions that differ from neutral, because the efficiency of their cold-and warm-defense mechanisms is declined and the ability to detect, and therefore respond to, temperature changes is reduced. Furthermore, Poehlman et al.[46] revealed that their metabolic rate is lower compared to the metabolic rate of younger people due to a decrease in muscle mass which reduces both the basal and resting metabolic rate.

The thermal sensation of the elderly was in general 0.5 scale units lower than TS of the young adults. The same trend was found for the thermal comfort votes; the elderly felt less comfortable than the young adults. During session S1 with the stable temperature condition (21.5°C) the elderly preferred a higher temperature, while the young adults requested no change in temperature. The difference in thermal sensation may be explained by a decreased thermoregulatory response (especially the vasoconstrictor response), indicated by the extent of vasomotion measured by the differences in skin temperatures between the young adults and the elderly[30 47 48]. During the experiments the elderly were continuously more vasoconstricted (i.e. the skin temperature of the fingertip was mostly lower than the skin temperature of the underarm) in comparison to the young adults.

In this study no significant correlation was found between the extent of vasomotion or fingertip temperature and thermal sensation parameters, although a relation in literature was found between these parameters[49]. Wang et al.[49] found that finger temperature (30°C) and finger-forearm gradient (0°C) are significant thresholds for overall thermal sensation. The experiments in the present study were conducted under cooler environmental conditions in comparison to the majority of the experiments in the study by Wang et al.[49] ($T_{neutral}$ in te present study was 21.5°C versus 25.8-27.1°C in Wang et al.[49]). Since the hands were not covered during both studies, this resulted in significant lower fingertip temperatures in the present study. Based on the results obtained in the present study one could conclude that both fingertip temperature and fingertip-forearm gradient are not applicable as thermal sensation predictors under conditions were the body is nearly continuously in vasoconstriction mode (fingertip-forearm gradient >0°C). In conditions where the temperature range is larger it probably can be used as predictor for thermal sensation. In this study a significant correlation with the extent of vasomotion was found only for thermal comfort.

It should be mentioned that for the elderly subjects healthy retired persons were selected which were normotensive and not taking any medications that might alter the cardiovascular or thermoregulatory responses to the temperature changes. The question is whether these healthy elderly subjects are representative for the elderly population because most elderly use medication. For instance in The Netherlands, in 2008 nearly 73% of the males in the age of 65 years and older were normotensive and taking medication that might alter the cardiovascular or thermoregulatory responses[50]. It is possible that the differences in thermal physiology and thermal comfort, between the majority of the elderly population and the young adults, are larger than we report in this study.

2.5 Conclusions

In the present study the differences between young adults and elderly in thermal comfort, productivity and thermal physiology in response to a moderate temperature drift have been investigated. From the presented results the following conclusions can be drawn:

(1) Thermal sensation of the elderly is in general 0.5 scale units (on a 7-point thermal sensation scale) lower than thermal sensation of younger adults.
(2) During a constant temperature level and equal clothing level, elderly prefer a higher ambient temperature in comparison to their younger counterparts, which is in line with previous studies.
(3) In this study, the PMV model was capable to predict thermal sensation (TS) of young adults in response to a moderate temperature drift which is in line with results obtained by previous studies. For elderly, the model is capable to predict the trends in thermal sensation. However, the thermal sensation vote is overestimated with 0.5 scale units; and therefore, for example, the predicted TS corresponds to a sensation equal to neutral, while they will actually feel slightly cool.
(4) Although the subjects were feeling less comfortable during the temperature drift in comparison to a constant temperature level, the conditions did not lead to unacceptable situations, i.e. the studied conditions were not unacceptable uncomfortable. Furthermore, productivity was not negatively influenced by the temperature changes. Therefore, a temperature drift up to ±2 K/h in the range of 17-25°C is assessed as applicable and will not lead to unacceptable conditions.

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Chapter 3

The prediction of thermal sensation

a mathematical model based on neurophysiology

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The lay-out has been adjusted to fit the style of this thesis.

Abstract

Thermal sensation has a large influence on thermal comfort, which is an important parameter for building performance. Understanding of thermal sensation may benefit from incorporating the physiology of thermal reception. The main issue is that humans do not sense temperature directly; the information is coded into neural discharge rates. This manuscript describes the development of a mathematical model of thermal sensation based on the neurophysiology of thermal reception. Experimental data from two independent studies were used to develop and validate the model. In both studies, skin and core temperature were measured. Thermal sensation votes were asked on the seven point ASHRAE thermal sensation scale. For the development dataset, young adult males (n=12, 0.04 Clo) were exposed to transient conditions; T_{air} 30-20-35-30°C. For validation, young adult males (n=8, 1.0 Clo) were exposed to transient conditions; T_{air}: 17-25-17°C. The neurophysiological model significantly predicted thermal sensation for the development dataset (r^2=0.89, $p<0.001$). Only information from warm-sensitive skin and core thermoreceptors was required. Validation revealed that the model predicted thermal sensation within acceptable range (root mean squared residual=0.38). The neurophysiological model captured the dynamics of thermal sensation. Therefore, the neurophysiological model of thermal sensation can be of great value in the design of high-performance buildings.

3.1 Introduction

Thermal comfort, determined by the influence of the indoor environmental parameters on thermal sensation, is regarded as an important performance indicator of building performance. Therefore, accurate mathematical models of thermal sensation are extremely useful in design of new high-performance buildings. Recently, de Dear[1] reintroduced the concept of 'thermal alliesthesia', which deals with the neurophysiological mechanisms responsible for thermal sensation. According to de Dear, with the concept of alliesthesia it should be possible to explain in the future: 'why occupants of today's so called sustainable buildings can enjoy positive indoor environmental quality in indoor climates that would have failed the criteria established under yesterday's standards of thermal comfort'.

In this study we aim to expand the synthesis between neurophysiology and mathematical modeling to make a better prediction of the thermal sensation. One of the key principles in the neurophysiology of thermal reception is that humans do not sense temperature directly. Temperature information is coded into the firing rate of temperature-sensitive neurons (thermoreceptors). These neurons are found all over the body. Two types of thermoreceptors can be distinguished: 'cold' or 'warm' sensitive (see Figure 3.1). Skin contains both types of thermoreceptors, whereas deeper laying tissues (e.g. intestines, spinal cord, and hypothalamus) contain mostly warm-sensitive thermoreceptors[2].

The main hypothesis is that through simulation of the neurophysiological pathways the dynamics of thermal sensation can be captured. Therefore, we developed a new model for thermal sensation based on the neurophysiology of thermal reception and integration through neural pathways.

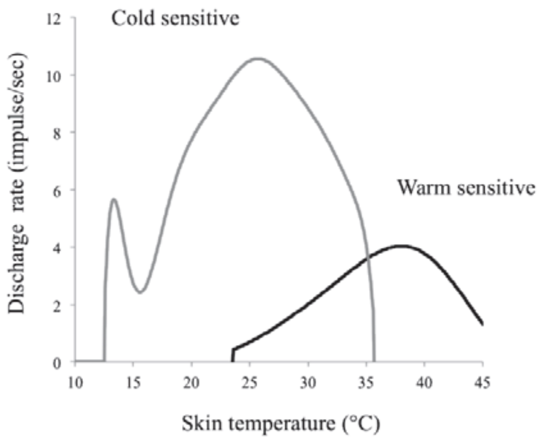

Figure 3.1 Averaged steady state neuron discharge rate vs. skin temperature for cold sensitive (gray line) and warm sensitive (black line) neurons of cat tongue (after Mekjavic and Morrison[3] and Zotterman[4])

Context

Both thermal comfort and energy use play an important role in the performance of a building. About one-third of the primary energy used in developed countries is consumed by heating, ventilating, and air conditioning in residential, commercial, and public buildings[5]. This reveals the high importance of reducing the energy use in buildings. However, satisfaction of the occupants with their thermal environment mainly determines the success of the application of low-energy Heating Ventilation and Air Conditioning (HVAC) systems. Much effort has been taken to design optimal energy HVAC systems; this resulted in among others, low temperature heating systems, high temperature cooling systems, different ventilation principles, etc. However, the Annex 37[6] study revealed that an optimal energy use does not always results in an increased comfort level. Non-uniform thermal conditions, which may occur owing to application of low energy systems, can be responsible for discomfort (e.g. a low temperature floor heating system in combination with natural ventilation[7]. Contrary, Arens et al.[8] concluded that through asymmetrical and transient thermal environments, higher levels of thermal comfort could be achieved in comparison with steady-state uniform environments. Regarding transient environments, de Dear and Brager[9] concluded that satisfaction with the thermal environment does not mean that this environment has to be controlled at a constant indoor air temperature[9]. A study by Schellen et al.[10] confirms this statement. Furthermore, compared to a constant temperature, allowing the temperature to drift could be a means to reduce energy use.

To adequately design optimal environmental conditions in the future, both in an energy-friendly and comfortable way, more knowledge on the interaction between the system, indoor climate, and the human body is indispensable.

Thermal sensation

Thermal sensation and satisfaction with the thermal environment is a complex phenomenon, and therefore complicated to predict in the design phase. Owing to the large differences between persons, both psychological and physiological, it is difficult to satisfy everyone in the same room. Many researchers have studied the parameters that affect thermal sensation with the objective of developing a model to predict thermal sensation. The most used and referred model is the predicted mean vote (PMV) model of Fanger[11]. This model is included in current building standards to predict thermal sensation, and therefore often used to assess the thermal comfort in the design phase. This model intended to be a method that could be used by HVAC engineers to determine the optimum environmental conditions (combination of air temperature, mean radiant temperature, relative humidity, mean air velocity, activity level, and clothing) to satisfy the largest possible percentage of a given group of occupants. It was assumed that a person is most comfortable in a thermal neutral condition, which is defined as the condition wherein a person does not prefer either a colder or warmer environment.

Although this method is frequently used and implemented in building regulations, many researchers showed the limitations of the model, e.g. for differences between subpopulations (males/females, young/ older people, etc), thermal neutrality, expected discomfort, and driving mechanisms (dependent parameters), for thermal comfort[9 12-15].

According to de Dear[1], the PMV theory from Fanger led to the thermal comfort mantra 'cool, dry, still indoor air', which was achieved by static isothermal indoor climates. As described above, a growing interest is on dynamic non-uniform environments as they can provide an energy-saving potential, more comfortable environment, and probably healthier environment[1 16]. The above-mentioned studies indicate there is a need for new sensation models that cope with dynamic, transient environments and individual effects and requirements.

de Dear et al.[17] showed with a mathematical simulation that the discharge rate of skin thermoreceptors correlated to the change in thermal sensation during sudden temperature transitions[17]. Hence simulating the actual physiology of humans (i.e. neuron discharge rate instead of using skin temperatures) can be highly beneficial when designing buildings while optimizing energy costs and thermal comfort.

Neurophysiology of thermal reception

Most knowledge of thermoreceptor responses comes from experiments on isolated nerves of anesthetized animals (e.g. cats, rabbits, and primates); nevertheless, the fundamental properties of thermoreception also have been confirmed in man[18]. Still, the exact neuron discharge rate vs. temperature may differ substantially between species or between tissues. However, the general characteristics of thermoreception are assumed to be sufficient to serve the purpose of this study.

Zotterman et al.[4] reported the averaged nonlinear characteristic of thermoreceptor firing rates from steady-state temperature experiments on cat tongue. The maximum steady-state discharge rate for cold sensitive receptors lies around 25°C (11 impulses/s) and for warm-sensitive receptors the maximum firing rate lies around 38°C (4 impulses/s)[4 19]. Contrary, other researchers showed that in cat nose the maximum steady-state discharge rate for cold-sensitive receptors was at 27°C (9 impulses/s) and for warm-sensitive neurons the maximum was at 46°C (36 impulses/s)[20]. Therefore, it can be concluded that thermoreceptor data reported in literature differ considerably.

In addition to the steady-state discharge rate, time dependent changes in skin temperature (i.e. direction and rate of temperature change) also influence the discharge rate. For instance, warm-sensitive neurons increase their discharge rate when heated, and even more when strongly heated, whereas during cooling the discharge rate of warm-sensitive neurons is decreased (Figure 3.2).

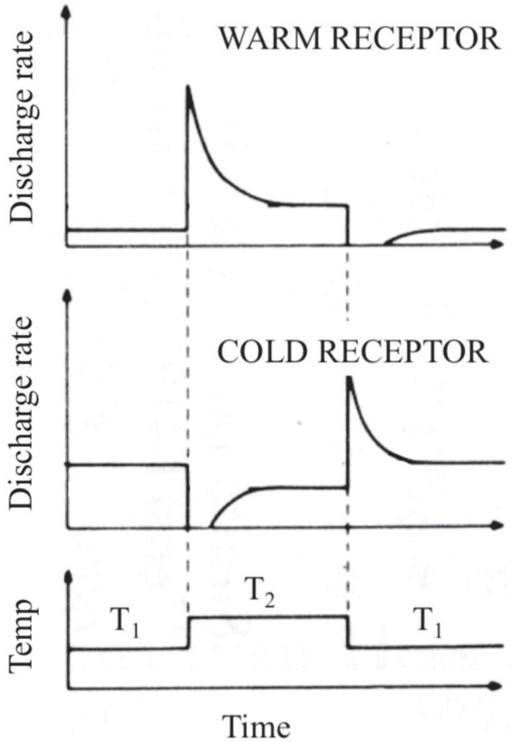

Figure 3.2 Schematic view of dynamic neuron discharge rate of temperature sensitive neurons. With increasing temperature warm thermoreceptors show an initial overshoot in discharge rate and cold thermoreceptors show an initial undershoot. Vice versa for decreasing temperature. Modified from Hensel[18].

The neural pathway from local thermal reception to thermal sensation is described in literature as follows[21 22]. (i) The thermoreceptors bring the information to the spinal cord (i.e. from peripheral skin and deep body tissues) and to the trigeminal nucleus (i.e. from face skin). (ii) From the dorsal horn (top of spinal cord) and trigeminal nucleus, second-order neurons project to the thalamus. This is a different pathway than for thermoregulation, because for thermoregulation the secondary neurons connect to the hypothalamus instead of the thalamus[22 23]. (iii) The thalamus projects to the insular cortex, which is presumed to be the brain area for perception and localization of thermal stimulus intensity[21].

3.2 Methods

The mathematical model developed in this study uses experimentally measured skin and core temperature as input variables. Temperature recordings were then transduced to their equivalent neuron discharge rate. Finally, the neuron discharge rates were correlated to the experimentally measured sensation votes.

Experiments

In this study, two data sets of independent experiments were used. The first data set was used for development of the model; the second data set was used for validation. In both studies, core temperature was measured with an ingested telemetric pill (Cortemp, HQ Inc., Palmetto, FL, USA). The skin temperatures were measured according to EN-ISO 9886[24] by wireless iButtons (Thermochron iButton DS1291H, Dallas Maxim) at the 14-points as proposed by EN-ISO 9886[24-26]. Thermal sensation votes were asked on a continuous seven-point thermal sensation interval scale, where each point on the line could be marked[27]. As a result, the thermal sensation could be assessed within ±0.05 scale unit of accuracy. The ASHRAE thermal sensation scale is represented in Table 3.1.

Table 3.1 Seven-point ASHRAE thermal sensation scale[27]

Thermal sensation	Corresponding term
-3	Cold
-2	Cool
-1	Slightly cool
0	Neutral
+1	Slightly Warm
+2	Warm
+3	Hot

For the development dataset, male participants were lying and wearing shorts only (0.04 Clo). Firstly, participants were exposed to baseline air temperature (30°C, 0.5h). Next, participants were exposed to mild cold followed by warm conditions (20°C, 1h; 35°C, 1h). Finally, participants were exposed to baseline conditions again for 1 h[28]. For the validation data set, male participants were sedentary and dressed (1.0 clo, including desk chair). The participants were exposed to a transient condition; temperature range: 17–25°C, duration: 8h, temperature drift: first 4 h: +2°C/h, last 4h: -2°C/h[10]. Thus, participants were exposed to considerably different conditions in both datasets. Subject characteristics are shown in Table 3.2.

Table 3.2 Subject characteristics in experiments used for model development and for validation

Thermal sensation	Model development (n=12)	Validation (n=8)
Age (year)	24.9±1.0	23.6±1.2
Mass (kg)	76.1±3.3	82.7±8.6
Height (m)	1.80±0.02	1.83±0.11
Body fat (%)	16.7±1.4	14.5±3.3
BMI (kg/m^2)	23.4±0.9	24.8±3.1

Modeling of thermal reception and neural pathways

For the development phase of the thermosensation model, skin temperature and core temperature recordings were used. First, the discharge rates of skin cold (*C*) and warm (*W*) thermal receptors and core warm (H_{warm}) receptors were calculated as described below.

Calculation of neuron discharge rate

As described in the introduction, different thermoreceptor data exist in literature. However, with respect to mathematical modeling of thermoreceptor data, only a study by Mekjavic and Morrison[3] was found. They based their mathematical neuron discharge rate model on the thermoreceptor data presented by Zotterman[4]. Therefore, the simulated discharge rate of temperature sensitive neurons at the periphery is modeled as a steady-state discharge rate and dynamic response to temperature changes and according to Mekjavic and Morrison[3]:

$$\boldsymbol{c_t = \left(\frac{1}{\Delta t}\right) \cdot \sum_j \left(S_{t-\Delta t} + \left(A_0\left(1 - exp\left(-\frac{j}{K}\right)\right) + DA\left(exp\left(-\frac{j}{K_e}\right) - exp\left(-\frac{j}{K_i}\right)\right)\right)\right)} \quad (3.1)$$

Here, c_t is the discharge rate for cold-sensitive neurons at timepoint t (w_t for warm-sensitive neurons), Summation over j from $j=0$ to Δt -1, $S_{t-\Delta t}$ is the steady-state neuron discharge rate at $t=t-\Delta t$, A_0 and A are gain factors that depend on the difference of steady-state discharge rates between two moments of time ($A_0=S_{t-\Delta t}-S_t$ and $A=5.0S_{t-\Delta t}|A_0|$). K=5.5, K_i=3.3, and K_e=5.5 are static, inhibitory, and excitatory gain factors, respectively. D is a sign operator indicating an excitatory or inhibitory response. When cold-sensitive neurons are heated, D is negative, when the same neurons are cooled, D is positive and vice versa for warm-sensitive neurons. The steady-state discharge rate of neurons is calculated as:

$$S_t = \sum_j X_j T^j \quad (3.2)$$

where x_j is the *j*-th order coefficient as given in Table 3.3 and *T* is the local temperature. The steady state response of core temperature neurons is also calculated according to Mekjavic and Morrison[3] by shifting measured core temperature by -2°C.

Local skin temperatures were used instead of mean skin temperature; using mean skin temperature would lead to significant errors in calculation of the average discharge rate of temperature-sensitive neurons, owing to the nonlinear characteristic of neuron discharge rate vs. temperature. For instance, the average discharge rate of two cold-sensitive neurons with temperature (T_1 = 20°C and T_2 = 30°C) is not equal to the discharge rate of a neuron with temperature T_{mean} = 25°C (see Figure 3.1). Local neuron discharge rates are integrated at the spinal cord. This is calculated by averaging neuron discharge rate over skin positions ($P_{warm} = \sum W/n$ and $P_{cold} = \sum C/n$). Here, P_{warm} and P_{cold} (P stands for peripheral) are the averaged (i.e. integrated) peripheral warm and peripheral cold discharge rates and n is the number of positions where skin temperature is experimentally measured. From the horn (i.e. top of spinal cord), second-order neurons project to the thalamus and from the thalamus further to the insular cortex. There the thermal information from the body core (H_{warm}) and skin (P_{cold} and P_{warm}) is integrated. Some hypotheses on the neural pathways involved in thermal sensation exist[9 29]. Therefore, we developed several models where the subject averaged thermal sensation vote was used as a dependent variable (see Table 4). Each model represents a different hypothesis, or assumption, of the neural pathway involved in thermal sensation. All variables are expressed in the discharge rate unit 'impulses per second'. Therefore, the model coefficient signs define excitation and inhibition within the neural pathway, a positive sign denotes excitation and a negative sign denotes inhibition. The first model is based on the assumption that only skin thermoreception contributes to thermal sensation[1]. The second model assumes that all three forms of thermoreception (i.e. skin cold thermoreception, skin warm thermoreception, and core warm thermoreception) project individually to the thermal sensation[29]. The third model assumes that core body thermoreception and skin warm thermoreception contribute to thermal sensation. Finally, the fourth model assumes that core body thermoreception and skin cold thermoreception contribute to thermal sensation.

The neuron discharge rates were correlated to the experimentally measured sensation votes by multiple regression analysis. All calculations were performed using Matlab 2010a for Mac. Only one model was selected for validation against the independent data set. Model selection for validation was based on the following criteria: (i) all B-coefficients significantly differed from zero (ii) highest explained variance (i.e. highest r^2-value).

Table 3.3 Coefficients to calculate the static neuron discharge rate of cold and warm sensitive neurons [values are modified from Mekjavic and Morrison[3]

Coefficient	Cold sensitive neuron	Warm sensitive neuron
x_0	-0.19005313e-6	0.1526647e-5
x_1	0.85318078e-5	-0.5147704e-4
x_2	-0.16974919e-5	0.7707699e-3
x_3	0.19724509e-4	-0.67475955e-2
x_4	-0.14833377e-3	0.38244284e-1
x_5	0.75486723e-1	-0.14664175e-0
x_6	-0.26343323e-0	0.38526706e-2
x_7	0.62289589e-2	-0.68496075e-4
x_8	-0.95563808e-4	0.78889647e-6
x_9	0.85949930e-6	-0.53173142e-8
X_1	-0.34432887e-8	0.15936041e-10

Table 3.4 Thermosensation models that were tested on experimental data

$S = B_0 + B_1 P_{cold} + B_2 P_{warm}$	(1)
$S = B_0 + B_1 H_{warm} + B_2 P_{cold} + B_3 P_{warm}$	(2)
$S = B_0 + B_1 H_{warm} + B_2 P_{warm}$	(3)
$S = B_0 + B_1 H_{warm} + B_2 P_{cold}$	(4)

S is the thermal sensation vote as defined on the seven-point ASHRAE scale for thermal sensation. H_{warm} (impulse/s) is the neuron discharge rate corresponding to measured core temperature. P_{cold} (impulse/s) is the averaged neuron discharge rate of skin cold sensitive thermoreceptors. P_{warm} (impulse/s) is the averaged neuron discharge rate of skin warm sensitive thermoreceptors.

Validation

The thermo sensation model was validated by calculation of the root mean squared residual (RMSR) between model prediction and measured sensation votes of the validation data set. The model prediction quality was considered acceptable when RMSR<1, thus the model prediction should be within 1-scale points of the measured sensation vote. This value was based on a power calculation to have 95% chance to detect a significant error in model prediction using n=8 subjects for validation. Given the variation in sensation votes as estimated from the development dataset, a statistical detection power of 95% is feasible when the average prediction error ≥1-scale unit. The power calculation for the 'one-sample test' is as follows:

$$Z_\gamma = \sqrt{\frac{n\delta^2}{\sigma^2}} - Z_{0.5\alpha} \tag{3.3}$$

Here, Z_{γ} is the value of the standard normal distribution corresponding to the type II error rate (power=1-γ=0.95), n is the sample size (n=8), δ is the prediction-error, σ is the standard deviation as estimated from the development dataset and $Z_{0.5\alpha}$ is the value of the standard normal distribution corresponding to the type I error rate (α=0.05).
Model prediction was performed by repetition of the thermoreceptor discharge rate calculation procedure as described in the model development phase. However, now, skin and core temperature data from the validation data set were used.

3.3 Results

Model development phase
Regression analysis revealed that all models, each with different assumptions on the neural pathways, significantly explained the thermal sensation vote (see Table 3.5). However, only in model 3 and model 4 did all B-coefficients differ significantly from zero. In models 2 through 4, the core warm thermoreception pathway had a significant negative contribution to the thermal sensation. Hence, during the mild thermal challenge, a decrease in core temperature related to a warm thermal sensation. In model 3, the skin warm thermoreception pathway had a significant positive contribution to the thermal sensation. Thus, warm or heated skin related to a warm thermal sensation. Vice versa, in model 4, the skin cold thermoreception pathway had a significant negative contribution to the thermal sensation, such that cold or cooled skin related to a cold thermal sensation. The measured sensation votes and the prediction of model 3 on the development data set are shown in Figure 3.3.

Table 3.5 Regression coefficients ±95% CI (B's) with the corresponding variable, explained variance (r^2), and P-value of sensation models during development phase

Model	B_0	B_1	B_2	B_3	r^2	P-value
1	-0.12±55.1	-0.6±4.3 (P_{cold})	1.9±9.6 (P_{warm})		0.81	$<1.8x10^{-6}$
2	36.4±49.6	-14.8±9.6 (H_{warm})*	0.7±3.5 (P_{cold})	3.9±7.7 (P_{warm})	0.89	$<2.1x10^{-7}$
3	44.0±32.8*	-14.3±9.0 (H_{warm})*	2.3±0.9 (P_{warm})*		0.89	$<2.5x10^{-8}$
4	56.1±30.7*	-13.9±9.4 (H_{warm})*	-1.0±0.4 (P_{cold})*		0.87	$<8.2x10^{-8}$

*p<0.05

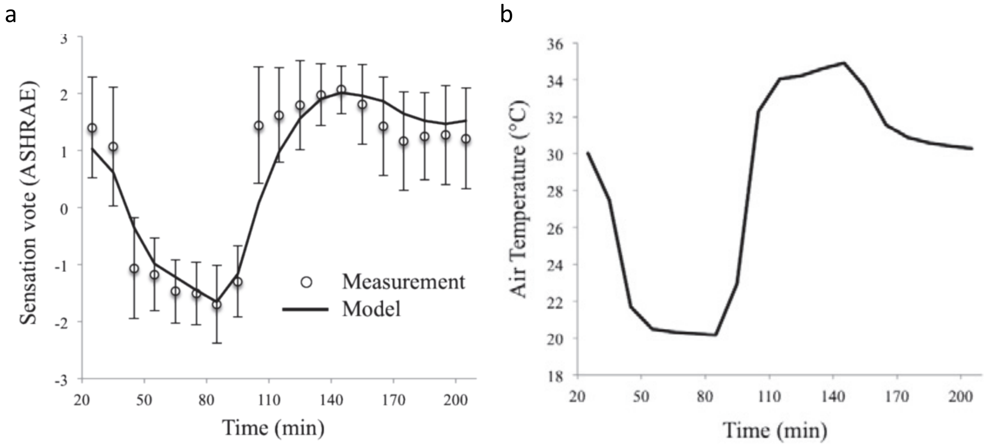

Figure 3.3(a) Averaged sensation votes and model fit (Model 3) of the development data set. Error bars represent the standard deviation **(b)** Thermal condition to which participants were exposed.

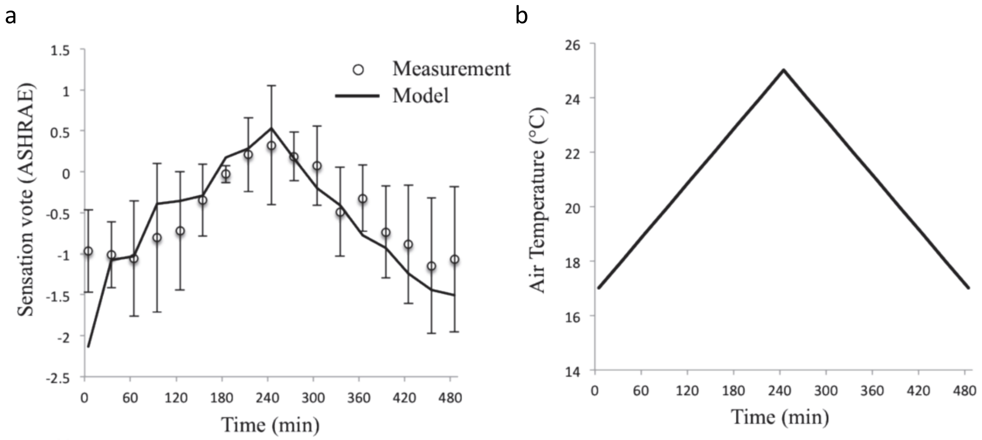

Figure 3.4(a) Averaged sensation votes and model prediction (Model 3) on the validation data set. Error bars represent the standard deviation **(b)** Thermal condition to which participants were exposed.

Model validation phase

Model 3 was selected for the validation phase as it best explained the variation (r^2=0.89). The sensation votes of the validation set and the model prediction are shown in Figure 5.4. The root mean square error (RMSR) of the thermal sensation prediction on the validation set was 0.38, which means that on average there was a 0.38 prediction error in thermal sensation. The maximum error observed was 1.16 scale points at the beginning of the experiment. The minimum error observed was 0.02 scale points at t=100 min. In general, the model predictions were within the standard deviation of the measurements.

3.4 Discussion

In this study, a mathematical model of thermal sensation based on neurophysiology was validated on an independent dataset. The results indicate that the simulation of the neural pathways was able to capture characteristics of thermal sensation. Such a model of human thermal sensation can be of great value in designing of high-performance buildings.

A comfortable environment could be described as an environment where the average rating of a group of persons is between -1 and +1 on the ASHRAE thermal sensation scale[11 25]. The model developed in this study was able to predict thermal sensation within 0.5-scale unit accuracy for both datasets (development and validation). Foda et al.[30] found for four different thermal sensation models a discrepancy between predicted and measured overall thermal sensation within ±1.0 scale unit. Thus, the model presented in this paper provides a greater accuracy and therefore more detailed information can be obtained regarding the overall thermal sensation. In practice, this could be beneficial because small deviations from a neutral thermal sensation (i.e. an overshoot or undershoot in thermal sensation) could provide a more comfortable thermal environment[14 15].

In current building practice, the PMV model of Fanger[11] is used to predict the future thermal sensation of occupants. However, as mentioned in the introduction this model has limitations regarding the prediction of thermal sensation (e.g. for different subpopulations). Van Hoof et al.[31] concluded in an extensive literature review that multi-segmental models of human physiology have a large potential to predict high-resolution thermal sensation of occupants in both the design phase of a building and laboratory conditions[31]. Especially, a large potential exists for complex environments regarding non-uniform and transient conditions which, in the end, could turn out to be the most comfortable environments[1]. However, van Hoof et al. also concluded that it is a great challenge to link the outcomes of a thermophysiological model to thermal sensation.

Until now, few studies have been available where physiological responses are related to thermal sensation. All current models require a body temperature setpoint to simulate thermal sensation. Fiala[32] developed the dynamic thermal sensation (DTS) model to predict the dynamic thermal sensation based on core temperature, mean skin temperature, and rate of change in mean skin temperature[32]. Another study conducted by Zhang et al.[33-35] related physiological responses to local thermal sensation based on differences between local skin temperature and the setpoint of skin temperature for a specific body part, rate of change in local skin temperature, and rate of change in core temperature[33-35]. Although these models show promising results, one could argue whether setpoints are a good representation of the physiology behind thermoregulation or thermal sensation[36 37].

In this study, a thermal sensation model was developed based on the neurophysiology of thermal reception and neural integration. Several hypotheses of the neural pathways that predict thermal sensation were tested (see Table 3.5). Interestingly, the best model only required thermal information from warm-sensitive receptors of skin and core. The reason for this becomes clear after analysis of simulated core and skin thermoreception over time. Figure 3.5 shows the simulated neuron discharge rate for core warm receptors (H_{warm}) and integrated skin cold (P_{cold}) and warm (P_{warm}) receptors. The signals of P_{cold} and P_{warm} are almost mirrored images of each other; therefore, both signals contain the same information. It is possible that in more extreme situations (colder, hotter, or larger temperature changes), information of both cold and warm skin receptors is necessary to correctly predict thermal sensation. For instance, when skin temperature decreases below 26°C, temperature information is dominated by the discharge rate of skin cold-sensitive thermoreceptors (Figure 3.1): the discharge rate of warm-sensitive thermoreceptors decreases to zero. Likewise, above 35°C, virtually no skin cold thermoreceptor input is generated, and all information is coded by skin warm thermoreceptors (Figure 3.1). In more neutral environments, however, skin warm and cold thermoreceptors seem to reveal the same. To the best of our knowledge, only one other study correlated thermal reception to thermal sensation[17]. de Dear et al.[17] showed that the change in thermal sensation correlated to the discharge rate of both cold and warm skin thermoreceptors during a sudden ambient temperature transition. The authors did not report correlations to absolute sensation votes. The results presented in this paper suggest that apart from skin thermal reception, absolute thermal sensation is also dependent on warm core thermoreceptors. It could be that skin thermoreceptors correlate well to changes in thermal sensation, yet the core thermoreceptors are important for an absolute 'basal' level of thermal sensation. We will again illustrate this with Figure 3.5. This figure shows that there is a delayed response of the core thermoreceptors relative to the skin thermoreceptors (t=30–90 min). The warm core thermoreceptors decrease their discharge rate (Figure 3.5b), while skin thermoreception already returned to near baseline values (Figure 5c). Note that the delay of core thermoreception might differ depending of the exact site and method of core temperature measurement[23 38]. Owing to the slow response, abdominal core thermoreception cannot be associated with thermal sensation during sudden ambient temperature transitions. However, during rewarming, the afterdrop in core temperature is clearly visible in the core warm thermoreception. An afterdrop in core temperature is caused by the return of cooled blood from the peripheral tissues[39]. Although the range of the discharge rate change for core warm thermoreceptors is not as large as for skin warm thermoreceptors (H_{warm}: 3.4–3.5 pulse/s and P_{warm}: 1.9–3.1 pulse/s), the associated weight (B) is considerably larger for core thermoreception than for skin thermoreception (B_{Hwarm} = -14.3 and B_{Pwarm}=2.3), which evens out the difference in discharge rate. Hence, core thermoreception has a large long-lasting influence on thermal sensation and skin thermoreception has a fast changing influence on thermal sensation. The negative sign of the core warm thermoreception pathway model coefficient may seem counter-intuitive at first, because it suggests that a decrease in core temperature relates to a warm thermal sensation. However, during the mild thermal challenge, core temperature remained stable during mild cold, yet during rewarming, core temperature dropped on average by 0.3°C[28]. A paradoxical decrease in core temperature during rewarming or an increase in core temperature during mild cold has been described in physiological literature[23 40]. The inverse relation between core temperature change and thermal sensation during a mild thermal challenge might be part of thermal alliesthesia, as during stable conditions a high core temperature is associated with a warm thermal sensation and thermal discomfort[41]. Another issue for thermal alliesthesia relates to the dominance of thermoreception to thermal sensation. When the thermal environment continuously changes, there is a large contribution of thermoreception to the overall thermal sensation. This can be explained by the importance of detecting changes in the thermal environment to maintain thermal homeostasis. However, when the ambient environment is more stable, the relative influence of non-thermal factors may increase. Therefore, thermoreception and thermal sensation may have a stronger coupling during thermal transients relative to stable thermal conditions. Overall, this suggests that the currently developed model may be suitable for predicting thermal sensation during transient thermal conditions, yet less so during stable thermal conditions.

The model presented in this study relies on simulated neuron discharge rate. In literature, different experimentally measured thermoreceptor data exist. For instance, a study by Hensel and Kenshalo[20] showed a near 10-fold increase in the maximum steady-state discharge rate of warm-sensitive neurons in comparison with the data presented by Zotterman[4] (36 impulses/s vs. 4 impulses/s, respectively). Especially during transient conditions, such differences could have a large impact on model performance, which is mainly because the magnitude of the dynamic response scales with the difference between two steady-state discharge rates. For instance, when a warm-sensitive neuron is heated using the data presented by Hensel and Kenshalo[20], a higher steady-state discharge rate would also result in a larger dynamic response. Vice versa, when a warm sensitive neuron is cooled, its discharge rate is also suppressed more. Theoretically, cooling could even nullify the discharge rate of warm-sensitive neurons, leaving only cold-sensitive neurons to obtain information on the thermal status of the body. Therefore, future studies should elucidate how using different thermoreceptor data might alter the results of this study.

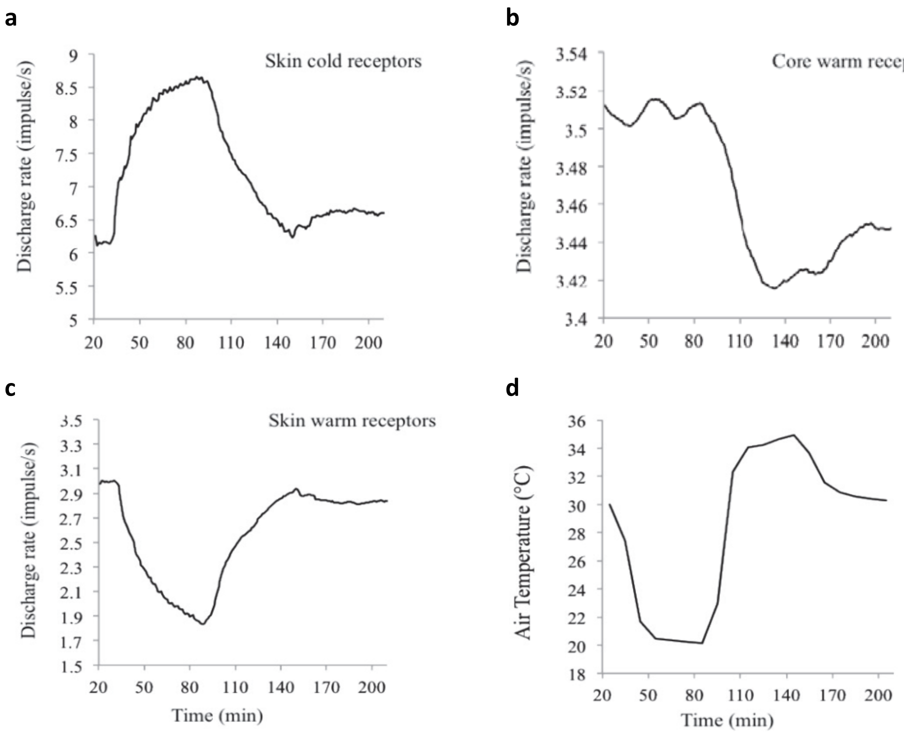

Figure 3.5 Simulated thermoreceptor discharge rates of: **(a)** skin cold thermoreceptors (P_{cold}); **(b)** core warm thermoreceptors (H_{warm}); and **(c)** skin warm thermoreceptors (P_{warm}) **(d)** The thermal condition participants were exposed to.

In summary, the neurophysiological approach for developing a mathematical thermal sensation model as presented in this paper offers a method to predict the thermal sensation under complex non-uniform and transient mild thermal environments. Furthermore, this approach can be extended to a thermal sensation prediction on a local body part level; however, more research is needed for this. Therefore, future work should focus on:

- relative importance of specific skin areas to whole body thermal perception,
- relative importance of core temperature measurement site to thermal perception,
- thermoreception in more extreme environments (e.g. colder, warmer, and larger temperature changes),
- steady-state thermoreception characteristics,
- inclusion of other subpopulations such as, females, older people, or people with obesity,
- application of local thermoreception to local comfort.

3.5 Conclusion

In this study, a new model for predicting thermal sensation is developed. This model is based on the neurophysiology of thermal reception. The model is validated on an independent dataset. The only dependent parameters for thermal sensation in the model are core body warm thermoreception and skin warm thermoreception. The model was capable to significantly predict thermal sensation within 0.5-scale unit accuracy for both the development dataset and the validation dataset. In current building practice, an accuracy of ±1.0 is considered as acceptable. Though, rather small deviations from optimum (neutral), <1.0- scale unit could provide a more comfortable thermal environment and occupants would therefore be more satisfied with their environment. The presented method can be highly beneficial for predicting thermal sensation under complex environments with respect to non-uniform and transient environments, especially in combination with thermophysiological models to link physiological responses to thermal sensation. Therefore, the neurophysiological model of thermal sensation can be of great value in the design of high performance buildings.

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PART II

NON-UNIFORM ENVIRONMENTS

Chapter

4

Gender differences

in physiology, thermal comfort and productivity during passive and active cooling - the influence of local effects on thermal sensation under non-uniform environmental conditions

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The lay-out has been adjusted to fit the style of this thesis.

Abstract

Applying high temperature cooling concepts, i.e. high temperature cooling (T_{supply} is 16-20°C) HVAC systems, in the built environment allows the reduction in use of (high quality) energy. However, application of high temperature cooling systems can result in whole body and local discomfort of the occupants. Non-uniform thermal conditions, which may occur due to application of high temperature cooling systems, can be responsible for discomfort. Contradictions in literature exist regarding the validity of the often used predicted mean vote (PMV) index for both genders, and the index is not intended for evaluating the discomfort due to non-uniform environmental conditions. In some cases, however, combinations of local and general discomfort factors, for example draught under warm conditions, may not be uncomfortable.

The objective of this study was to investigate gender differences in thermophysiology, thermal comfort and productivity in response to thermal non-uniform environmental conditions. Twenty healthy subjects (10 males and 10 females, age 20-29 years) were exposed to two different experimental conditions: a convective cooling situation (*CC*) and a radiant cooling situation (*RC*). During the experiments physiological responses, thermal comfort and productivity were measured. The results show that under both experimental conditions the actual mean thermal sensation votes significantly differ from the PMV-index; the subjects are feeling colder than predicted. Furthermore, the females are more uncomfortable and dissatisfied compared to the males. For females, the local sensations and skin temperatures of the extremities have a significant influence on whole body thermal sensation and are therefore important to consider under non-uniform environmental conditions.

4.1 Introduction

Thermal comfort is an important aspect regarding the satisfaction of occupants with their environment, and therefore regarded as an important building performance indicator. Thermal comfort is a complex phenomenon and it is therefore difficult to satisfy everyone in the same room when no options are allowed to adapt to the conditions. This is due to the large differences between persons, both psychological and physiological. However, during the design phase of a building it is useful to predict the thermal comfort of the occupants in advance. Fanger[1] studied the thermal conditions necessary to achieve thermal comfort. His studies resulted in the PMV (Predicted Mean Vote) index, expressed as the predicted thermal sensation on the 7-point ASHRAE thermal sensation scale[2], under uniform environmental conditions for a group of persons. This index is based on environmental parameters, activity level (metabolic rate) and clothing insulation, and are included in standards regarding the assessment of thermal comfort[2 3]. These guidelines are widely used by heating and air-conditioning engineers to prescribe and design the thermal environment[4]. Although Brager and de Dear[5] and Humphreys and Nicol[6] showed a good agreement between the PMV and actual mean votes in mechanical conditioned buildings, other studies found a discrepancy between the PMV and the actual thermal sensation[4 7 8] . These studies argue that differences, among others, are caused by gender and age. According to Fanger[1] females and males have similar preferred thermal neutral temperatures and therefore would prefer the same boundary conditions to achieve thermal comfort. Yet, other results show that the thermoneutral zone of women is shifted upward in comparison to men[9]. Karjalainen[10] concluded from an extensive literature study that in more than half of the studies where females and males have been compared with respect to thermal comfort, females expressed more dissatisfaction than males for the same thermal environments. Furthermore, he found that females are more sensitive to fluctuations around the optimum temperature in comparison to men. Fanger[1] found this as well, but these differences were considered insignificant. However, Karjalainen[10] states, based on literature, that we should not longer neglect the differences in gender while designing indoor environments.

In addition to occupant satisfaction, the energy-use of a building is an important performance indicator as well since one-third of the primary energy in developed countries is used for heating, ventilation and air-conditioning of buildings[11]. The Annex 37[12] study revealed that an optimal energy use not always results in an increased comfort level. Non-uniform thermal conditions (e.g. vertical temperature differences), which may occur due to application of low energy systems, can be responsible for discomfort[13]. In some cases, combinations of local and general discomfort factors, for example draught under warm conditions, may not be uncomfortable[14]. Under asymmetrical thermal environments higher levels of thermal comfort could furthermore be achieved in comparison to uniform environments[15 16].

It is important to assess thermal comfort adequately in the design phase, to avoid discomfort when the building is erected and in use. In general, the combined effects of convective flows and radiant asymmetries play an important role in the assessment of thermal comfort and are therefore important to study. Yet, the relations between local thermal sensation and comfort, and whole body thermal sensation and comfort, and differences in gender under moderate thermal environments remain unclear. More knowledge on the interaction between the system, indoor climate and human body is indispensable to design optimal systems in the future. Since cooling is becoming increasingly important regarding the conditioning of residential, commercial and public buildings[17], the objective of this research was to study the effects of different cooling principles (convective, in terms of increased air velocity, and radiant, in terms of applying a cold radiant panel) on human local and whole body thermal comfort, physiological responses and productivity. Furthermore, emphasis is on gender differences since several studies have shown that thermal perceptions significantly differ between males and females; which may result in different thermal neutral and comfortable conditions for both genders[4 10 18-21].

4.2 Methods

Subjects

Twenty young adults (20-29 years; 10 M, 10 F) participated in the experiment; their characteristics are presented in Table 4.1. All subjects were healthy, normotensive, non-obese, non-smokers and not taking any medication which might alter the cardiovascular or thermoregulatory responses. Eight female subjects were taking oral contraceptives and therefore their hormone level is controlled during the whole menstrual cycle which resulted in an internal body temperature equal to that of females without contraceptives in their luteal phase[22]. Two female subjects who were not taking contraceptives were therefore studied during the luteal phase of their menstrual cycle. Body fat percentage was determined, according to the Siri equation, by means of skinfold thickness[23]. Skin folds were measured at four sites: subscapular, suprailiacal, and at the triceps and biceps[24]. Subjects refrained from alcoholic beverages in the evening and morning prior to the test, but were allowed to eat a small breakfast. During the experiments, the subjects wore standardized clothing, consisting of jogging pants, polo shirt, underpants, socks and low heeled shoes. Clo-values were determined using EN-ISO 9920[25], McCullough et al.[26] and McCullough et al.[27]. The total thermal resistance of the clothing ensemble, including desk chair, was calculated to be 0.6 clo. The subjects continuously performed office tasks; their metabolic rate was estimated to be approximately 1.2 met[3].

The volunteers were given detailed information regarding the purpose and the methods used in the study, before written consent was obtained. However, they were not informed on the actual conditions they were exposed to.

Table 4.1 Subject characteristics

Subject characteristics	M (n=10)	F (n=10)	P value
Age (year)	24.7±2.0	24.0±1.6	N.S.
Height (cm)	181.8±8.34	169.6±8.68*	P < 0.03
Mass (kg)	77.3±8.5	64.7±9.2*	P < 0.02
BMI (kg/m^2)	23.5±3.4	22.5±2.5	N.S.
Whole body fat% (%)	16.3±4.7	18.3±6.3	N.S.

Values are presented as mean ± SD
M males, *F* females, *BMI* body mass index
*Significant difference between genders ($p < 0.05$)

Experimental conditions

Two different cooling cases were studied; cooling through convection (CC) and cooling through radiation (RC). Convective cooling occurred through an increased air velocity, where the supply temperature equaled the room temperature. Radiant cooling occurred through applying a cold radiant panel (ceiling). Both cases were designed to achieve a predicted neutral thermal sensation (PMV≈0).

CC –Cooling through convection

Olesen[14] has shown that an increased air velocity (draught under warm conditions) is not necessarily uncomfortable and can provide a comfortable cooling situation. Furthermore, if air-conditioning is not necessary within certain temperature limits, allowing an increased air-velocity around the occupant for cooling purposes could reduce the energy-use. The case characteristics of case *PC* are given in Table 4.2, separated for male and female subjects. The measured air velocities during the measurements with females were higher because of practical limitations regarding the adjustment of the surface area. Males also joined in another experiment. Therefore the switching of the inlet surface area differed between males and females.

Table 4.2 Case summary, Case *CC*

Variable	M (n=10)	F (n=10)
Operative temperature [°C]	25.2±0.2	25.3±0.2
Air temperature [°C]	25.5±0.2	25.5±0.3
Relative humidity [%]	34.1±1.1	32.4±0.9
Air velocity [m/s]	0.23±0.03	0.32±0.02
Wall temperature [°C]	25.0±0.1	25.1±0.3
Floor temperature [°C]	24.9±0.1	25.2±0.1
Ceiling temperature [°C]	25.0±0.1	25.1±0.4
Mean radiant temperature [°C]	25.0±0.1	25.1±0.2
PMV [-]	0.3±0.05	0.1±0.07

Values are presented as mean ± SD

RC –Cooling through radiation by the ceiling

Radiant ceiling panels are considered as an interesting alternative to active convective cooling (supplying cold air) to improve thermal comfort and to reduce the energy consumption in buildings[28 29]. Furthermore, they can be used during winter for heating. These panels impose a non-uniform thermal environment, introduce temperature asymmetries and can cause vertical temperature gradients[12 29]. The exposure conditions for the *RC* condition are given in Table 4.3. The setup conditions for the *RC* case were designed to achieve a PMV-index of 0. As supply air temperature conditions where controlled at the corresponding operative temperature, the floor temperature was raised to compensate for the cooling provided by the ceiling. The resulting vertical temperature gradient and radiant asymmetry can cause a percentage of dissatisfied (PD) due to local discomfort according to EN-ISO 7730[3]. As it can be derived from results shown in Table 4.3, the vertical air temperature difference and radiant asymmetry (cold ceiling) where within the PD<10% range.

Table 4.3 Case summary, Case *AC*

Variable	M (n=10)	F (n=10)
Operative temperature [°C]	24.4±0.1	24.3±0.1
Air temperature [°C]	24.2±0.1	24.1±0.1
Air velocity [m/s]	0.14±0.01	0.13±0.00
Relative humidity [%]	33.3±1.0	32.7±0.1
Wall temperature [°C]	23.6±0.0	23.2±0.1
Floor temperature [°C]	28.9±0.1	28.9±0.0
Ceiling temperature [°C]	18.0±0.2	17.9±0.1
Mean radiant temperature [°C]	24.7±0.0	24.5±0.1
Δ Plane radiant temperature (floor – ceiling) [°C]	8.1±0.2	8.3±0.1
Δ Air temperature Left (1.1m - 0.1m) [°C]	0.6±0.0	0.7±0.0
Δ Air temperature Right (1.1m - 0.1m) [°C]	0.4±0.0	1.0±0.0
PMV [-]	0.1±0.02	0.0±0.00*
PD Vertical air temperature difference [%]	Left:	Left:
	0.1±0.0	0.1±0.0
	Right:	Right:
	0.2±0.0	0.2±0.0
PD Cool Ceiling [%]	0.3±0.0	0.3±0.1

Values are presented as mean ± SD`
*p < 0.05 versus males

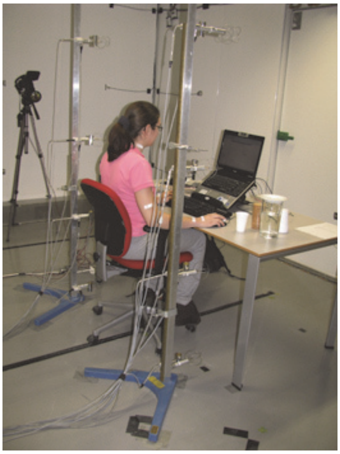
During both cases fresh air, conditioned by an air-handling unit (Verhulst Klimaattechniek BV, Drunen, The Netherlands) at a constant temperature of 24.5°C and 30% R.H., was supplied through mixing ventilation. The case differences between genders are considered small.

Protocol

Subjects visited the climate chamber (Figure 4.1) during winter [December 2010 - March 2011, average outside temperature ranged from -1.4 to 6.7°C[30]]. For this study, the subjects visited the climate chamber for four hours during the morning or afternoon. The male subjects, furthermore, visited the climate chamber two times more for another related experiment. The order of all cases was randomized. After written consent was obtained, the subjects swallowed a temperature telemetric pill and changed clothes. Next, the subjects performed a light exercise of 5 minutes to obtain skin vasodilatation in order to ensure that all subjects entered the climate room in an equal thermal state. Vasodilatation was assessed by the skin temperature difference between forearm and top of the forefinger[31 32]. Furthermore, the subject characteristics (height, weight, and fat percentage) were determined and the skin temperature sensors were attached.

After entering the climate room, the experiment started with an acclimatization period (30 min). During this period they received an instruction regarding the use of the questionnaires. After completion of the first case a new acclimatization period of 30 minutes followed (as preparation for the second case). During this period the subjects had the opportunity to visit the rest room. A detailed time line is given in Figure 4.2.

a



b

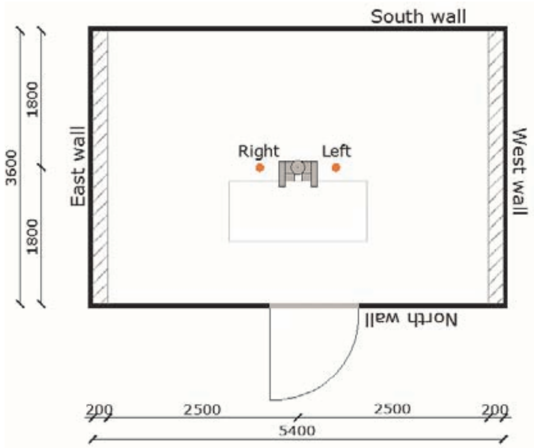


Figure 4.1 **(a)** test subject in experimental set-up; **(b)** floor plan where the orange dots indicate the measurement stands and the grey hatched surfaces represent the plenum boxes

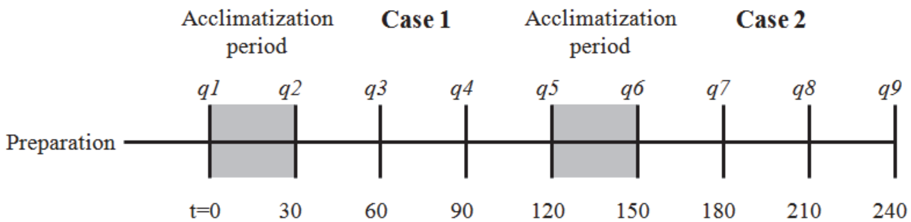


Figure 4.2 Time line of measurement protocol; q is representing the questionnaire moments

Measurements

Physical and physiological measurements

Skin temperature was measured at 1 min intervals by wireless iButtons (Thermochron iButton, DS1291H, Maxim, CA, Sunnyvale, USA, accuracy ±0.1°C) at 24 locations to assess possible differences between the left and right side of the human body[33]. Ibuttons were attached with semi-permeable adhesive tape (Fixomull; BSN medical gmbh, Hamburg, Germany). Mean skin temperature was calculated according to the 14-point weighing as proposed by EN-ISO 9886[34] (Point 1-14, Figure 4.3a). Distal skin temperature was calculated as average of instep, ankle, finger tip, hand, and forehead skin temperature. To avoid a disproportional distribution, forehead and instep temperature had a weighing factor of 2. Proximal skin temperature was calculated as an average of the scapula, paravertebral, upper chest, and abdomen skin temperature. Core temperature was determined by measuring the intestinal temperature at a 1 min interval through an ingestible telemetry pill

(CorTemp, Ingestible Core Body Temperature Sensor, HT150002, HQ Inc., Palmetto, FL, USA, accuracy ±0.1°C).

Air temperature (NTC Thermistor, type SC95, accuracy ±0.1°C), relative humidity (RH) (Humidity Sensors, Honeywell HIH- 4000 series), air velocity (hot sphere anemometer, Dantec, estimated accuracy 15%[35], surface temperature (NTC Thermistor, U-type EU-UU-10-PTFE, accuracy ±0.1°C) carbon dioxide (Carbon Dioxide Transmitter, Vaisala 0–2000 ppm), and illuminance (Lux meter, Hager model E2) were measured according to EN-ISO 7726[36]. Air temperature, RH, and air velocity were measured on two comfort stands at 0.1, 0.6, 1.1 and 1.7 m height. These comfort stands were placed on the left and right side of the subject, at a distance of 0.2m. The average surface temperature at each surface was derived from nine measurement points on each surface (at a grid of 3x3). The mean radiant temperature was determined according to the surface temperatures and view factors related to the position of the subject.

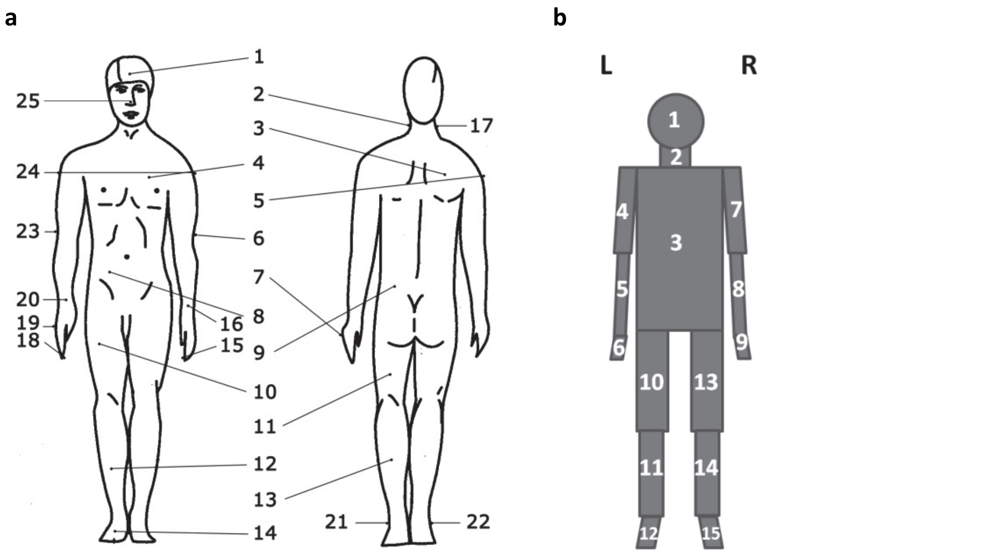


Figure 4.3 (a) Measurement sites skin temperature; **(b)** Schematic representation of body parts to assess local thermal sensation and comfort

Questionnaires

Every 30 minutes, starting at t=0 min, the test subjects filled in a questionnaire. Thermal sensation votes, both global and local for each body part (Figure 4.3b), were asked on a continuous 7-point ASHRAE thermal sensation interval scale, where each point on the line could be marked (Figure 4.4)[2]. Global and local thermal comfort were asked on a ISO-defined 4-point thermal comfort scale[37]. Visual analogue scales (VAS) were used to assess adverse perceptions and the perceived indoor environment[38]. A question to assess perceived stress was included as well.

Productivity was assessed using the Remote Performance Measurement (RPM) method[39]. Within this method, the productivity was estimated by two simulated office tasks: text typing and addition. The questionnaires and simulated office tasks were presented in Dutch to the subjects through an Internet browser.

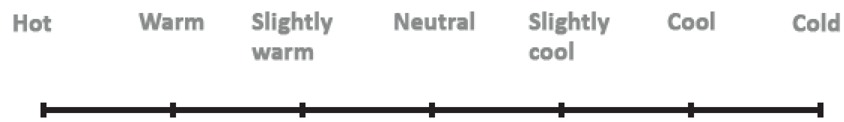


Figure 4.4 Continuous 7-point ASHRAE thermal sensation interval scale[2]

Data analysis

For the statistical analyses, physical and physiological responses of the whole measurement period, except the acclimatization period, were used (i.e. Case 1: t=30 to t=120 and Case 2: t=150 to t=240; Fig. 4.2). The subjective responses were analyzed from four questionnaires of each case (i.e. Case 1: q2-q5 and Case 2: q6-q9; Fig. 4.2). The differences in physical and physiological measurements were tested using ANOVA. Differences in subjective responses between the two experimental cases were studied using the non-parametric Wilcoxon signed-rank Test. Spearman-rho tests were used to study the correlations between local skin temperatures (averaged over 10 minutes; 5 minutes prior to the questionnaire and 5 minutes during the subjects filled in the questionnaire), local thermal sensations, and whole-body thermal sensation. Significant effects are reported for $p<0.05$. The commercially available software package PASW Statistics 18.0 (SPSS Inc., Chicago, USA) was used to analyze the data.

4.3 Results

Physiological measurements

Mean, distal en proximal skin temperatures of the females were significantly lower ($p<0.001$) than of males in both cases (*CC* and *RC*; Table 4.4 and Figure 4.5). Besides, mean core temperature of the females was significantly higher in comparison to the males in both cases (Table 4.4). Mean, distal and proximal skin temperatures of the males were significantly lower during *RC* in comparison to *CC*. Mean and distal skin temperatures of the females were significantly higher during *RC* in comparison to *CC*. Furthermore, female core temperature was significantly lower during *RC* in comparison to CC. The physiological responses of the males are constant during both cases (Figure 4.5). During *CC* case (Figure 4.5a) the mean, distal and proximal skin temperatures for females show a drop after t=80 while no increase in core temperature could be observed. During *RC* case (Figure 4.5b) the distal skin temperature of the females decreased during the experiment, which is caused by a decrease in skin temperature of the hands (increase in vasoconstriction, Figure 4.6). The extent of vasomotion, the difference (gradient) between fingertip and forearm temperature, during both cases for males and females is represented in Figure 4.6. Positive values indicate vasoconstriction (forearm temperature is higher than finger tip temperature), while negative values indicate vasodilatation.

The fingertip–underarm gradient for the females reflects continuously vasoconstriction during both cases at both the left and right side of the body. Furthermore, the right side of the body is significantly more vasoconstricted in comparison to the left side. For the males this effect was only observed during the *RC* case, the fingertip–underarm gradient at the right side was significantly higher in comparison to the left side (mean 1.2±0.58°C vs -0.4±0.58 respectively). The distribution of mean local skin temperatures during both cases, separately for males and females, is represented in Figure 4.7. The majority of the local skin temperatures of the females are significantly lower during both cases in comparison to the local skin temperatures of the males ($p<0.01$). The skin temperatures of arms and hands show the largest differences between males and females.

Table 4.4 Mean, distal and proximal skin temperatures of males and females during both experimental conditions

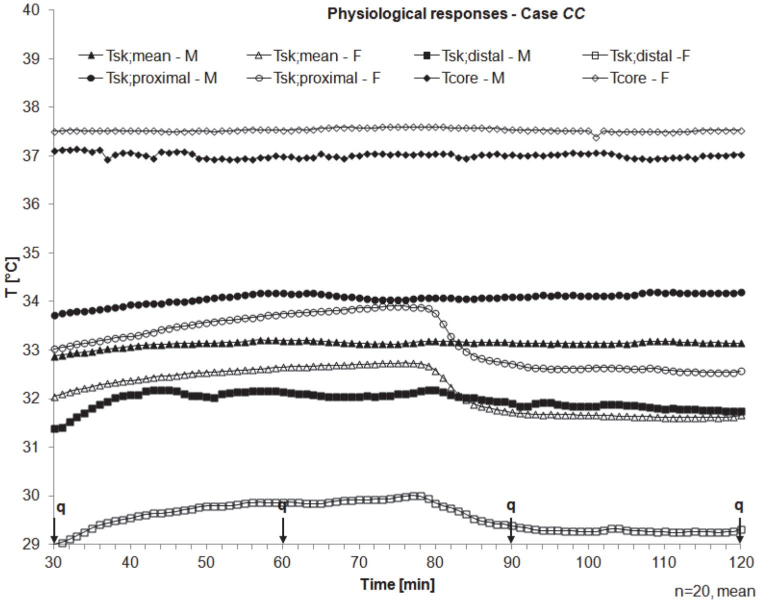
	Case *CC*		Case *RC*	
Variable	M (n=10)	F (n=10)	M (n=10)	F (n=10)
Mean skin temperature [°C]	33.1±0.07	32.2±0.44*	32.8±0.05^	32.5±0.09*^
Core temperature [°C]	37.0±0.05	37.5±0.04*	37.0±0.04^	37.4±0.04*^
Distal skin temperature [°C]	32.0±0.17	29.5±0.28*	31.3±0.26^	30.2±0.56*^
Proximal skin temperature [°C]	34.1±0.12	33.2±0.50*	33.7±0.13^	32.3±0.08*

Values are presented as mean ± SD

*p < 0.001 versus males

^p < 0.001 versus case *PC*

a



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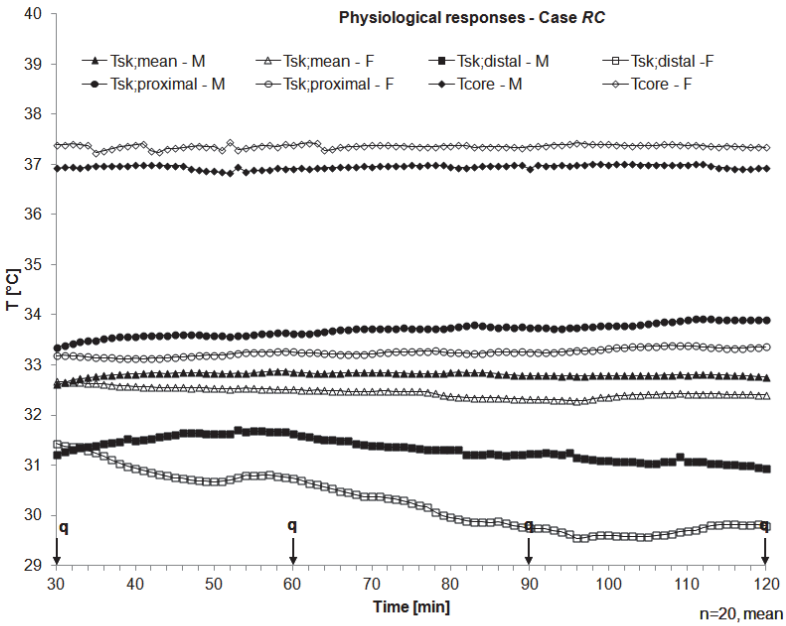
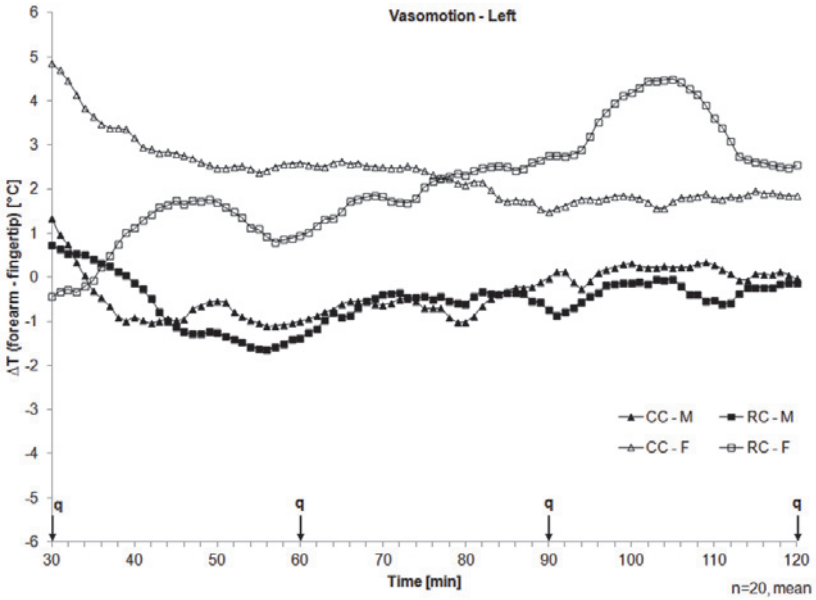


Figure 4.5 Mean, distal and proximal skin temperatures (T_{sk}) of male (M) and female (F) subjects during **(a)** *CC* case and **(b)** *RC* case. Q is representing the moment of questionnaire

a



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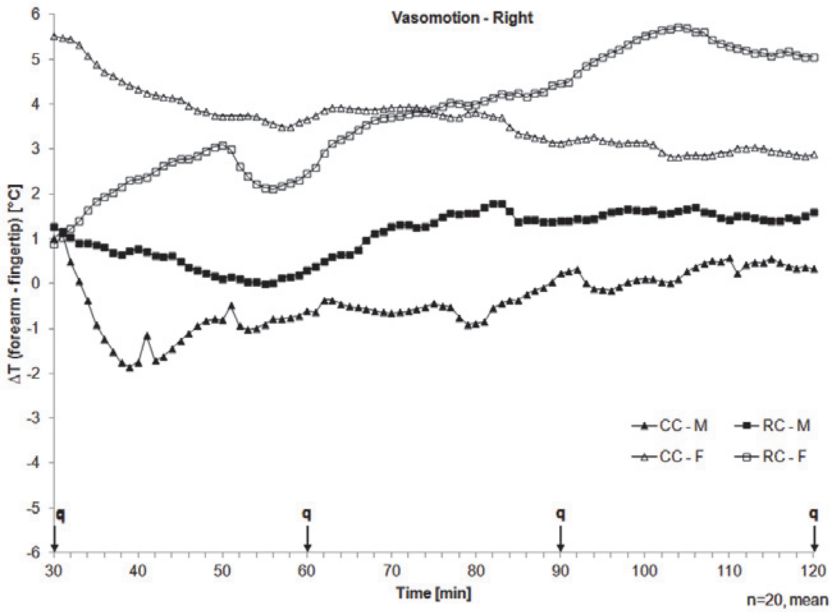

Figure 4.6 Mean difference between forearm and fingertip temperature ($\Delta T_{(forearm\ -\ fingertip)}$) of male (M) and female (F) subjects during both experimental conditions; **(a)** Left side body **(b)** Right side body. Q is representing the moment of questionnaire

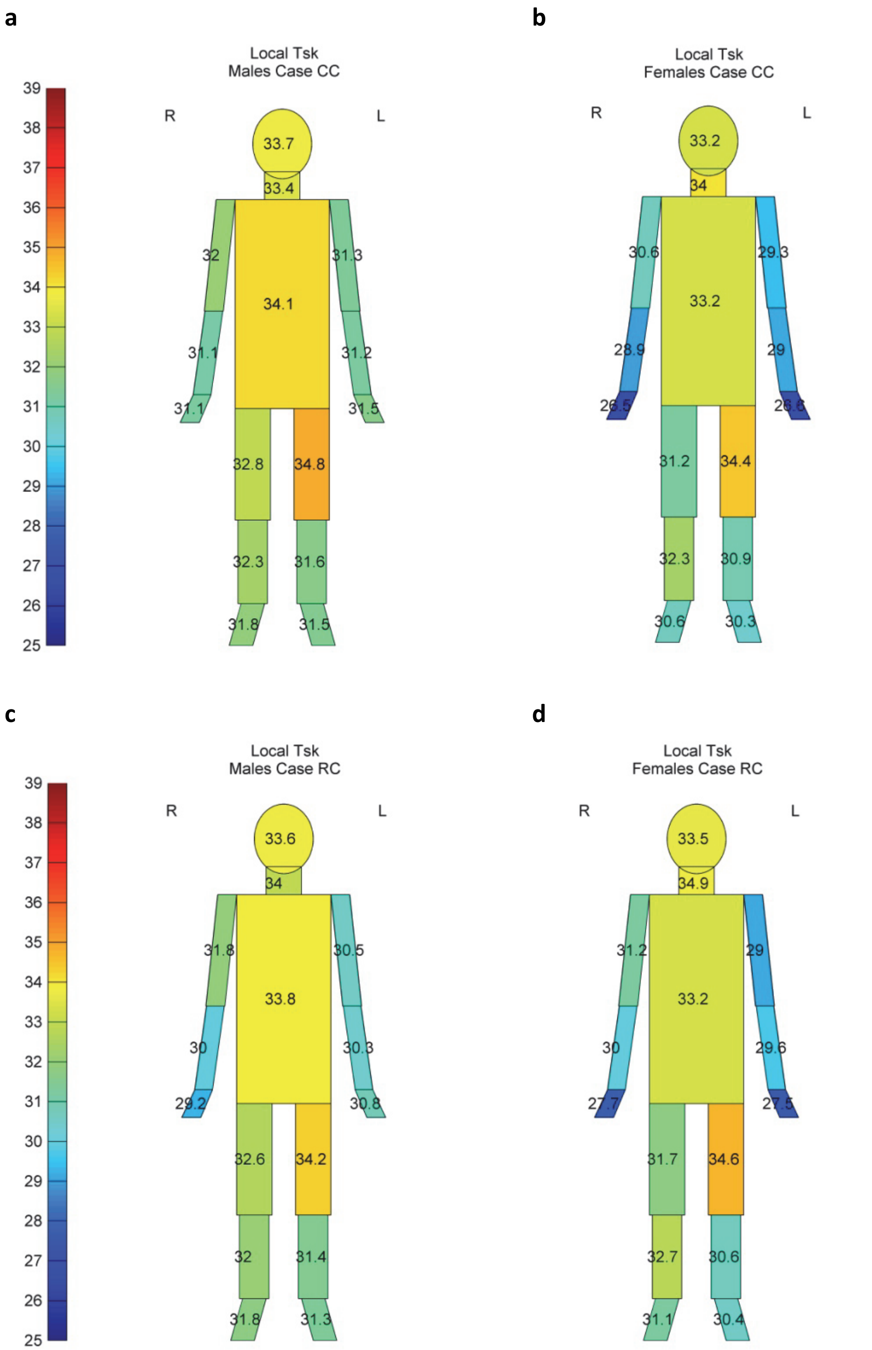

Figure 4.7 Mean local skin temperatures; **(a)** Males case *PC* **(b)** Females case *PC* **(c)** Males case *AC* **(d)** Females case *AC*

Subjective responses

The subjective responses were analyzed from four questionnaires of each case (i.e. Case 1: q2-q5 and Case 2: q6-q9; Figure 4.2). With respect to thermal sensation, both the averaged predicted mean vote (PMV[1]) and the averaged actual mean thermal sensation vote (TSV) are presented in Table 4.5. The PMV is calculated using the measured physical parameters. The subjective votes were for both genders and cases significantly lower in comparison to the predicted mean vote ($p<0.001$). In general, the subjects were feeling significantly colder than predicted. Besides, the females voted significant colder sensations during both conditions in comparison to the males (Figure 4.8). For the males no clear time effects could be observed. During *CC* case a slight decrease in TSV of the females can be observed after t=90, which is probably caused by a decrease in mean, distal and proximal skin temperatures (after t=80, Figure 4.5a). During *RC* case the females seem to cool down and tend to warm up after t=90 due to a significant ($p<0.01$) increased vasoconstrictor tone (Figure 4.6, $\Delta T_{forearm\text{-}fingertip}$ increases up to 6°C).

Regarding thermal comfort, the females felt significantly ($p<0.05$) more uncomfortable than the males during both cases (Figure 4.9). Although the females warmed up after t=90 during *RC* case and felt warmer (TSV increased from -1.0±0.76 to -0.7±0.78; see Figure 4.8) they kept feeling slightly uncomfortable (1.4±0.97 on t=90 vs 1.4±0.70 on t=120).

Furthermore, a higher percentage of females found the thermal environment unacceptable (*CC*: 30%, *RC*: 25%) compared to the male subjects (*CC*: 0%, *RC*: 5%).

Table 4.5 Predicted mean vote (PMV) and actual mean vote (AMV) of males and females during both experimental conditions

	Case *CC*		Case *RC*	
Variable	M (n=10)	F (n=10)	M (n=10)	F (n=10)
PMV [-]	0.3±0.05	0.1±0.07^	0.1±0.02#	0.0±0.02^#
AMV [-]	-0.3±0.64*	-0.4±0.95*^	-0.3±0.41*	-0.6±0.69*^

Values are presented as mean ± SD

*p < 0.001 versus PMV

^p < 0.05 versus males

#p < 0.001 versus *CC* case (within gender)

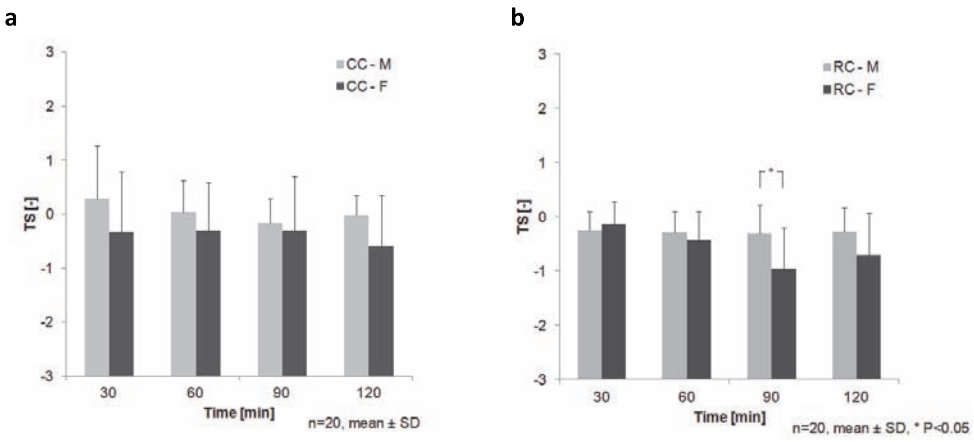

Figure 4.8 Actual mean votes; **(a)** *CC* case and **(b)** *RC* case

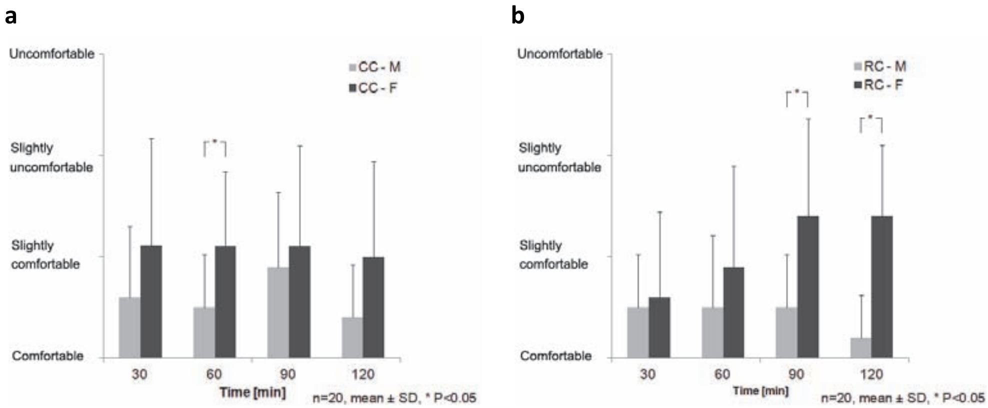

Figure 4.9 Mean thermal comfort votes; **(a)** *CC* case and **(b)** *RC* case.

Local effects

The authors assumed that the discrepancy between the PMV and TSV occurred due to local effects caused by non-uniform environmental conditions. Therefore, the hypotheses were tested that local thermal sensation (local TS) and local skin temperature significantly influenced whole-body thermal sensation (TSV). In Figure 4.10 mean local thermal sensations are presented, separately for both cases and gender.

The largest F ratio's were found for the uncovered extremities (the hands and forearms both left and right) and the upper arms; i.e. the experimental manipulation had the largest effect on these body parts.

Males

The largest correlation for local TS and TSV of the males were found for the hands. Although the correlation was significant, the r was relatively low (around 0.2). The largest correlation for local TS versus local skin temperature for the males was found for the right hand (r=0.4).

Females

Significant and relatively high correlations were observed between WB TS and local TS of right hand (r=0.73), right forearm (r=0.75), right upper arm (r=0.73), left hand (r=0.67), left forearm (0.63), left upper arm (r=0.57), neck (r=0.48) and head (0.60). Furthermore, a significant (relatively high) correlation was found between local TS and skin temperature of right hand (r=0.53), right forearm (r=0.53), right upper arm (r=0.62), left hand (r=0.39) and left upper arm (r=0.44).

Productivity

The results of the simulated office tasks were analyzed both for the amount of completed additions and correct additions. *A priori* the results were normalized; the maximum score of each subject was equal to 100%, and all other scores of the subject were related to this score. The results indicate a significant case effect for the average normalized correct additions of the males, their amount of correct additions were lower during the radiant cooling case in comparison to the convective cooling case ($p<0.05$). No significant case effects were found within the female group (Figure 4.11). Furthermore, no significant effects were found between the genders.

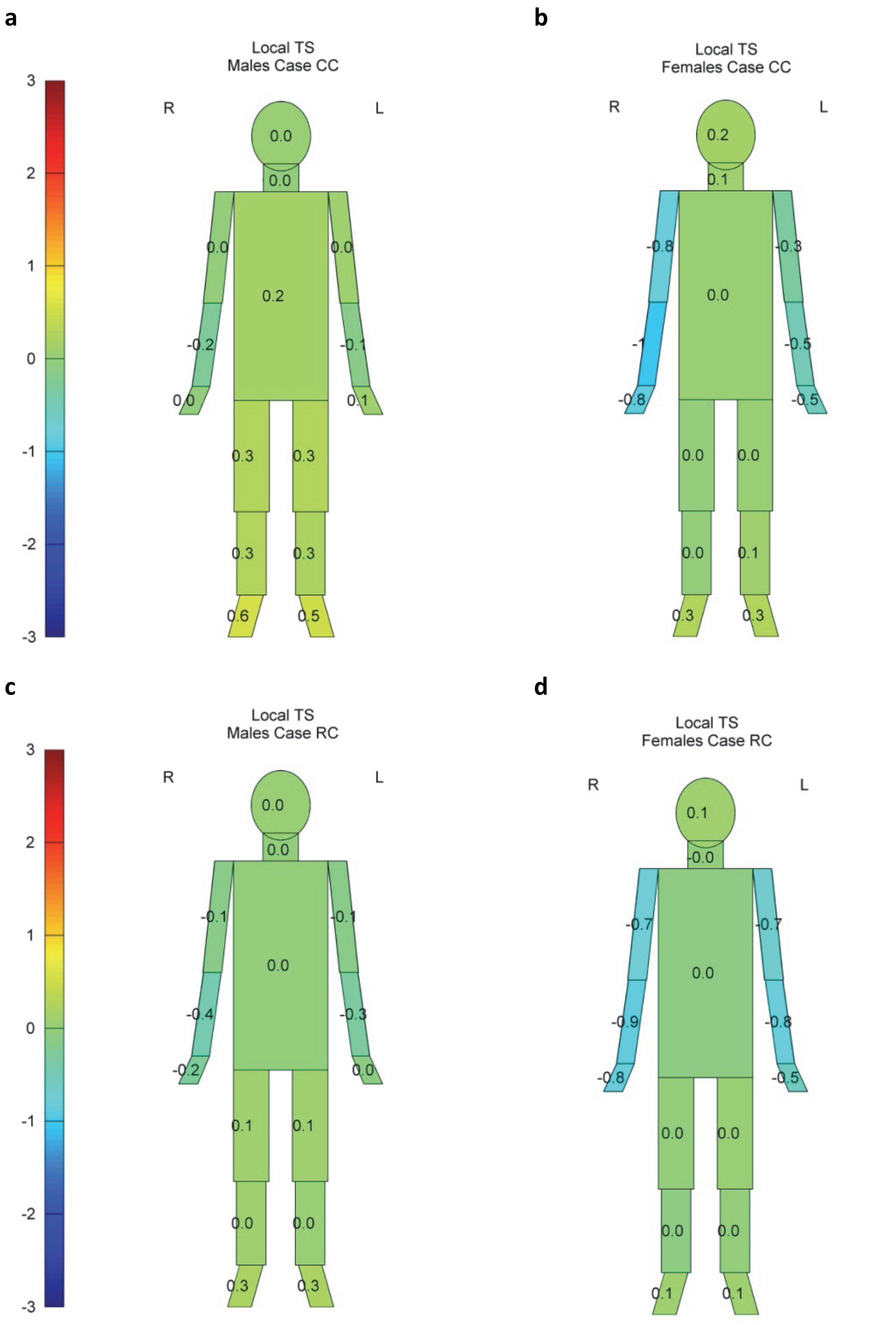

Figure 4.10 Mean local thermal sensations; **(a)** Males *CC* case **(b)** Females *CC* case (c) Males *RC* case (d) Females *RC* case

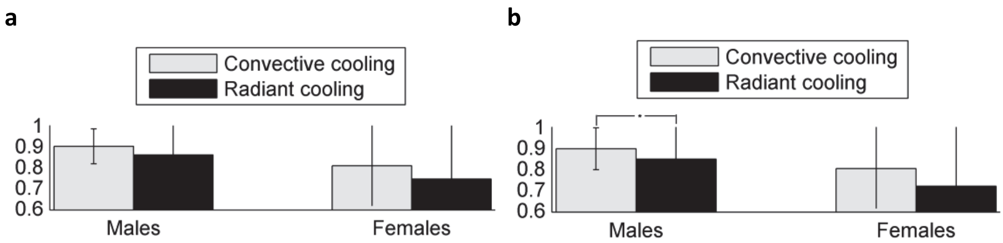

Figure 4.11 (a) Average normalized completed additions ± SD **(b)** Average normalized correct additions ± SD; *p<0.05.

4.4 Discussion

In this study the differences in physiological responses, thermal comfort and productivity between males and females in response to non-uniform environmental conditions were studied. The subjects were exposed to two different conditions: a convective cooling situation (*CC* case) and a radiant cooling situation (*RC* case).

The results show that in general the females were more uncomfortable in comparison to the males under the same environmental conditions. Although the mean air velocity during *CC* case was higher for the females compared to the males, the same trend in differences between the genders in physiological and subjective responses were observed for both *CC* and *RC* case. The distal skin temperatures of the females were significantly lower compared to the males. For the females a significant relation was found between the local skin temperatures of the hands, forearms and upper arms and the related (local) thermal sensations.

For both genders the extent of vasoconstriction was larger at the right side of the body compared to the left side. This is probably caused by the positioning of the inlet (at the right side of the subject). Furthermore, all subjects were right-handed and operated therefore the computer mouse with their right hand, which may explain why their right hand was colder compared to their left one[40].

The calculated power, based on the results achieved for *RC* case , for the whole-body thermal sensation votes (TSV) is 40% (α=0.05). In advance, a smaller standard deviation was expected on the results. Therefore, for future studies it is advisable to include more subjects per sample to enlarge the power of the results. In case a difference in TSV between two groups of 0.5 and a maximum standard deviation of ±0.5 is considered, the minimum amount should be 16 persons per sample.

However, with respect to the results found in this study, a clear trend is visible in differences in thermal sensation and comfort between the two genders.

For females a high correlation was found between the local thermal sensation of the hands, forearms and upper arms and whole body thermal sensation (TSV). This is in line with previous studies where women complained about cold extremities and, in fact, exhibited cooler distal skin regions than men[18 20 41]. Krauchi et al.[42] found in a study on cold extremities and difficulties initiating sleep, under 2800 subjects, that women complain 4.5 times more about cold hands and feet. In this study no significant differences were found for the feet, which might be explained by the posture of subjects during the experiments. During *RC* case furthermore the increased floor temperature could be an explanation.

These studies found no significant differences in local thermal discomfort levels at the same local skin temperature levels between genders. However, in the presented study significant negative effects of low (in comparison to proximal skin temperature) local skin temperatures were found for the uncovered body parts on local thermal sensation (TS) of these body parts. Yet, at lower local skin temperature levels of the proximal body parts no significant differences in TS of these body parts could be observed between males and females (Figure 4.7 and 4.10).

Following the above, the significant differences which were found in TSV (actual mean thermal sensation vote) are caused by local TS of the distal body parts and distal skin temperatures. This finding is confirmed by the significant and relatively high correlation between TSV, local TS and local skin temperatures. Note that this only applies for the female group. This result is in line with the results found by Krauchi et al.[42], who found that thermal discomfort of cold hands is correlated with a cool finger temperature. Contrary, Zhang et al.[16] found that the most important explaining parameters for TSV are the forehead, neck and chest. The experiments in that study were performed using an air-sleeve which was attached to one specific body part. Subsequently, the influence on TSV of cooling or warming this body part was studied. Afterwards, the developed model was validated against experimental results obtained from measurements in vehicles (very inhomogeneous environment). In our study, the approach was to expose the subjects to more realistic conditions with respect to the built environment. The intention was, however, to impose sufficient differences between and within the cases to achieve clear results and to draw conclusions for less critical situations which may occur in practice. The differences in setup between this study and the study of Zhang et al.[16] may explain the different conclusions.

The lower female skin temperatures, both distal and proximal can be explained morphologically[43]. Women have, among others, a larger peripheral heat sink and greater body insulation when vasoconstricted (except hands and feet). This latter might explain the significant correlation between skin temperature and local TS of the distal body parts. Another explanation for the cold extremities could be the increase in progesterone levels during the luteal phase, which cause an increase in the internal threshold temperature for vasodilation and sweating. Consequently, the extremities remain colder[9].

Compared to Fanger[44], the mean skin temperatures, of both males and females, which were found in our study were slightly, but significant, lower than the comfortable skin temperatures found in the reviewed studies. This might indicate that the subjects in the present study are at the cold side of comfort. However, one could argue whether the mean skin temperature is a good predictor for thermal comfort[8].

Previous studies found that women are more dissatisfied with their thermal environment in comparison to males[18 45 46], which is found in this study as well (Figure 4.9). For a non-uniform environment, this was also found by Hashiguchi et al.[13].

In our experiments, subjects in the age between 20-29 years were studied. From literature we know that temperature sensitivity decreases with age[47]. Older adults tend to fail sensing a thermal imbalance and/or they are failing in responding to it appropriately[48]. In addition, Kingma et al.[9] concluded that the thermoneutral zone (TNZ) is narrower for older adults than for young ones. Furthermore, the TNZ for females is shifted upward compared to the TNZ of males. However, the exact range of the TNZ for both groups (females and older adults) is yet unknown. Consequently, thermal sensation and comfort is affected by physiological ageing and age related behavioural changes[49]. Schellen et al.[50] found that older male subjects prefer higher operative temperatures compared to their younger counterparts to achieve thermal comfort. Following the above, the differences found in this study and the effects of local parameters on thermal sensation and comfort may enlarge when the age increases.

Olesen[14] stated that draught under warm conditions (i.e. convective cooling *CC*) might be comfortable and therefore could reduce the energy-use in terms of cooling. In this study no significant differences in whole body thermal sensation (TSV) were observed between *CC* and *RC* case for both genders. The predicted mean vote (PMV), however, did indicate significant case effects (Table 4.5) where *CC* case is assessed as warmer. Remark that these effects are within the accuracy of PMV (±0.5). For both genders, the TSV was significantly lower than the PMV. Thus, the subjects were feeling significantly colder than predicted. Especially, for the females this resulted in a slightly uncomfortable situation (Figure 4.9). For the females, the results indicate that *RC* case is more uncomfortable than *CC*, but this is not significant.

The experiments were conducted during the winter/ early spring period (December-March), which could have influenced the thermal perception of the subjects and may explain partly the sensations on the cold side of neutral. However, the subjects were already 1-1.5 hour in the laboratory prior to the start of the experiment. Furthermore, the focus in this study was not specifically on the effects of cooling compared to warming, but on the differences between gender in response to a non-uniform environment. Nevertheless, already at relatively low outside temperatures a cooling demand can exist in office buildings, due to relatively high internal heat loads, well insulated building envelopes and solar contribution. Therefore it is possible that occupants of typical office buildings can be exposed to cooling conditions early in the season and even in the winter.

The differences in set-up conditions of RC case (AC) are considered as small (ΔPMV=0.2). The difference between males and females in AMV for case CC is smaller than for case RC,

while the opposite is true for the PMV. Therefore we conclude that the difference in AMV of both genders is not related to the differences in set-up conditions.
With respect to the prediction of thermal comfort obtained using PMV-index, the sensitivity of the boundary conditions (i.e. clothing insulation and activity level) on the results should be taken into account. For example, Ferraro et al.[51] found a lower (~5-10%) metabolic rate for sedentary females compared to males. Particularly, in field studies errors were found regarding the estimation of clothing insulation and activity levels; these errors contribute to the inaccuracy of the PMV[4].
From the productivity results no significant conclusions can be drawn, probably because the sample size is too small with respect to this. However, the results show consistency in the direction of change for both genders between the convective cooling and radiant cooling conditions. More research is needed to further elaborate on this.

The presented data do not allow concluding that draught under warm conditions is acceptable in terms of thermal comfort.
In terms of cooling, it can be concluded that the set-points for females need to be increased to improve satisfaction with thermal environment, which is in agreement with Choi et al.[45].

4.5 Conclusion

In this study both males and females were exposed to non-uniform environmental conditions. Prior to the experiments, the predicted mean vote (PMV) was calculated. For both experimental conditions the predicted mean vote was approximately neutral (PMV≈0). The results of this study indicate:

1. Under non-uniform conditions, the actual mean thermal sensation votes (TSV) significantly differ from the PMV for both genders. The subjects were feeling significantly colder than predicted.
2. Females are more uncomfortable and dissatisfied under the same environmental conditions compared to males. Note that in this study mean thermal sensation was colder than predicted. For thermal sensations warmer than predicted, this should be investigated further.
3. For females, local thermal sensation and skin temperature of the extremities (hands and arms) is of high importance for whole body thermal sensation TSV. For males, local thermal sensation and skin temperature of the extremities are less important.
4. In terms of cooling, the operative temperatures for females need to be increased by ~1.2K to improve satisfaction with the thermal environment.

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Chapter

5 Effects of different cooling principles

on thermal sensation and physiological responses

This chapter is submitted to Energy and Buildings. Co-authors: M.G.L.C. Loomans, M.H. de Wit, B.W. Olesen and W.D. van Marken Lichtenbelt.
The lay-out has been adjusted to fit the style of this thesis.

Abstract

Applying low exergy cooling concepts in the built environment allows reduction of use of high quality energy sources. Non-uniform thermal conditions, which may occur due to application of lowex systems, can result in discomfort. Two different cooling principles were studied: passive (through convection in terms of increased air velocities) and active cooling (through convection or radiation). Furthermore, two different ventilation techniques were included: mixing and displacement ventilation. Ten male subjects (age: 20-29) were exposed to six different cases: *1.PC-C-M*; p*assive* cooling through *mixing* ventilation, *2.AC-C-M; active* cooling through *convection* by *mixing* ventilation, *3.AC-C-D*; a*ctive* cooling through *convection* by *displacement* ventilation, *4.AC-R-M-C; active* cooling through *radiation* by the *ceiling* and *mixing* ventilation, *5.AC-R-M-F; active* cooling through *radiation* by the *floor* and *mixing* ventilation, and *6.*AC*-R-D-F; active* cooling through *radiation* by the *floor* and *displacement* ventilation.

Though all cases were designed at PMV≈0, subjective data indicate significant differences between the cases. For the prediction of thermal sensation and thermal comfort under non-uniform conditions, the operative temperature only is not sufficient. Combined local factors play an important role in the comfort assessment. Furthermore, non-uniform environments, as case *6,* can achieve a comparable or even a more comfortable assessment compared to uniform environments.

5.1 Introduction

Thermal comfort is one of the main requirements for successful application of low-exergy and low energy HVAC (heating, ventilation and air-conditioning) systems. The Annex 37 study of the International Energy Agency[1] revealed that an optimal energy/exergy use not always results in an increased comfort level. Application of these systems can result in local and/or global discomfort. Non-uniform thermal conditions (e.g. vertical temperature gradients), which may occur due to application of these systems, can be responsible for discomfort[2]. On the opposite, Arens et al.[3] and Zhang et al.[4] concluded that under non-uniform environments higher thermal comfort levels could be achieved in comparison to uniform thermal environments. In some cases combinations of local and general discomfort factors may not be uncomfortable. For example, draught under warm conditions may even provide comfortable cooling conditions. Furthermore, it could reduce the energy-use if air-conditioning is not necessary within certain temperature limits[5]. It is important to assess thermal comfort adequately in the design phase, to avoid that expected comfortable conditions turn out to be uncomfortable. In general, both convective flows and radiant asymmetries affect thermal comfort. The combined effects however are not extensively investigated and are therefore important to study. More knowledge on the interaction between the system, indoor climate and the human body is indispensable to design optimal systems in the future.

Cooling is assessed as an important aspect regarding both the conditioning and energy -use of residential, commercial and public buildings[6]. In literature, many studies can be found on the efficiency of different cooling systems with respect to the energy-use. Radiant cooling systems, both ceiling and floor systems, are regarded as interesting alternative compared to convective cooling systems (all air systems) to improve thermal comfort and to reduce the energy consumption[7-12]. Furthermore, radiant cooling systems can provide a comfortable thermal indoor environment. The draught risk due to a cold downstream air flow can be reduced because, in comparison to convective systems, the ventilation air can be supplied at higher temperatures[13]. Different radiant cooling systems are currently in use, mainly ceiling and floor systems. Compared to ceiling systems, floor systems are more efficient due to the higher view factor of the occupant. However, the convective heat transfer coefficient of floor cooling is lower compared to ceiling cooling. Radiant floor cooling can achieve equal thermal comfort levels at higher surface temperatures compared to ceiling systems[13]. This despite the fact that these panels impose a non-uniform thermal environment and may introduce a vertical temperature gradient.

Besides the need for cooling, there exists also a ventilation demand. The most commonly applied ventilation principles are mixing and displacement ventilation. Displacement ventilation is mostly used in buildings with high internal heat loads where mainly cooling is required; in most cases an upward displacement ventilation is used, where the inlet is located near the floor[14]. Mixing ventilation is the most widely used ventilation principle, because it can be used for both heating and cooling and it can cope with higher heat loads compared to displacement ventilation[14]. However, the efficiency of displacement ventilation, compared to mixing ventilation, is higher[13].

Different cooling systems, both convective and radiant, together with different ventilation principles have been studied extensively on energy efficiency, but also on thermal comfort (e.g. [8 9 13 15-19]). However, in these studies a comparison has been made on individual system level, or two types of systems are compared (i.e. radiant vs convective cooling, displacement vs mixing ventilation). To the best of our knowledge, no study is available where different techniques are compared on subjective and physiological responses. Therefore, the objective of this study was to investigate the effects of different cooling techniques (i.e. passive and active, and through convection and radiation) and different ventilation principles (i.e. mixing and displacement ventilation) on subjective and physiological responses. Furthermore, emphasis is on the influence of non-uniformity (i.e. temperature stratification, radiant asymmetries and local increased air velocities) on local effects (local skin temperatures and local thermal sensations) and subsequently whole body thermal assessment.

5.2 Methods

Ten male subjects visited the climate chamber[20] for six different experimental conditions. Two different cooling principles were studied: *passive* (PC, in terms of increased air velocities) and *active* cooling (AC). With respect to the *active* cooling cases, two different cooling systems were studied: *active* cooling through *convection* and *active* cooling through *radiation*. Regarding the *active* cooling through *convection*, a distinction was made between supplying cold air by *mixing* and *displacement* ventilation. For the *active* cooling through *radiation* cases, two different radiant panel configurations were studied: *active* cooling through *radiation* by the *ceiling* and *floor*. The air supply temperature equaled the average room temperature; to enlarge the effect of a vertical temperature gradient between the floor and ceiling, the floor and ceiling respectively were heated. As indicated by Causone et al.[13], a special interest is on *active* cooling through *radiation* by the *ceiling* in combination with *displacement* ventilation. The following case identification is used: the first two letters indicate the cooling principle (PC or AC), the third letter indicates the cooling system (C for convection and R for radiation), the fourth letter indicates the ventilation technique (M for mixing ventilation and D for displacement ventilation), and the fifth letter indicates, in case of cooling though radiation, the panel configuration (C for ceiling and F for floor). In summary the following cases were studied:

1. PC-C-M — *Passive* cooling through *convection* by *mixing* ventilation
2. AC-C-M — *Active* cooling through *convection* by *mixing* ventilation
3. AC-C-D — *Active* cooling through *convection* by *displacement* ventilation
4. AC-R-M-C — *Active* cooling through *radiation* by the *ceiling* and *mixing* ventilation
5. AC-R-M-F — *Active* cooling through *radiation* by the *floor* and *mixing* ventilation
6. AC-R-D-F — *Active* cooling through *radiation* by the *floor* and *displacement* ventilation

A graphical representation of the six different cases is given in Figure 5.1.

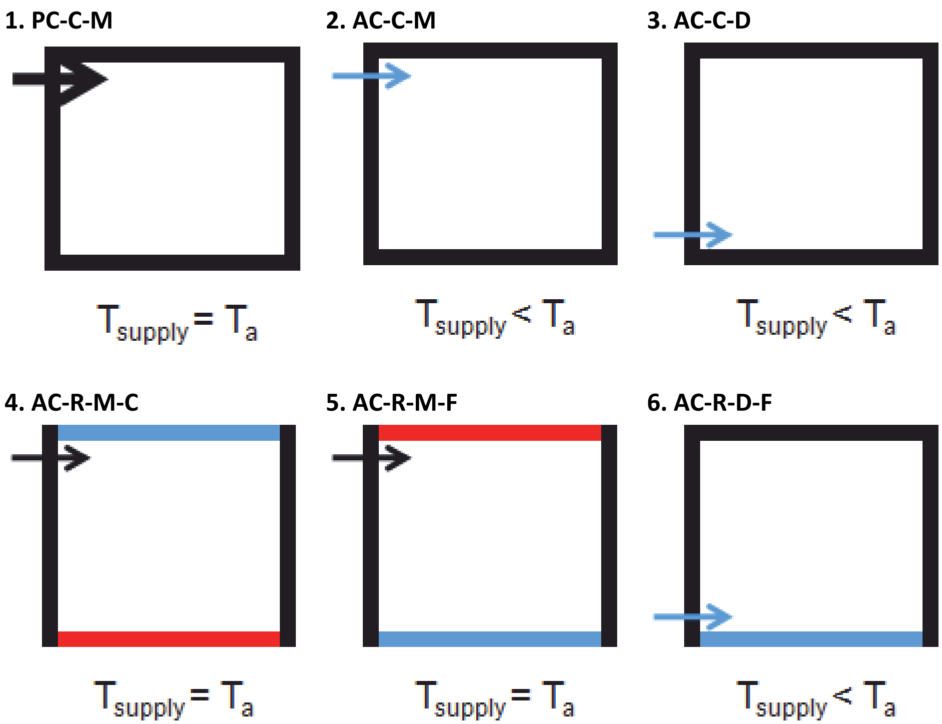

Figure 5.1 Graphical overview of experimental cases; **(1)** *Passive* cooling through *mixing* ventilation, **(2)** *Active* cooling through *convection* and *mixing* ventilation, **(3)** *Active* cooling through *convection* and *displacement* ventilation, **(4)** *Active* cooling through *radiation* by the *ceiling* and *mixing* ventilation, **(5)** *Active* cooling through *radiation* by the *floor* and *mixing* ventilation, and **(6)** *Active* cooling through *radiation* by the *floor* and *displacement* ventilation

All cases were designed to achieve a neutral predicted thermal sensation (PMV≈0). The actual realized details of the experimental cases are presented in Table 5.1. The ventilation inlet is situated on the right side of the subject (Figure 5.2). The width and height of the inlet differed between the passive and active cooling cases to achieve higher or lower air velocities, the ventilation rate remained at a level of 110 m^3/h for all active cooling cases. To achieve a higher air velocity near the subject during the passive cooling case, the ventilation rate for case *1.PC-C-M* was 600 m^3/h. The fresh air was conditioned by an air-handling unit (Verhulst) at a constant relative humidity of 30%. As supply air temperature conditions where controlled at the corresponding operative temperature, the floor temperature in case *4.AC-R-M-C* and ceiling temperature in case *5.AC-R-M-F* were raised to compensate for the cooling provided by the ceiling and floor respectively. Therefore, mean radiant temperature and air temperature were nearly equal during all cases. With respect to the built environment this experimental design may be less realistic. However, in this way all cases can be compared to each other.

Table 5.1 Case details

Variable	**Case 1. PC-C-M**	**Case 2. AC-C-M**	**Case 3. AC-C-D**	**Case 4. AC-R-M-C**	**Case 5. AC-R-M-F**	**Case 6. AC-R-D-F**
Operative temperature [°C]	25.2±0.2	24.9±0.1	23.9±0.0	24.4±0.1	24.3±0.1	23.5±0.1
Air temperature [°C]	25.5±0.2	24.9±0.1	24.0±0.0	24.2±0.1	24.6±0.1	23.7±0.1
Air velocity [m/s]	0.23±0.03	0.15±0.01	0.06±0.00	0.14±0.01	0.07±0.01	0.10±0.01
Turbulence intensity [%]	67.8±5.2	30.4±1.5	23.4±1.4	34.8±1.6	15.0±1.8	18.6±1.5
Wall temperature [°C]	25.0±0.1	24.8±0.1	23.8±0.0	23.6±0.03	24.8±0.2	25.1±0.1
Floor temperature [°C]	24.9±0.1	24.8±0.1	23.7±0.0	28.9±0.1	19.7±0.2	19.8±0.2
Ceiling temperature [°C]	25.0±0.1	24.9±0.1	23.9±0.0	18.0±0.2	30.6±0.1	24.5±0.1
Mean radiant temperature [°C]	25.0±0.1	24.8±0.1	23.8±0.0	24.7±0.03	24.0±0.1	23.3±0.1
Δ Plane radiant temperature (floor – ceiling) [°C]	n/a	n/a	n/a	8.1±0.2	8.0±0.2	5.1±0.2
Δ Air temperature Left (1.1m - 0.1m) [°C]	0.2±0.1	0.7±0.0	1.3±0.1	-0.6±0.0	3.2±0.2	4.1±0.2
Δ Air temperature Right (1.1m - 0.1m) [°C]	0.4±0.1	0.1±0.1	1.4±0.1	-0.4±0.0	3.7±0.2	4.1±0.3
PMV [-]	0.3±0.05	0.1±0.03	0.1±0.0	0.1±0.02	0.2±0.0	0.0±0.0

Values are presented as mean ± SD (n=10)

Subjects

Ten male subjects (characteristics in Table 5.2) participated in the experiments. The volunteers were given detailed information regarding the purpose and the methods used in the study, before written consent was obtained. However, they were not informed on the actual conditions they were exposed to.

All subjects were healthy, non-obese, non-smokers and not taking any medication which might alter the cardiovascular or thermoregulatory responses. Body fat percentage was determined, according to the Siri equation, by means of skinfold thickness[21]. Skin folds were measured at four sites: subscapular, suprailiacal, and at the triceps and biceps[22]. Subjects refrained from alcoholic beverages in the evening and morning prior to the test, but were allowed to eat a small breakfast. During the experiments, the subjects wore standardized clothing, consisting of a jogging pants, polo shirt, underpants, socks and shoes which did not cover the ankles. Clo-values were determined using EN-ISO 9920[23], McCullough et al.[24] and McCullough et al.[25]. The total heat resistance of the clothing ensemble, including desk chair, was calculated on 0.6 clo. The subjects continuously performed office tasks; their metabolic rate was estimated to be approximately 1.2 met EN-ISO 7730[26].

Table 5.2 Subject characteristics

Age (year)	24.7±2.0
Height (cm)	181.8±8.3
Mass (kg)	77.3±8.5
BMI (kg/m^2)	23.5±3.4
Bodyfat% (%)	16.3±4.7

Values are presented as mean ± SD (n=10)

Protocol

Subjects visited the climate chamber (Figure 5.1) during winter (December 2010 - March 2011, average outside temperature ranged from -1.4 to 6.7°C[27]). During a visit they were exposed to two (1 session, half a day, 4h) or four (2 sessions, whole day, 8h) different cases. In total, they participated in the experiments for 1.5 day. The order of the cases was randomized. After written consent was obtained, the subjects swallowed a temperature telemetric pill and changed clothes. Next, the subjects performed a light exercise (stepping on a small platform) –for a period of 5 minutes to obtain skin vasodilatation in order to ensure that all subjects entered the climate room in an equal thermal state. Vasodilatation was assessed by the skin temperature difference between forearm and top of the forefinger[28 29]. Furthermore, the subject characteristics (height, weight, and fat percentage) were determined and the skin temperature sensors were attached. After entering the climate room, the experiment started with an acclimatization period (30 min, Fig.5.3). During this acclimatization period the environmental conditions were equal to the environmental conditions of the case which followed. During this period they received an instruction regarding the use of the questionnaires. After completion of the first case a new acclimatization period of 30 minutes followed (as preparation for the second case). During this period the subjects had the opportunity to visit the rest room. A detailed time line, of one session (two cases) is given in Figure 5.3.

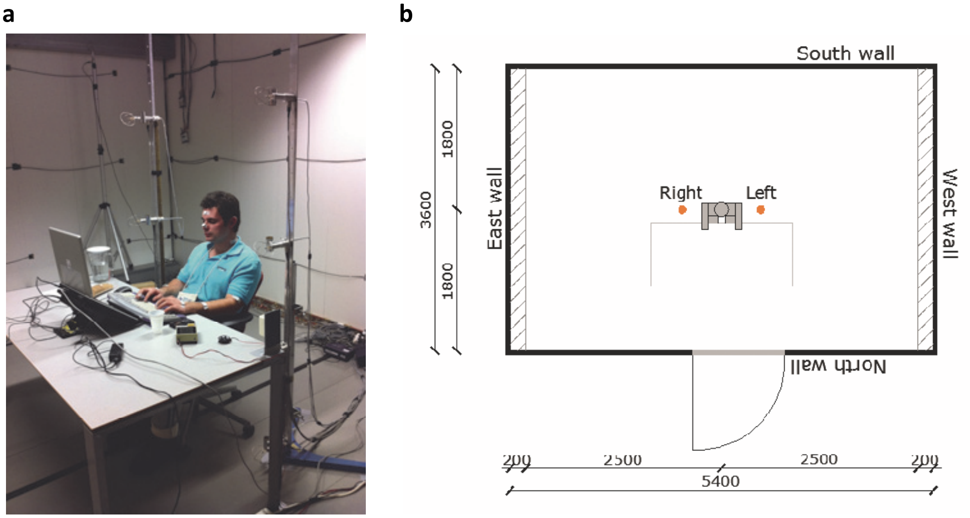

Figure 5.2 (a) test subject in experimental set-up; **(b)** floor plan where the dots indicate the measurement stands and the grey hatched surfaces represent the plenum boxes

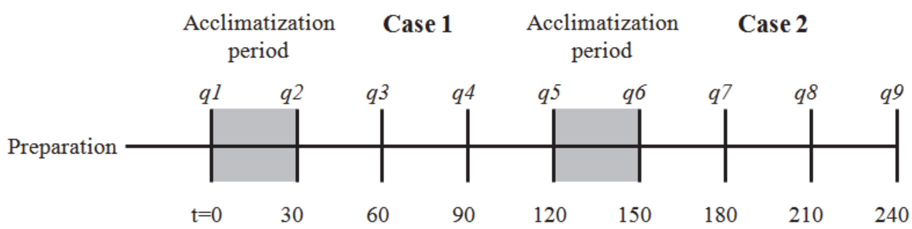

Figure 5.3 Time line of measurement protocol; q is representing the questionnaire moments

Measurements

Physical measurements

Air temperature (NTC Thermistor, type SC95, accuracy ±0.1°C), relative humidity (RH) (Humidity Sensors, Honeywell HIH- 4000 series), air velocity (hot sphere anemometer, Dantec, estimated accuracy 15% [30]), surface temperature (NTC Thermistor, U-type EU-UU-10-PTFE, accuracy ±0.1°C) carbon dioxide (Carbon Dioxide Transmitter, Vaisala 0–2000 ppm), and illuminance (Lux meter, Hager model E2) were measured according to EN-ISO 7726[31]. Air temperature, RH, and air velocity were measured on two comfort stands at 0.1, 0.6, 1.1 and 1.7 m height. These comfort stands were placed on the left and right side of the subject, at a distance of 0.2m. The average surface temperature for each surface was derived from nine measurement points on each surface (at a grid of 3x3). The mean radiant temperature was determined according to the surface temperatures and view factors related to the position of the subject.

Physiological measurements

Skin temperature was measured at 1 min intervals by wireless iButtons (Thermochron iButton, DS1291H, Maxim, CA, Sunnyvale, USA, accuracy ±0.1°C) at 24 locations to assess possible differences between the left and right side of the human body[32]. Ibuttons were attached with semi-permeable adhesive tape (Fixomull; BSN medical gmbh, Hamburg, Germany). Mean skin temperature was calculated according to the 14-point weighing as proposed by EN-ISO 9886[33] (Point 1-14, Figure 5.4a). Distal skin temperature was calculated as average of instep, ankle, finger tip, hand, and forehead skin temperature. To avoid a disproportional distribution, forehead and instep temperature had a weighing factor of 2. Proximal skin temperature was calculated as an average of the scapula, paravertebral, upper chest, and abdomen skin temperature. Core temperature was determined by measuring the intestinal temperature at a 1 min interval through an ingestible telemetry pill (CorTemp, Ingestible Core Body Temperature Sensor, HT150002, HQ Inc., Palmetto, FL, USA, accuracy ±0.1°C).

Questionnaires

Every 30 minutes, starting at t=0 min, the test subjects filled in a questionnaire. Thermal sensation votes, both global and local for each body part (Figure 5.4b), were asked on a continuous 7-point ASHRAE thermal sensation interval scale, where each point on the line could be marked[34]. Global and local thermal comfort were asked on an ISO-defined 4-point thermal comfort scale[35]. Visual analog scales (VAS) were used to assess adverse perceptions and the perceived indoor environment[36]. A question to assess perceived stress was included as well. The questionnaires were presented in Dutch to the subjects through an Internet browser.

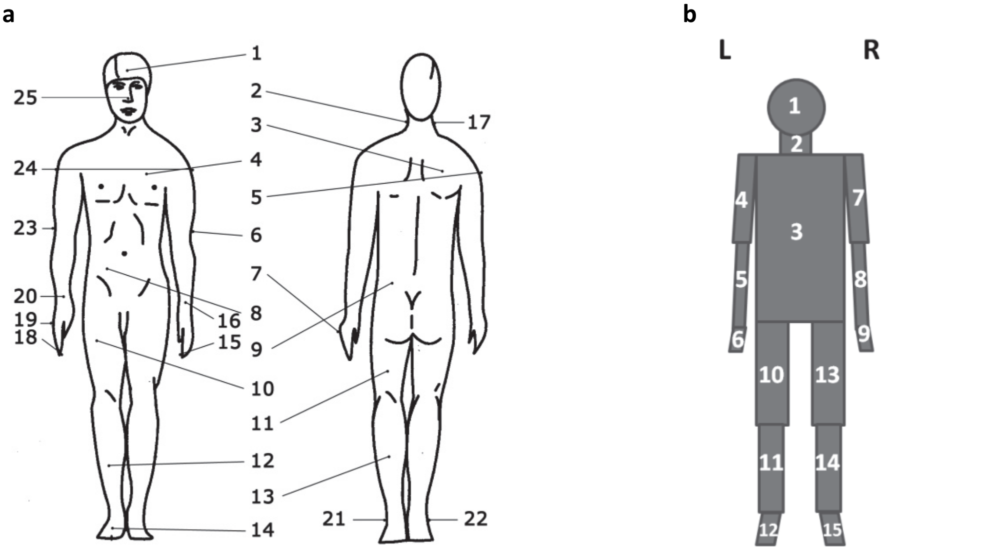

Figure 5.4 (a) Measurement sites skin temperature, **(b)** schematic representation of body parts to assess local thermal sensation and comfort

Data analysis

For the statistical analyses, physical and physiological responses of the whole measurement period, except the acclimatization period, were used (i.e. Case 1: t=30 to t=120 and Case 2: t=150 to t=240; Fig. 5.3). The subjective responses were analyzed for four questionnaires of each case (i.e. Case 1: q2-q5 and Case 2: q6-q9; Fig. 5.3). The differences between the cases, in physical and physiological measurements, were tested using ANOVA. Differences in subjective responses were studied using the non-parametric Wilcoxon signed-rank Test. Spearman-rho tests were used to study the correlations between local skin temperatures, local thermal sensations, and whole-body thermal sensation. Significant effects are reported for $p<0.05$. The commercially available software package PASW Statistics 18.0 (SPSS Inc., Chicago, USA) was used to analyze the data.

5.3 Results

Physiological measurements

Mean, distal, and proximal skin temperatures and core temperature differed significantly between the cases (ANOVA, p<0.001; Table 5.3). Although the differences were relatively small (some within the measurement accuracy), highest mean skin temperatures were found during case *5.AC-R-M-F*. Highest distal skin temperature was found during case *5.AC-R-M-F*, followed by case *1.PC-C-M*. Lowest distal skin temperatures were measured in case *2.AC-C-M* and *4.AC-R-M-F*. Highest proximal skin temperatures were measured during case *5.AC-R-M-F*, followed by case *6.AC-R-D-F*. Lowest distal proximal skin temperatures were found during case *4.AC-R-M-F*. In figure 5.5, the mean local skin temperatures are presented for the different cases. During case *2.AC-C-M* and *4.AC-R-M-C* the hands and forearms were significant (p<0.01) colder compared to the other cases. Furthermore, during case *5.AC-R-M-F* and *6.AC-R-D-F* the feet and left lower leg were significant (p<0.01) colder compared to the other cases.

Table 5.3 Mean, distal, and proximal skin temperatures and core temperature during all experimental cases

Variable	**Case 1. PC-C-M**	**Case 2. AC-C-M**	**Case 3. AC-C-D**	**Case 4. AC-R-M-C**	**Case 5. AC-R-M-F**	**Case 6. AC-R-D-F**
Mean skin temperature [°C]	33.1±0.1*	32.9±0.1*	33.0±0.0*	32.8±0.1*	33.2±0.2*	33.1±0.1*
Core temperature [°C]	37.0±0.1*	37.0±0.0*	36.9±0.1*	37.0±0.0*	37.0±0.1*	37.1±0.0*
Distal skin temperature [°C]	32.0±0.2*	31.3±0.2*	31.9±0.3*	31.3±0.3*	32.1±0.4*	31.6±0.3*
Proximal skin temperature [°C]	34.1±0.1*	33.8±0.1*	33.9±0.2*	33.7±0.1*	34.4±0.3*	34.2±0.1*

Values are presented as mean ± SD, *significant case effect (ANOVA, p<0.001)

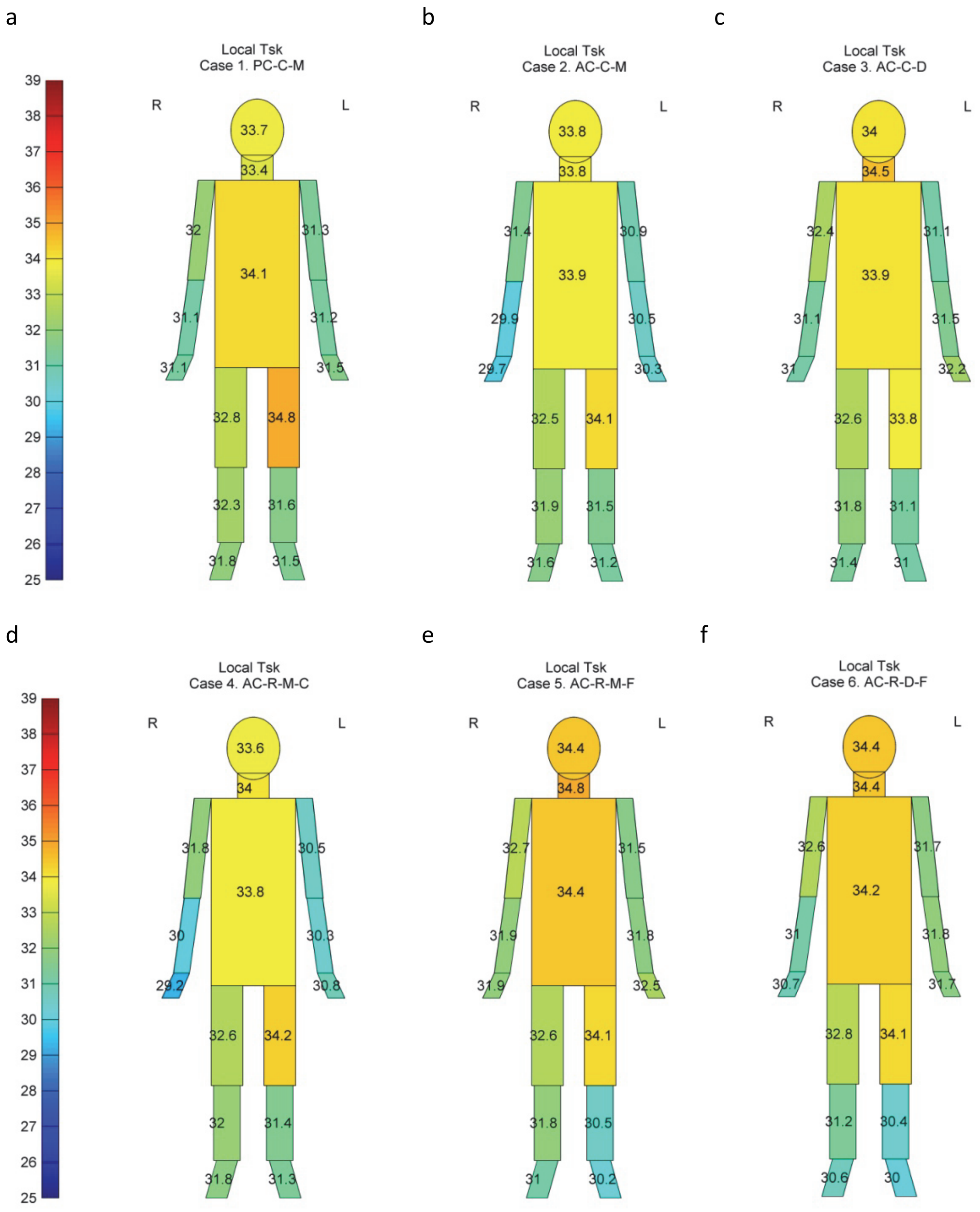

Figure 5.5 Mean local skin temperatures; **(a)** Case 1. PC-C-M, **(b)** Case 2. AC-C-M, **(c)** Case 3. AC-C-D, **(d)** Case 4. AC-R-M-C, **(e)** Case 5. AC-R-M-F, and **(f)** Case 6. AC-R-D-F

Subjective responses

Thermal sensation was asked on a continuous 7 point ASHRAE thermal sensation scale, the corresponding terms are listed in Table 5.4. The case effect was significant (ANOVA, $p<0.05$) different for whole body thermal sensation (thermal sensation vote, TSV) (Figure 5.6). With respect to the means (TSV, Table 5.4) and medians, the lowest whole body thermal sensation (TSV) was found for case *4.AC-R-M-C* (*active* cooling through *radiation* by the *ceiling*), the highest mean TSV was found for *5.AC-R-M-F* (*active* cooling through *radiation* by the *floor*). The TSV's were furthermore compared with the predicted mean vote index (PMV) according to EN-ISO 7730[26]. Since this index is often used in building practice to assess the thermal comfort during building design phase. The PMV's were for all cases significantly different from the TSV (Wilcoxon signed-rank test, $p<0.05$; Table 5.5). For all cases, except case *1.PC-C-M* (*passive* cooling through *mixing* ventilation), the differences were within the accuracy of the PMV (±0.5 scale units). For case *1.PC-C-M* the subject were feeling significantly colder than predicted. The TSV's from case *3.AC-C-D* (*active* cooling through *convection* by *displacement* ventilation) showed the best agreement with the PMV. Besides, the thermal sensation data of this case were closest to neutral and showed less deviation within and between the subjects (Figure 5.4). The largest deviations in thermal sensation were observed for case *5.AC-R-M-F* (*active* cooling through *radiation* by the *floor*).

Table 5.4 ASHRAE 7-point thermal sensation scale[34]

Thermal sensation	Corresponding term
-3	Cold
-2	Cool
-1	Slightly cool
0	Neutral
+1	Slightly warm
+2	Warm
+3	Hot

Table 5.5 Predicted mean vote (PMV) and actual mean vote (AMV) for all experimental cases

Variable	Case 1. PC-C-M	Case 2. AC-C-M	Case 3. AC-C-D	Case 4. AC-R-M-C	Case 5. AC-R-M-F	Case 6. AC-R-D-F
PMV [-]	0.3±0.1	0.1±0.03	0.1±0.0	0.1±0.02	0.2±0.04	0.0±0.0
AMV [-]	-0.3±0.64*	-0.1±0.45*	0.1±0.4	-0.3±0.41*	0.5±0.59*	0.2±0.3*

Values are presented as mean ± SD, *p<0.05 versus PMV

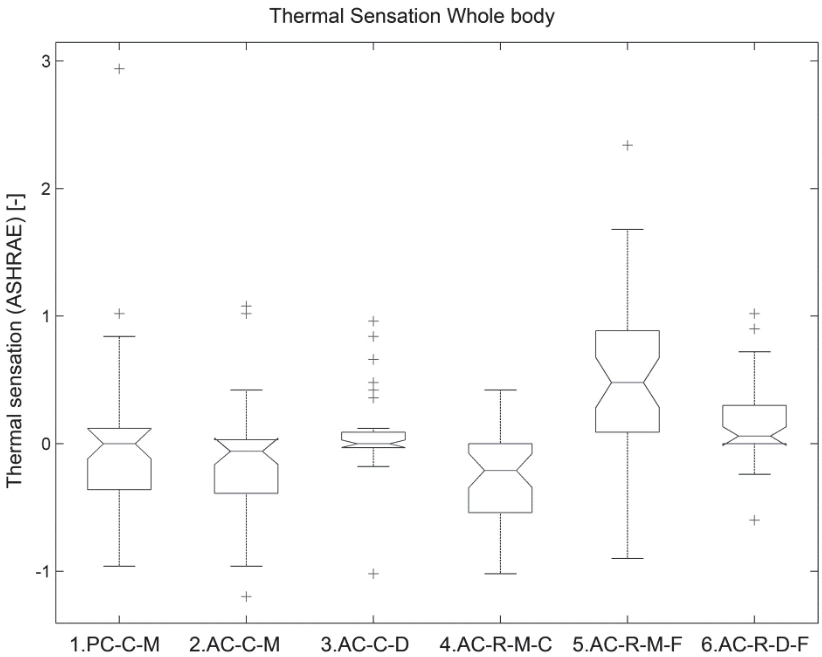

Figure 5.6 Boxplot whole body thermal sensation, the line within the box indicates the median, the bottom and top of the box represent respectively the 25^{th} and 75^{th} percentile, the black horizontal lines present 1.5 IQR, and the crosses indicate outliers.

The average local thermal sensations for each case separately, are represented in Figure 5.7. Data of the forearms indicate slightly colder sensations compared to the other body parts for case *1.PC-C-M*, *2.AC-C-M* and *4.AC-R-M-C*. Although, all local skin temperatures and sensations were significantly ($p<0.05$) influenced by the cases, no high correlations ($r<0.4$) were found between local skin temperatures and local thermal sensations and whole body thermal sensation. Furthermore, no relevant correlations ($r<0.45$) were found between local effects (i.e. skin temperature and thermal sensation) and local air temperature, air velocity and surface temperatures.

In Figure 5.8 the thermal comfort votes are presented for all cases. Both case *3.AC-C-D* and *6.AC-R-D-F* are assessed as most comfortable, based on the percentage of comfortable votes (75% comfortable and 25% slightly comfortable). Case *1.PC-C-M* and *5.AC-R-M-F* are assessed as most uncomfortable. With respect to local thermal comfort, significant case effects were observed for the forearms as well. For both whole body thermal sensation and comfort, no significant predictive parameters could be indicated.

In Table 5.6 the predicted percentages of dissatisfied (PD), due to different local discomfort parameters, are given, according to EN-ISO 7730[26] and ASHRAE[34]]. Furthermore, the maximum allowed PD, according to ASHRAE and the B category of EN-ISO 7730, is given per parameter. The PD caused by a vertical temperature difference between the head and ankles is exceeded in cases 5.AC-R-M-F and 6. AC-R-D-F. The PD caused by a warm floor is exceeded in case 4.AC-R-M-C. In cases 5.AC-R-M-F and 6. AC-R-D-F the PD caused by a radiant asymmetry between ceiling and floor (PD warm or cool ceiling) is exceeded as well. In cases 1 to 3 all local discomfort parameters were within the given limits.

Table 5.6 Predicted Percentage of Dissatisfied (PD) due to local discomfort according to EN-ISO 7730[26] and ASHRAE[34].

Variable	**Norm**	**Case 1. PC-C-M**	**Case 2. AC-C-M**	**Case 3. AC-C-D**	**Case 4. AC-R-M-C**	**Case 5. AC-R-M-F**	**Case 6. AC-R-D-F**
PD Draft (DR) [%]	<20	17.1±2.7	11.0±1.2	1.7±0.2	9.8±0.5	1.7±0.4	3.9±0.5
PD Vertical air temperature difference [%]	<5	Left: 0.3±0.0 Right: 0.5±0.1	Left: 0.4±0.0 Right: 0.5±0.0	Left: 0.7±0.1 Right: 1.3±0.1	Left: 0.1±0.0 Right: 0.2±0.0	Left: 7.4±1.4 Right: 14.0±2.3	Left: 9.6±1.2 Right: 14.6±2.1
PD Warm or Cool floor [%]	<10	5.9±0.0	5.9±0.0	5.5±0.0	12.0±0.2	9.0±0.4	8.8±0.4
PD Warm or Cool Ceiling	<5	0.1±0.0	0.1±0.0	0.2±0.0	0.3±0.0	13.7±0.5	6.9±0.4

Values are presented as mean ± SD

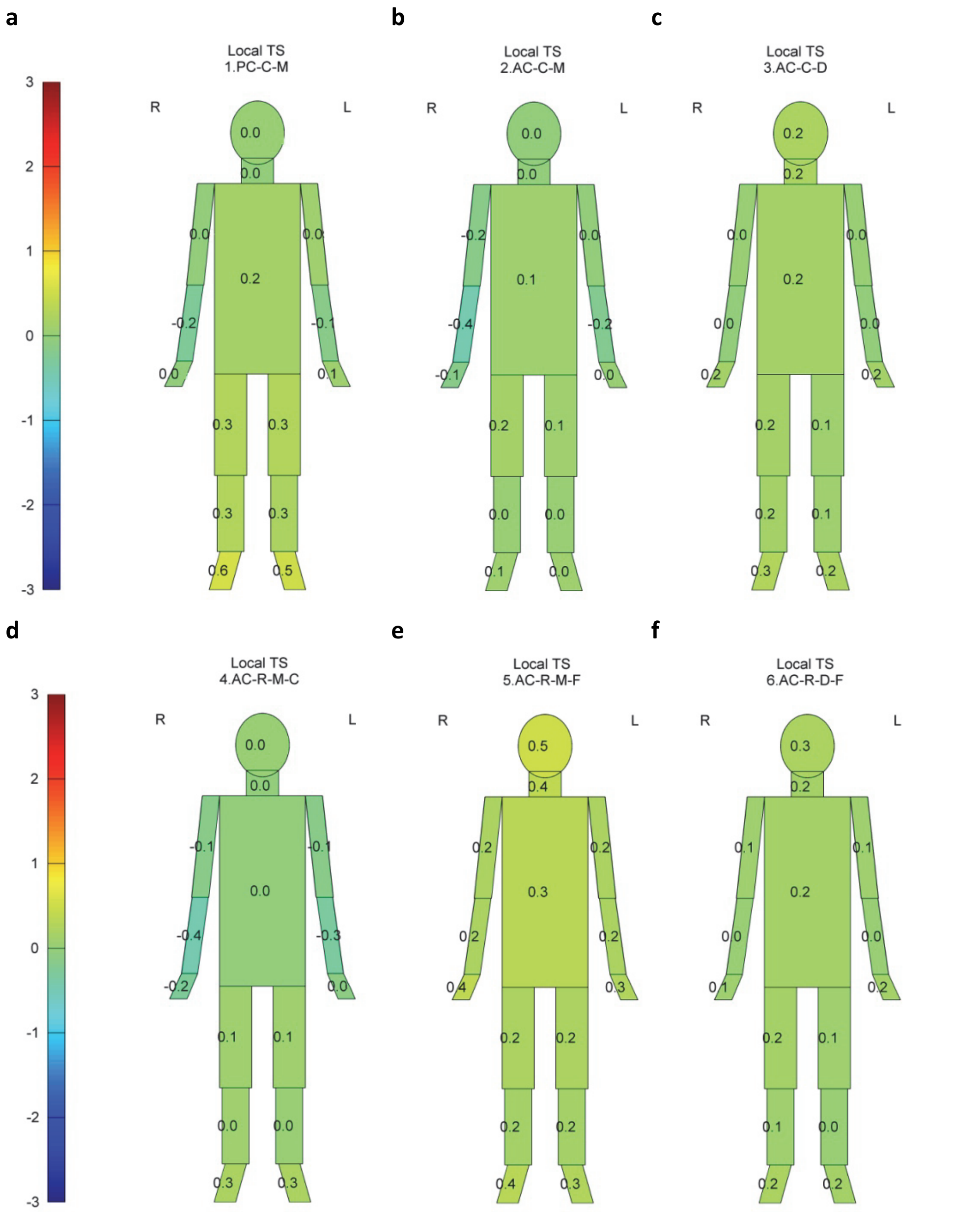

Figure 5.7 Mean local thermal sensation; **(a)** Case 1. PC-C-M, **(b)** Case 2. AC-C-M, **(c)** Case 3. AC-C-D, **(d)** Case 4. AC-R-M-C, **(e)** Case 5. AC-R-M-F, and **(f)** Case 6. AC-R-D-F

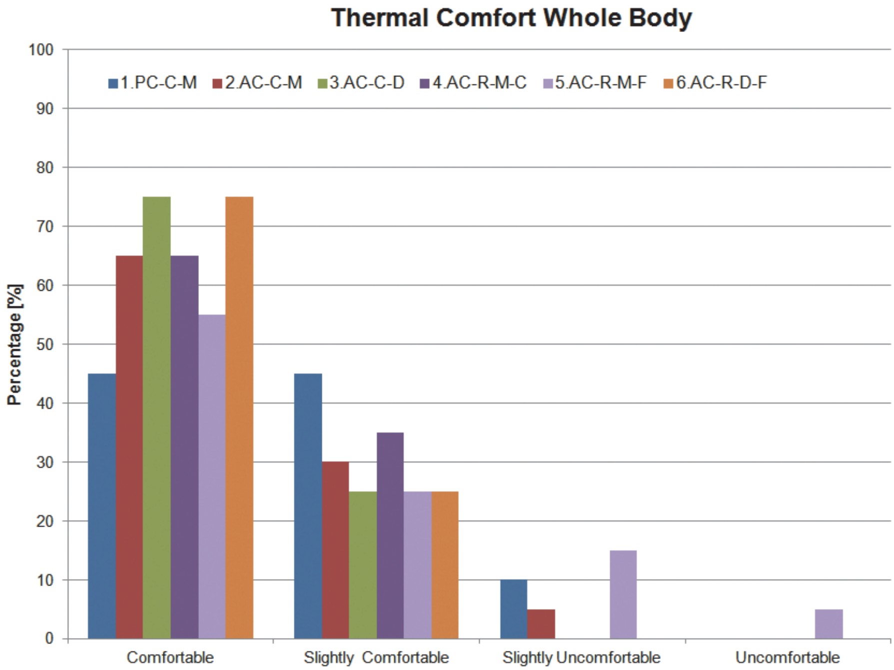

Figure 5.8 Frequency plot of thermal comfort votes for all cases

5.4 Discussion

All cases were designed at a neutral PMV index (PMV≈0). However, thermal sensation data were significantly different between the six different experimental cases. The lowest whole body thermal sensation votes were observed in cases *1.PC-C-M* (*passive* cooling through *convection* by *mixing* ventilation) and *4.AC-R-M-C* (*active* cooling through *radiation* by the *ceiling* in combination with *mixing* ventilation) (TSV=-0.3±0.64 and -0.3±0.41). Highest whole body thermal sensation votes were observed in case *5.AC-R-M-F* (*active* cooling through *radiation* by the *floor* in combination with *mixing* ventilation). The largest discrepancy with the PMV was found case *1* (average difference was 0.6 scale units), which indicates that the subjects were feeling significantly colder than predicted. In case *5.AC-R-M-F* (*active* cooling through *radiation* by the *floor* in combination with *mixing* ventilation) the subjects were feeling significant warmer than predicted and warmer compared to the other cases (Figure 5.6), although the operative temperature and PMV were in line with case *4* (Table 5.1). Furthermore, small but significant differences were observed in body temperatures (some within measurement accuracy). Previous studies indicate that local effects, due to non-uniform environmental conditions influence whole-body thermal sensation and comfort[3 4 37]. Therefore, the authors tested the hypothesis that local skin temperatures and local thermal sensation and comfort influence whole-body thermal sensation and comfort. Although significant local effects were found, these local effects (i.e. local thermal sensation and comfort and local skin temperatures) could not be indicated as significant predictive parameter. Besides, significant case effects (Table 5.1) were observed with respect to the physical parameters (e.g. air temperature and air velocity). However, these parameters could not be marked as predictive parameter as well regarding whole-body thermal sensation. Therefore, it is not yet clear in which way local effects influences whole body subjective votes (both thermal sensation and comfort). These results are contrary to the results presented in Zhang et al.[4]; they found significant and high correlations between local skin temperatures and whole-body thermal sensation. The differences between our study and the study of Zhang et al. might be explained by the differences in measurement set-up that has been applied. The experiments in the study of Zhang et al. were performed using an air-sleeve which was attached to one specific body part. Subsequently, the influence on whole body TSV of cooling or warming this body part was studied. In our study, the approach was to expose the subjects to more realistic conditions with respect to the built environment. The intention was, however, to impose sufficient differences between and within the cases to achieve clear results and to draw conclusions for less critical situations that may occur in practice.

During cases *4.AC-R-M-C* and *5.AC-R-M-F* the subjects were exposed to, respectively, cooling through the *ceiling* and *floor*. Although mean operative temperature differed on average only 0.1°C, TSV differed substantially (-0.3±0.41 vs. 0.5±0.59). This indicates that the operative temperature only is not sufficient regarding the prediction of thermal sensation under non-uniform thermal environments. With respect to the plane radiant temperature asymmetry, a warm ceiling is more critical regarding discomfort compared to a cool ceiling[26]; which is confirmed in this study.

Case *5.AC-R-M-F* is perceived as most uncomfortable; the largest deviation from a neutral thermal sensation occurred and the largest (statistical) dispersion with respect to the TSV was found within the results for this case (Figure 5.6). During this case the subjects were feeling significantly warmer than predicted; as a result 45% of the thermal comfort votes differed from ‘Comfortable’ (Figure 5.8). According to the thermal sensation votes, case *3.AC-C-D* (*active* cooling through *convection* by *displacement* ventilation) appears to be most comfortable (averaged AMV including standard deviation closest to neutral). From the thermal comfort votes (Figure 5.8), both case *3.* and *6.AC-R-D-F* (*active* cooling through *radiation* by the *floor* in combination with *displacement* ventilation) are assessed as most comfortable (75% of the votes are ‘comfortable’ and 25% ‘slightly comfortable’).

In literature, radiant panels (for both heating and cooling) are regarded as interesting alternative to all air systems with respect to thermal comfort and energy-efficiency[7 13 17 19]. In this study no clear preferences were found for either convective or radiant cooling systems, based on the thermal sensation and thermal comfort votes (both local and whole-body). The ventilation efficiency of a displacement ventilation system (DV) is higher compared to a mixing ventilation system, and can therefore provide a higher air quality at breathing level[38]. However, due to the stratified characteristics of DV, thermal comfort is regarded as an important design aspect, especially in combination with a radiant cooling floor system[13 39]. In our study, the experimental cases using displacement ventilation (case *3* and *6*) are considered as most comfortable. Though the differences between all cases are considered as small apparently less cooling is required (i.e. higher operative temperatures are allowed) for case *1* and *4* compared to case *5*.

With respect to the Predicted Percentage Dissatisfied (PD) due to local discomfort, both case *5* and *6* exceeded the comfort limits regarding the vertical air temperature difference between head and ankles, and radiant asymmetry between ceiling and floor. However, case *6* is assessed as comfortable while case *5* is perceived as less comfortable which may indicate that the PD due to radiant asymmetry has more weight when compared to the PD due to a vertical temperature difference. In case *4* the limit with respect to a warm floor is exceeded. Yet, based on the subjective votes, we can conclude that the presence of one local discomfort factor will not result in global thermal discomfort. Rather, the combination of several local discomfort factors can result in global discomfort, although the individual local discomfort factors are within their limits; this effect can be noticed in case *1.PC-C-M*. However, more research is needed to clearly indentify these influences.

5.5 Conclusion

For the prediction of thermal sensation and thermal comfort under non-uniform conditions, the operative temperature only is not sufficient. Highly non-uniform environments, as case *6.AC-R-D-F (active* cooling through *radiation* by the *floor* and *displacement* ventilation) can achieve a comparable or even a more comfortable assessment compared to uniform environments, as case *2.AC-C-M* (*active* cooling through *convection* by *mixing* ventilation). Under the studied uniform conditions the thermal sensation can be predicted well by the PMV index. Contrary, non-uniform environments, as case *4.AC-R-M-C* (*active* cooling through *radiation* by the *ceiling* and *mixing* ventilation) can achieve significantly different thermal sensation votes as predicted in advance. Although in this study the differences were within the accuracy of the PMV, this difference can be enlarged in case the environmental conditions tend away from neutral. The differences are most probably caused by local effects (local thermal sensations and local skin temperatures) and the presence of combined local discomfort factors. More research is needed to indentify the relations between these local effects, local discomfort factors and whole body thermal assessment. Prudence is required in order to design thermal comfortable conditions if low exergy/energy systems (e.g. high temperature cooling by means of radiation) are applied.

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Chapter

6

Downdraught assessment during design

experimental and numerical evaluation of a rule of thumb

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Abstract

Large glass façades are popular architectural features in building design nowadays. However, these façades can result in interior downdraught during periods with low outdoor temperatures. A rule of thumb exists to assess the downdraught risk, based on window height and window temperature[1]. In this paper the validity of this rule of thumb is evaluated by an experimental and a numerical study.

In the experimental part ten healthy male subjects (age 20-26 year) are exposed to two different downdraught conditions in a controlled climate chamber. Experimental results are also used to validate the numerical models. In the numerical (Computational Fluid Dynamics) part a parameter study has been performed to assess the influence of window height and window surface temperature beyond the range tested in the climate chamber. In addition, different floor temperatures have been investigated to evaluate the effect of floor heating as a possible design option to prevent downdraught.

Based on both experimental and numerical results the existing rule of thumb is shown to be conservative. Furthermore, the numerical results reveal that an increased floor temperature (i.e. floor heating) can increase the downdraught risk. Therefore, it is recommended to modify the rule of thumb by incorporating the floor temperature as a parameter.

6.1 Introduction

Glazed façades and atria are popular architectural building design features. These features are regarded as beneficial measures in terms of daylight. However, these façades may cause comfort related problems due to downdraught. In case of downdraught the air layer close to a cold surface (i.e. window) is cooled, which causes this layer to flow downwards due to buoyant forces. In this paper the term 'downdraught' is used for this type of buoyancy driven flows.

If the cold air flow is not compensated for by an upstream air flow, the cold air can penetrate into the living zone[2]. Until ten years ago downdraught related problems were mainly solved by placing heating appliances underneath glazed façades and large windows. With the improvement of the thermal performance of windows and window systems since, additional heating appliances may not be necessary anymore[3-7]. However, in current building practice often a cautious approach is taken. Therefore, radiators, convectors or floor heating systems are installed beneath windows while they might not be required with respect to downdraught.

According to Huizenga et al.[4] two aspects are important regarding a glazed façade in relation to thermal comfort: cold radiant asymmetry and draught. Radiant asymmetry is influenced by the surface temperature of the window, posture and position of the subject and human factors like clothing level and metabolism. Draught is affected by the air velocity, turbulence intensity and air temperature.

Several numerical and experimental studies have been conducted to improve understanding of the flow principle and the effect of several solutions to prevent downdraught. Heiselberg, among others, concluded that windows up to 2.5 meter height do not cause downdraught related problems in case of well-insulated glazing systems (expressed by a maximum temperature difference between the room air and the window surface of 2.5°C) with the occupied zone starting at 0.6 meters from the window[2].

To assess the risk of downdraught in the design phase several rules of thumb are available. Olesen, among others, defined a rule of thumb that allows assessment of the maximum window height (h in m) in combination with the U-value of the glazing (U_{glass} in W/m^{2}K) with given constraints on the maximum accepted air velocity (v_{air} in m/s) in the living area (Equation 6.1)[1]. If a lower maximum accepted air velocity is considered, equation 6.2 can be applied[8].

$$U_{glass} * h \leq 4.7 \text{ W/mK} \qquad v_{air;max}=0.18 \text{ m/s} \qquad (6.1)$$

$$U_{glass} * h \leq 3.2 \text{ W/mK} \qquad v_{air;max}=0.15 \text{ m/s} \qquad (6.2)$$

The numerical and experimental studies from which the rule of thumb has been derived, show some limitations: - Only draught is taken into account, while according to Huizenga et al.[4] radiation also has a significant influence on thermal comfort related to downdraught; - The results are not validated in experiments with human subjects; - In most studies the window height is limited to two or three meters, while it is expected that frequently installed higher windows cause more problems related to thermal comfort.

As this particular rule of thumb is still applied in practice, the question is to what extent it is able to predict downdraught risk correctly. As the rule of thumb also does not address contemporary counteracting design solutions, the query arises whether low-temperature heating systems (e.g. floor heating) are able to prevent downdraught.
Following the above, the objective of this study is to validate the presented rule of thumb in an experimental study with human subjects and evaluate its applicability for high windows and configurations with floor heating.

The research method applied experiments with human volunteers in a climate chamber and numerical modeling with Computational Fluid Dynamics (CFD) to evaluate alternative configurations. The experiments with the human volunteers were designed *a priori*. Since, the configuration of the climate chamber did not allowed an evaluation of the downdraught risk with respect to the window height, a numerical study was performed to analyze the effects of the window height. The numerical model is validated against experimental results obtained under the same conditions as the subjects were exposed to.

6.2 Experimental facility

Both the experiments with human subjects and the experiments for validation of the CFD model were carried out in a climate chamber (thermophysiological test room, Figure 6.1). The test room is situated at the laboratory of the unit Building Physics and Systems of the department of the Built Environment at the Eindhoven University of Technology. The dimensions of the room are similar to a standard office room: 3.6x5.4x2.7m^3 (WxLxH). The test room is constructed of a well insulated chamber (wall thickness is 100mm). In this chamber the temperature of each surface can be controlled individually in the range of 11-35°C[9]. Cooling of these panels is possible through a connection to an aquifer system and ranges between 10 and 17°C. For heating, a boiler in combination with a supplementary electrical heater for fine-tuning the supplied water temperature is applied. The total temperature range of the supplied water is 11 – 35°C.
The air was conditioned by an air-handling unit (Verhulst); the ventilation rate was 150 m^3/h. Supply was through a slit (0.01 m height) along the width of the room, integrated in a plenum box (100x3600x200mm^3 WxLxH) positioned at the top of the smallest wall. The exhaust (0.2 m height) was positioned in a similar box at the top of the opposite wall.

Temperature control for air and water was provided through an embedded system (software programmed in LabView 8.6, National Instruments, Austin, USA).

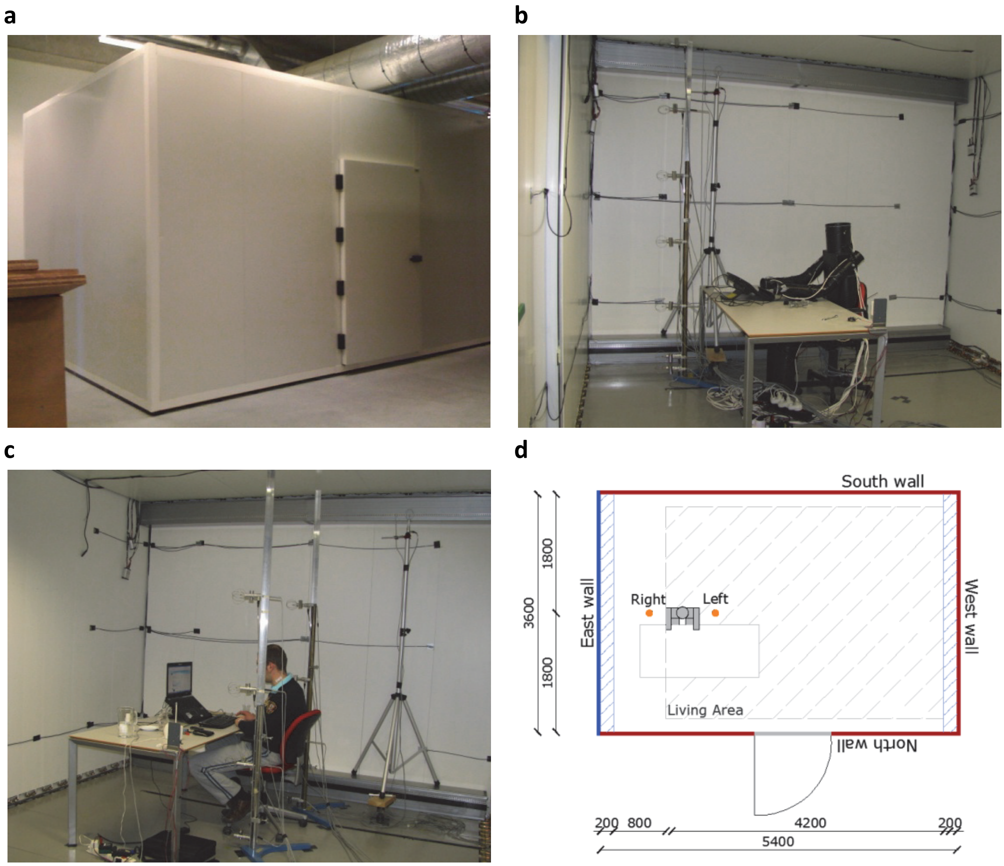


Figure 6.1 (a) Thermophysiological test room; **(b)** thermal manikin in experimental set-up; **(c)** test subject in experimental set-up; **(d)** floor plan where the orange dots indicate the measurement stands, the grey hatched surface represents the living area, the blue hatched surfaces represent the plenum boxes and the blue wall indicates the cold wall.

6.3 Subject experiments

This section describes the subject experiments in order to evaluate the applicability of the rule of thumb (Eq. 6.1 and 6.2). In total two cases have been investigated.

Method

Configuration and equipments

During the experiments both physical and physiological measurements have been performed continuously. Air temperature (NTC Thermistor, type SC95, accuracy ±0.1°C), relative humidity (RH) (Humidity Sensors, Honeywell HIH- 4000 series), air velocity (hot sphere anemometer, Dantec, estimated accuracy 15%[10]), surface temperature (NTC Thermistor, U-type EU-UU-10-PTFE, accuracy ±0.1°C) carbon dioxide (Carbon Dioxide Transmitter, Vaisala 0–2000 ppm), and illuminance (Lux meter, Hager model E2) were measured according to EN-ISO 7726[11]. Air temperature, RH, and air velocity were measured on two stands at 0.1, 0.6, 1.1 and 1.7 m height. These stands were placed on the left and right side of the subject, at a distance of 0.2m (the orange dots in Figure 1d). The average surface temperature for each surface was derived from nine measurement points on each surface (at a grid of 3x3). The mean radiant temperature was determined according to the surface temperatures and view factors related to the position of the subject.

Skin temperatures were measured according to EN-ISO 9886[12] by wireless iButtons (Thermochron iButton, DS1291H, Maxim, CA, Sunnyvale, USA, accuracy ±0.125°C) at 24 locations to assess possible differences between the left and right side of the human body[13]. Ibuttons were attached with semi-permeable tape (Fixomull; BSN medical gmbh, Hamburg, Germany). Mean skin temperature was calculated according to the 14-point weighing as proposed by EN-ISO 9886[12] (Point 1-14, Figure 6.2a). Distal skin temperature was calculated as average of instep, ankle, finger tip, hand, and forehead skin temperature. To avoid a disproportional distribution, forehead and instep temperature have been taken into account twice. Proximal skin temperature was calculated as an average of the scapula, paravertebral, upper chest, and abdomen skin temperature. Core temperature was determined by measuring the intestinal temperature through an ingestible telemetry pill (CorTemp, Ingestible Core Body Temperature Sensor, HT150002, HQ Inc., Palmetto, FL, USA, accuracy ±0.1°C), which was ingested 30 minutes before entering the climate room.

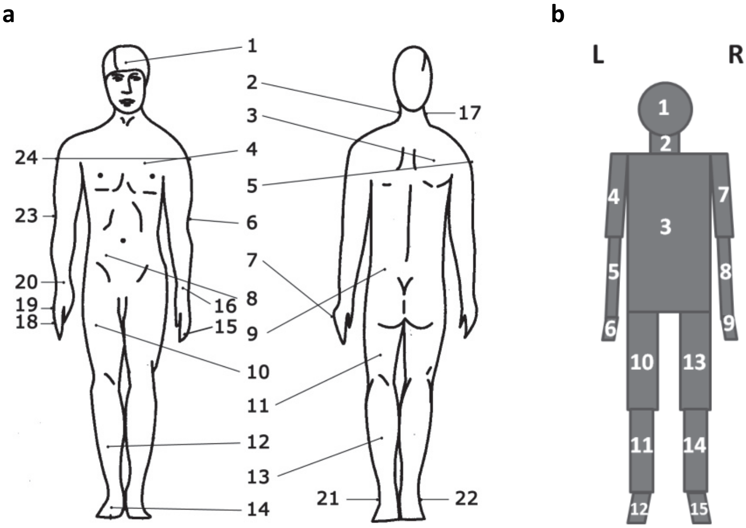


Figure 6.2 (a) Measurement sites skin temperature; **(b)** Schematic representation of body parts to assess local thermal sensation and comfort

Cases

For the subject experiments two different downdraught situations were defined. One case (S1) without compensation by a heating appliance and one case (S2) with compensation through a low temperature floor heating system. Downdraught was created by cooling the 'east wall' (Fig. 6.1d). The subjects were positioned at the boundary of the living area, i.e. one meter from the cold wall (see Fig 6.1d). This distance is adopted from EN-ISO 7730[14], note that this distance is larger than the distance assumed by Heiselberg[2].

Both cases were designed at a mean operative temperature of 21.5°C (S1: 21.6±0.04°C and S2: 21.8±0.03°C) which corresponds to a predicted neutral thermal sensation (PMV≈0; for a clo-value of 1.0 and an activity level of 1.2 met, see 'Protocol'). The mean operative temperature of case S2 is slightly, though significant ($p<0.05$), higher in comparison to case S1. Furthermore, when the cases are assessed to the rule of thumb they would both not be allowed (Uglass*h is for S1: 5.1±0.3 W/mK and for S2: 5.2±0.3 W/mK, maximum allowed is 4.7 W/mK). For this assessment the maximum allowed air velocity is set at 0.18 m/s (Equation 6.1), where the U-value of the glass is calculated according to Equation 6.3, which assumes an indoor-outdoor temperature difference of 34 K.

$$U_{glass} = \frac{T_{air;indoor} - T_{window}}{4.08} \tag{6.3}$$

The conditions for each case are listed in Table 6.1; mean operative temperature, air velocity, turbulence intensity and relative humidity were averaged from the measurement data from the two comfort stands that were applied during the measurements (Figure 6.1d: 'Right' and 'Left').

Table 6.1 Case summary

	Case S1	Case S2
Uglass*h [W/mK]	5.1 ± 0.3	5.2 ± 0.3
Mean operative temperature [°C]	21.6 ± 0.1	21.8 ± 0.2*
Mean air temperature [°C]	22.1 ± 0.1	22.2 ± 0.2
Surface temperature East wall [°C]	13.7 ± 0.4	13.7 ± 0.6
Surface temperature Floor [°C]	23.0 ± 0.0	24.3 ± 0.1*
Surface temperature remaining surfaces [°C]	23.2 ±0.1	22.7 ± 0.1
Mean radiant temperature [°C]	21.1 ± 0.1	21.3 ± 0.2*
Mean radiation asymmetry [°C]	6.1 ± 0.2	6.1 ± 0.3
Mean air velocity [m/s]	0.07 ± 0.01	0.09 ± 0.02*
Mean turbulence intensity [%]	25.9 ± 1.6	25.9 ± 1.3
Mean relative humidity [%]	46.9 ± 6.3	47.7 ± 6.0

*Significant case effect ($p<0.05$)

Subjects

Ten young male subjects, age 18 to 26 years, participated in the experiment. The volunteers were given detailed information regarding the purpose and the methods used in the study, before written consent was obtained. However, they were not informed on the actual conditions they were exposed to. All subjects were healthy, normotensive, non-obese, and not taking any medications that might alter the cardiovascular or thermoregulatory responses to the temperature changes; subject characteristics are listed in Table 6.2. Body fat percentage was determined by means of skinfold thickness, according the Siri equation[14]. Skin folds were measured at four sites: subscapular, suprailiacal, and at the triceps and biceps[15].

Table 6.2 Subject characteristics

	Mean ± Std.Dev	Minimum	Maximum
Age (yr)	23.5±1.7	20	26
Height (cm)	185.0±6.1	177.0	197.0
Weight (kg)	77.7±8.8	67.5	91.2
Body fat% (%)	16.8±3.9	8.7	23.5
BMI (kg/m^2)	22.6±1.6	21.4	25.9

Protocol

Subjects visited the climate chamber during winter (January-February 2011, average outside temperature ranged from 0.2 to 8.0°C[16]). During this one day visit they were exposed to, in total, four different conditions (two for this experiment (S1 and S2) and two for another related experiment). The order of the two experiments was alternated; e.g. subject 1 started with S1 and S2 in the morning and ended with the other experiment in the afternoon, subject 2 started with the other experiment in the morning and ended with S1 and S2 in the afternoon, subject 3 started with S1 and S2, etc. For practical reasons, the order of the experiments S1 and S2 was kept the same in all cases.

Prior to the measurements, the subjects performed a light exercise of 5 minutes to obtain skin vasodilatation in order to ensure that all subjects entered the climate room in the same thermal state[17]. Vasodilatation was assessed by the skin temperature difference between forearm and top of the forefinger[18 19]. Furthermore, the skin temperature sensors were attached, and the subjects characteristics (height, weight, and fat percentage) were determined.

After entering the climate room, the experiment started with an acclimatization period (30 min). During this period they received an instruction regarding the use of the questionnaires. After completion of the first case an acclimatization period of 30 minutes followed (as preparation for the second case). During this period the subjects had the opportunity to visit the rest room. A detailed time line is given in Figure 6.3.

During the experiments, the subjects wore standardized clothing, consisting of a cardigan, jogging pants, thin T-shirt, underpants, socks and shoes. The clo-values were determined according to McCullough et al. and EN-ISO 9920[20-22]. The total heat resistance of the clothing ensemble, including desk chair, was approximately 1.0 clo. The subjects continuously performed office tasks; their metabolic rate was estimated to be approximately 1.2 met[23].

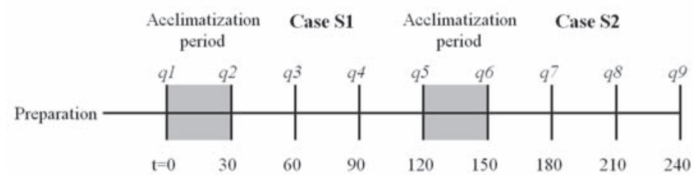


Figure 6.3 Time line of measurement protocol; q is representing the questionnaire moments

Questionnaires

Every 30 minutes, starting at t=0 min, the test subjects filled in a questionnaire. Thermal sensation votes, both global and local for each body part (Figure 6.2b), were asked on a continuous 7-point ASHRAE thermal sensation interval scale, where each point on the line could be marked[14 24]. Global and local thermal comfort were asked on a ISO-based 4-point thermal comfort scale ('Comfortable', 'Slightly Comfortable', 'Slightly Uncomfortable', and 'Uncomfortable')[25]. Visual analogue scales (VAS) were used to assess adverse perceptions and the perceived indoor environment[26]. A question to assess perceived stress was included as well. The questionnaires were presented to the subjects in Dutch through an Internet browser.

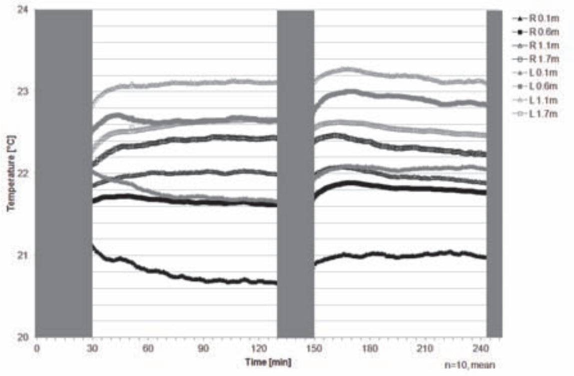
The differences in physical measurements were tested using ANOVA. Differences in physiological responses and subjective responses between the two experimental cases were studied using the non-parametric Wilcoxon signed-rank Test. Frequency analyses were used to indicate differences within thermal comfort votes and perceived air velocity. Significant effects are reported for $p<0.05$. The commercially available software package PASW Statistics 18.0 (SPSS Inc., Chicago, USA) was used to analyze the data.

Results

Physical measurements

Table 6.1 indicates significant ($p<0.05$) differences in mean operative temperature, floor temperature, mean radiant temperature, and mean air velocity between case S1 and S2. In Figure 6.4 the measured air temperatures and air velocities, averaged for all subjects, are represented. The first 30 minutes of each case (i.e. the period from t=0 to t=30 and t=150 to t=180) are not presented because this period is regarded as acclimatization period where the subjects became in equilibrium. Significant differences were found at both measurement stands for the temperature gradient (along the height; mean temperature difference between the sensors at 1.7m and 0.1m height) between case S1 ($\Delta T=1.4\pm0.17$°C) and S2 ($\Delta T=0.8\pm0.09$°C). The sensor at 0.1m height on the right side of the subject (closest to the cold wall) measured the lowest temperatures. During S2 this temperature raised due to the higher floor surface temperature, which caused a decrease in the temperature gradient between 0.1 and 1.7m height. Both sensors closest to the floor (0.1m; left and right) measured the highest air velocities and lowest temperatures. The air velocities at 0.1m at the right side of the subject exceed 0.15 m/s which, based on Equation 6.1, indicate downdraught during both experimental cases. The air velocities on the left side are lower in comparison to the right side, which is caused by a disruption of the flow field due to the subject. The mean radiant temperature asymmetry was in both cases 6.1°C. According to EN-ISO 7730[14] the percentage dissatisfied (PD) due to a cold wall is smaller than 10%, and should therefore not influence the draught perception.

a



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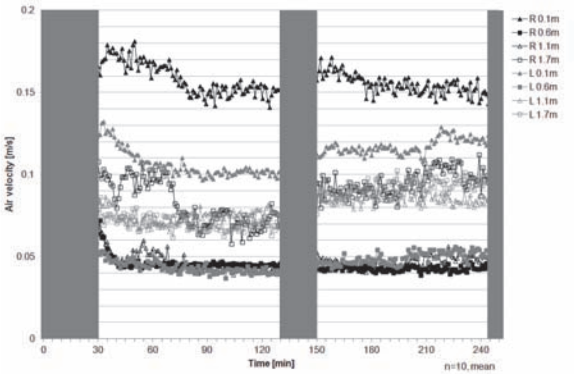

Figure 6.4 (a) Measured air temperatures on both comfort stands at different heights; **(b)** Measured air velocities on both comfort stands at different heights , R represents the stand on the right (cold wall) side of the subject, L represents the stand on the left side and the number indicates the distance in meters from the floor

Physiological measurements

Mean, distal and proximal skin temperatures, and core temperature, averaged for all subjects, are given in Figure 6.5. Furthermore the mean skin temperature of the left side (measurement sites 2,6,15,16,21,24) and the right side (5,17,18,20,22,23) of the body are presented.

The difference in mean skin temperature between S1 and S2 is significant (33.0±0.04°C vs. 32.9±0.08°C $p<0.01$), although these differences were within the measurement accuracy (mean difference 0.02±0.06°C). Difference in distal skin temperature between S1 (31.2±0.19°C) and S2 (30.9±0.24°C) was also significant ($p<0.01$; mean difference 0.29±0.14°C). Core temperature and proximal skin temperature were significant ($p<0.01$) higher during S2 (mean difference respectively 0.10±0.06°C and 0.10±0.10°C).

During both cases the skin temperature of the right side (closest to cold wall) of the subject was significant ($p<0.01$) lower in comparison to the left side (mean difference S1: 0.46±0.11°C and S2: 0.61±0.09°C). The skin temperature of the right side was significant lower ($p<0.01$) during S2 compared to S1). The skin temperature of the extremities (hands and feet) fluctuated more during both cases (range 30.5-32.5°C) than the skin temperatures of the body parts close to the core (range 34-35°C), to regulate the heat exchange with the environment.

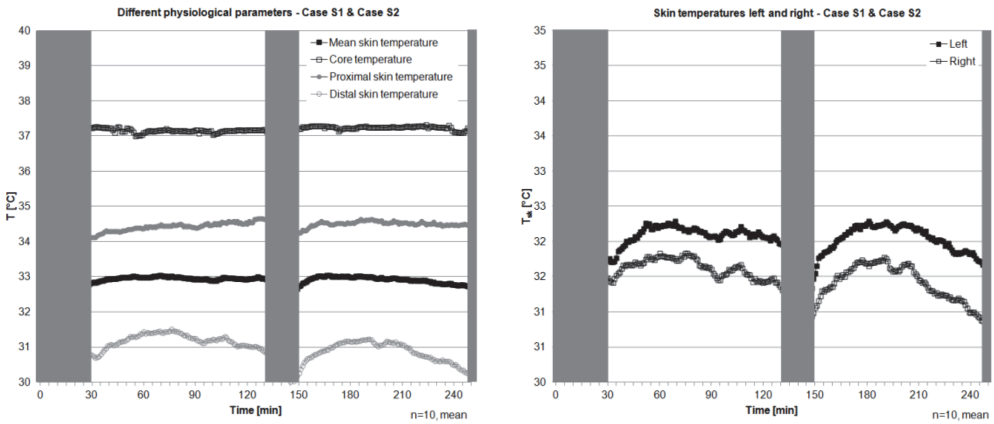

Figure 6.5 (a) Measured mean, proximal and distal skin temperatures and core temperature; **(b)** Mean skin temperature of the left and right (cold wall) side of the body

The increase in skin temperature of the left and right side of the subject and distal skin temperature during the first 30 min of S2 is most probably caused by vasodilatation ($\Delta T_{(forearm\text{-}fingertip)} \approx 0$) which is indicated in Figure 6.6. During the acclimatization period prior to case S2 subjects were allowed to leave the climate chamber to visit the rest room. The increase in vasoconstriction (t=150) most probably occurred because their hands were cooled due to hand washing. Furthermore, the small increase in vasodilatation (t=180) can be explained by a redistribution of the blood which occurred due to a change in posture (from standing to sitting). Subsequently, the increase (from t=210) in vasoconstriction is caused by cooling of the subjects due to the sedentary activity level.

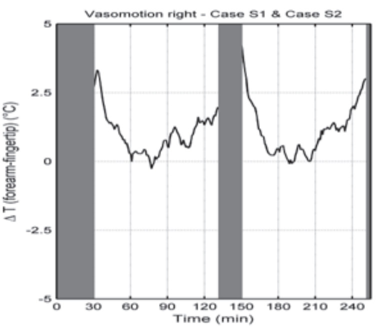

Figure 6.6 Mean difference between forearm and fingertip temperature during the cases S1 and S2. Vasoconstriction is indicated by positive values, vasodilatation by negative values.

Subjective responses

The subjective responses were analyzed for the last three questionnaires of each case (i.e. S1: q3-q5 and S2: q7-q9), to exclude possible effects from the acclimatization period. Mean whole-body thermal sensation (TS) during S1 (averaged for all subjects and three questionnaires) was 0.16 ±0.28, mean TS during S2 was 0.07±0.47 (all corresponding to approximately neutral). The difference in TS between both cases was not significant ($P>0.05$). In Figure 6.7 the results of the frequency analyses of whole-body thermal comfort (TC) votes and perceived air velocity are presented. The case effect on TC was not significant. However, differences in perceived air velocity were significant ($p<0.05$), where in case S2 more often, in comparison to S1, an air movement was observed by the subjects (Figure 6.7b). When the subjects registered an air movement, this air movement was mostly felt at head level.

Regarding thermal comfort of the local body parts, only the feet, lower arms and hands were on occasion slightly uncomfortable, however this did not significantly influence whole body TS and TC (data not presented). Although in S2 more often an air movement was noticed (Figure 6.7b), the subjects preferred no change in air movement in both cases. Furthermore, both cases (all subjects) were assessed as acceptable and no change in terms of warmer and cooler was preferred.

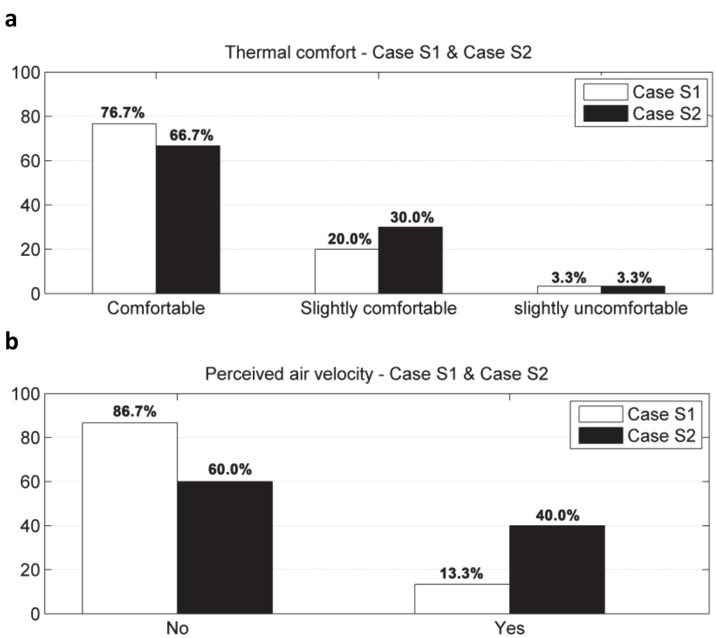

Figure 6.7 Frequency results of **(a)** thermal comfort and **(b)** perceived air velocity

Discussion human data

To the best of our knowledge, this study is the only one wherein subjective responses were taken into account to validate the rule of thumb of Olesen[1] to predict downdraught from cold surfaces. Previous studies focussed mainly on the flow principles and possible solutions to prevent downdraught[2 6 27]. However, cold radiant asymmetry and stratification could be, for example, of importance as well regarding thermal comfort in relation to downdraught[4 28].

The differences in realized conditions between both cases are relatively small, due to the requirements set with respect to the operative temperature. The objective of the experiments with subjects was to impose conditions which represent daily situations. Nevertheless, differences in subjective responses regarding the perceived air velocity were found between S1 and S2 (Figure 6.7). However, in practice larger differences can occur which may result in larger differences between the subjective responses. Besides, the results from the physical measurements show an increased air velocity and related decreased air temperature near the floor for both experimental cases. This indicates that the subjects were exposed to downdraught during both cases. But this downdraught was not registered by the subjects. They did not report any air movement around the feet. In the cases where subjects reported air movement, this was felt at head level, despite relatively low velocities and turbulence intensities (in the range of 0.05-0.1m/s and 20-25%).

The results show that the skin temperature is influenced by the cold wall (mean surface temperature S1:13.7±0.44°C and S2: 13.0±0.56°C. Significant differences were found in physiological responses between the two cases, but no significant differences were observed for the subjective responses. In general, both conditions were assessed by the subjects as comfortable (including slightly comfortable votes). Although, effects from local body parts on whole body thermal sensation and comfort were observed in Zhang et al.[29 30], no influences of local body parts on whole body thermal sensation and comfort were observed in this study. The subjective results are in line with the comfort prediction according to EN-ISO 7730[14]. However, following the rule of thumb[1] the conditions are not allowed because of an increased risk for uncomfortable conditions caused by downdraught.

Conclusion subject experiments

According to the rule of thumb both experimental conditions are not allowed with respect to an increased risk of down draught. However, both experimental conditions were perceived as comfortable by the subjects and the subjects did not prefer a change in air movement. Furthermore, the radiant temperature asymmetry was within the comfort limits according to EN-ISO 7730[14]. Therefore, both experimental conditions were regarded as acceptable.

6.4 Numerical model development and analysis

The subject experiments provide valuable information, but are limited regarding the number of variants that can be studied. Therefore, a variant study has been conducted to further analyse the rule of thumb which can be used to predict downdraught. To perform this study CFD has been used; for which a numerical model has been developed, this model will be discussed in the following.

Computational geometry and discretisation
The geometry is adopted from the climate chamber geometry, as discussed in Section 6.2, resulting in a computational domain with dimensions 5.4 x 3.6 x 2.7m^3 (LxWxH, Fig. 6.8a). With respect to the discretisation two types of grid have been developed: (1) a hybrid grid (1.4 million cells, Fig. 6.8b) for the model with human being (dimensions based on thermal manikin used for validation), combining both tetrahedral and hexahedral cells and (2) a structured grid (0.5 million cells, Fig. 6.8c) for an empty climate chamber. The latter model was developed to allow extension of the number of cases that could be investigated (e.g. geometries with different room heights). Additional models have been developed from these two types of grid for sensitivity analysis. All grids were generated using the commercially available software Gambit 2.4.6 (Ansys Inc, Canonsburg, USA).

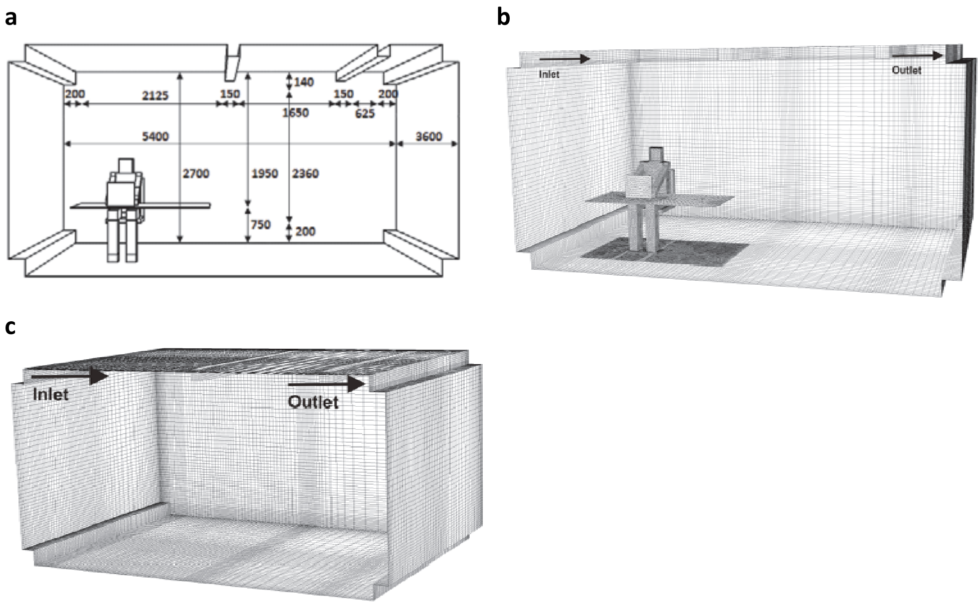

Figure 6.8 (a) Perspective view of computational domain; **(b)** View of the computational grid for the occupied model and (c) view of the computational grid for the empty model at some of the domain surfaces

Boundary conditions and solver settings

The commercially available software package Ansys Fluent 12.1.4 (Ansys Inc., Canonsburg, USA) has been used to solve the transient 3D Reynolds-averaged Navier Stokes (RANS) equations in combination with the Renormalisation Group (RNG) k-ε turbulence model[31] using enhanced wall treatment (average y^+ value cold wall: 10 [coarse grid], 5 [fine grid][32]). Stamou et al. have shown that by using this turbulence model accurate results can be obtained for the prediction of indoor air flow[33]. Buoyancy forces are modeled through the Boussinesq approximation.

The SIMPLE algorithm is used for pressure-velocity coupling, for pressure interpolation the body force weighted discretisation scheme is used and second order discretisation schemes are used for both the convection terms and viscous terms of the governing equations following the best practice guidelines[34]. Simulations have been performed with a time step of 1 second. Per time step 10 iterations were performed. In total 2700 time steps (45 minutes real time) were simulated. Convergence criterion for the scaled residuals was 10^{-5}. Furthermore, the achievement of a heat balance was an important criterion for acceptance of the solution. Despite the fact that steady state conditions were provided, the results of the simulation showed a transient (periodic) behaviour. This transient behaviour could not be referred back to the grid and solver settings. Instead the behaviour is explained by the geometrical and flow configuration which allows for flow instability. In the results, data from the last 900 seconds are averaged and completed with the standard deviation over that period.

During the simulations radiation was not taken into account, only the convective part was solved. To compensate for the radiation part the heat emission of the human being has been halved. Furthermore, the surface temperatures were fixed. The heat emission of the human being, in case of the empty model, is taken into account by implementing a User Defined Function (UDF). The boundary conditions for the initial models were adopted from the subject conditions (Table 6.1) and measured for a room with a thermal manikin (M1 and M2). The averaged measurement results for both cases, which have been used as boundary conditions, are given in Table 6.3.

Table 6.3 Boundary conditions for initial numerical models

	Case M1	Case M2
Inlet – Air temperature [°C]	22.0	22.0
Inlet – Air velocity [m/s]	1.0	1.0
Inlet – Turbulence intensity [%]	7	7
Inlet – Turbulence length scale [m]	0.0014	0.0014
Surface temperature East wall [°C]	13.8	13.4
Surface temperature North wall [°C]	23.1	22.7
Surface temperature South wall [°C]	23.2	22.7
Surface temperature West wall [°C]	23.2	22.8
Surface temperature Floor [°C]	23.0	24.3
Surface temperature Ceiling [°C]	23.3	22.9

Model analysis

As part of the model analysis, a comparison was made between measurement and simulation results for the different type of grids (occupied chamber and empty chamber). These results are presented in Fig. 6.9a and 6.9b. The comparison is shown for Case M2 (Table 6.3), for the air temperature and air velocity along the height of the comfort stand at the right side of the subject. At this position conditions for downdraught are assumed worst. The results for the structured grid of the empty room (with UDF) show improved agreement with the measurements compared to the hybrid grid with manikin for both air velocity (mean deviation 4% and 20% respectively) and air temperature (0.2% and 1.5% respectively). For air velocity, both grids predict the trend. Based on this comparison the variant study is conducted with the grid of the empty room.

Results for a limited grid sensitivity analysis for the empty room grid are shown in Figure 6.9c and 6.9d. Results again are shown for the most critical location with respect to downdraught. The finer grid has a double amount of cells (1.1 million cells). Following this experimental and grid sensitivity analysis the coarse grid is retained for further analysis.

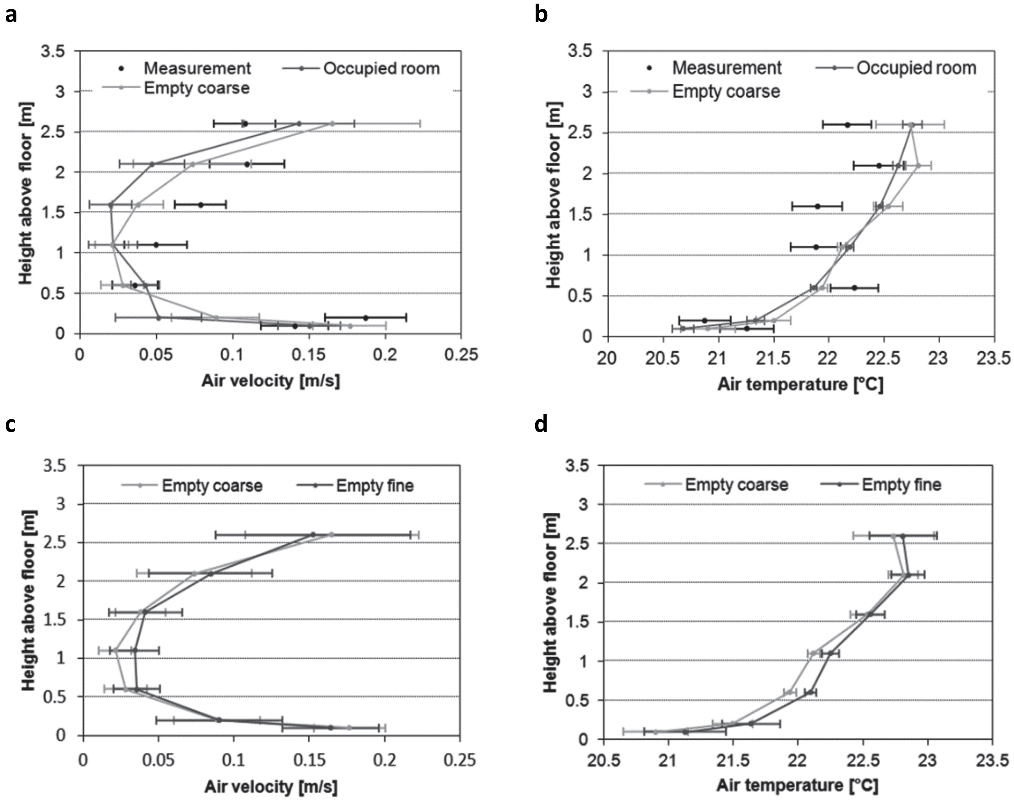

Figure 6.9 (a) Comparison of different grid configurations with measurement results for air velocity at the right side of the subject; **(b)** Comparison of different grids with measurement results for air temperature at the right side of the subject; **(c)** Comparison of air velocity profile along the height at the right side of the subject obtained with the coarse and fine grid and **(d)** Comparison of air temperature profile along the height at the right side of the subject obtained with the coarse and fine grid

6.5 Variant study

The subject experiments were confined within a fixed geometry and boundary conditions. Therefore a numerical variant study has been conducted to analyse the rule of thumb for downdraught analysis outside these constraints. The developed numerical model has been used for this study.
Jurelionis et al. show that higher windows cause more downdraught[35]. In existing downdraught studies, however, the window height is limited to 3m. Furthermore, the effect of downdraught is larger in case of a larger temperature difference between the room air and window surface[2]. Finally, the experimental results presented indicate an effect of the floor temperature on downdraught. Therefore, different floor temperatures, corresponding to low temperature heating systems, have been studied as well. In addition, a distinction has been made in a proportional distributed floor heating system and a local (near the window) denser floor heating system. The geometry of the climate chamber serves as basis for all models; the height has been increased for different variants, resulting in two additional configurations (5.4m and 8.1m height) with respectively 0.8 and 1.1 million cells.

Variants
In total 8 variants have been studied (Table 6.4), applying window height, window temperature and floor temperature as variables. Case M2 is used for the validation of the numerical model (Section 6.4). Wall temperatures have been defined to arrive at (nearly) similar winter indoor operative temperatures.

Table 6.4 Overview of different variants

Variant	Room dimensions (LxWxH)	Window height	Window temp	Floor temp	Wall temp	Operative temp
C1	5.4 x 3.6 x 2.7 m^3	2.7m	13°C	26.0°C	19.6°C	21.5°C
C2	5.4 x 3.6 x 2.7 m^3	2.7m	13°C	21.0°C	23.0°C	21.0°C
V1	5.4 x 3.6 x 5.4 m^3	5.4m	19°C	21.0 °C	21.6°C	21.0°C
V2	5.4 x 3.6 x 5.4 m^3	5.4m	16°C	26.0°C	20.3°C	21.5°C
V3	5.4 x 3.6 x 5.4 m^3	5.4m	16°C	21.0°C	22.4°C	21.0°C
V4	5.4 x 3.6 x 5.4 m^3	5.4m	13°C	26.0°C	20.8°C	21.5°C
V5	5.4 x 3.6 x 5.4 m^3	5.4m	13°C	21.0°C	23.2°C	21.0°C
V6	5.4 x 3.6 x 5.4 m^3	5.4m	13°C	26°C+30°C	20.6°C	22.0°C
V7	5.4 x 3.6 x 8.1 m^3	8.1m	13°C	21.0°C	23.3°C	21.0°C

temp = temperature

Results

Fig. 6.10a and 6.10b indicate the positions for which results are presented and compared. Comparison is done for window height, window temperature and floor temperature.

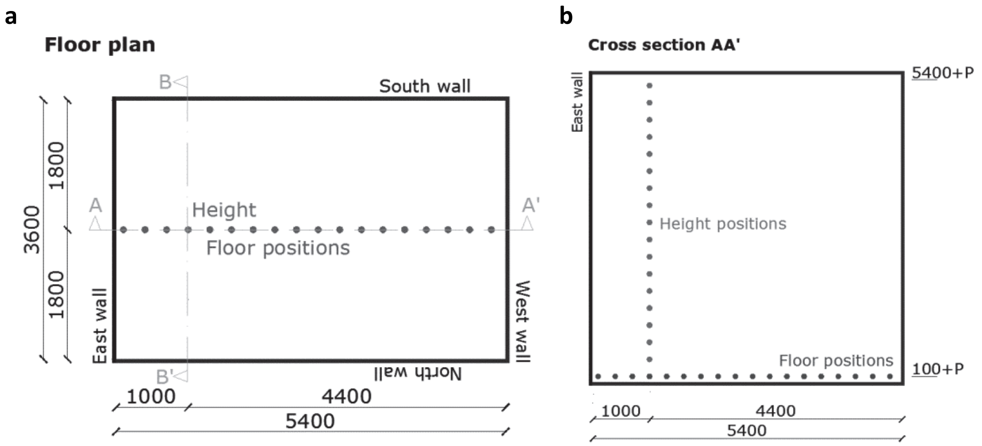

Figure 6.10. Different positions for which the variants are compared **(a)** floor plan and **(b)** Cross section AA'

The velocity magnitude along the height and width is significantly ($p<0.01$) influenced by the window height (variant C2, V5 and V7). Largest increase in velocity is found near the floor (Fig. 6.11a) at the interface of the living zone (distance to window: 1m). The temperature of the window significantly ($p<0.01$) influenced both velocity magnitude and air temperature distribution along the height and width of the room. Largest increase in both air velocity and air temperature (Fig. 6.11b) were found near the floor as well. An increase in floor temperature (Fig. 6.11c) caused a significant ($p<0.01$) increase in air velocity near the floor for both an equally distributed floor temperature (V4) and a local (near the window) warmer floor temperature (V6). In comparison to a floor temperature of 21°C (V5) the air velocity increases up to a maximum average air velocity near the floor of 0.31 m/s in variant V6. Note that in this case again flow instability was observed in the transient simulation results. The average air velocities over the height of the room (from 0.5m) do not differ significantly ($p>0.05$) for the different floor temperatures.

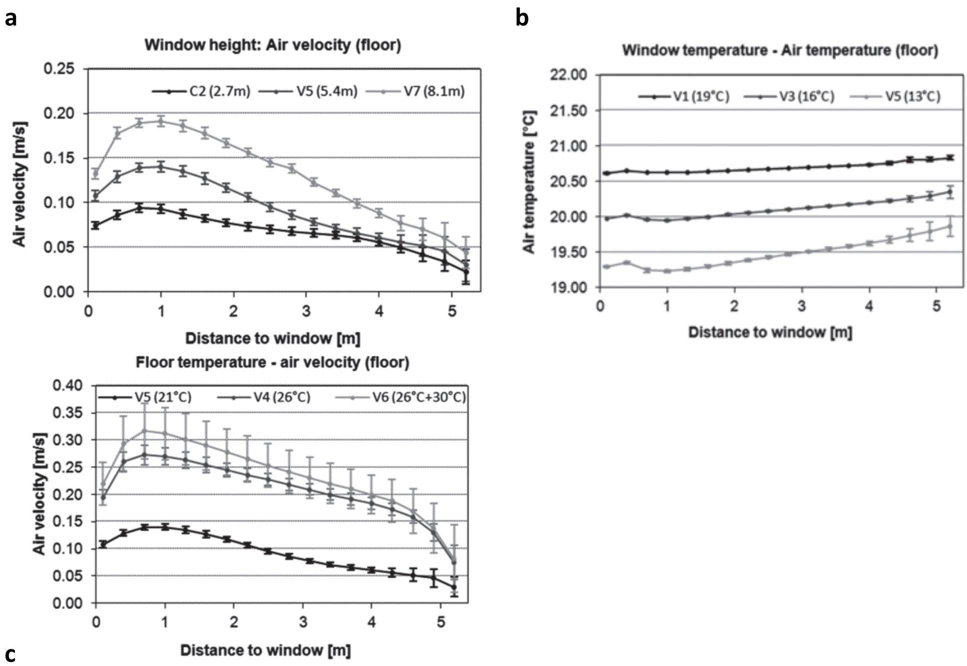

Figure 6.11 Influence of different **(a)** window heights, **(b)** window temperatures and **(c)** floor temperatures on resulting air velocity and air temperature near the floor in relation to the distance to the window

Thermal comfort

Thermal comfort level is assessed using EN-ISO 7730[14]. The whole body thermal sensation indices are calculated [Predicted Mean vote (PMV) and Predicted Percentage Dissatisfied (PPD)], as well as the predicted percentage dissatisfied (PD) due to local discomfort (caused by respectively draught (DR), a temperature gradient, a relative high floor temperature and radiant asymmetry). The results for the different indices are presented in Table 6.5. Fig. 6.12 visualizes the draught rate for cross section AA' (Fig. 6.11a) for variant V4 (floor temperature is 26°C) and V5 (floor temperature is 21°C). The results indicate that highest draught rates are present near the floor and are higher for a higher floor temperature.

Table 6.5 Results of global and local thermal comfort indices for the different variants, PMV represents predicted mean vote, PPD represents predicted percentage dissatisfied and PD represents percentage dissatisfied

Variant	PMV* [-]	PPD* [%]	PD* Draught rate [%]	PD* Temp. gradient [%]	PD* Floor temp. [%]	PD* Radiant asymm. [%]
C1	0.27	5.2	5.0	0.2	6.8	0.8
C2	0.38	5.4	0.0	0.1	7.1	1.1
V1	0.42	5.5	0.0	0.2	7.1	0.2
V2	0.32	5.2	4.9	0.2	6.8	0.5
V3	0.37	5.3	0.0	0.2	7.1	0.6
V4	0.26	5.2	6.1	0.1	6.8	1.0
V5	0.31	5.2	2.4	0.1	7.1	1.3
V6	0.33	5.3	7.0	0.1	6.8	0.7
V7	0.29	5.2	3.7	0.1	7.1	1.3

*Values are presented as mean

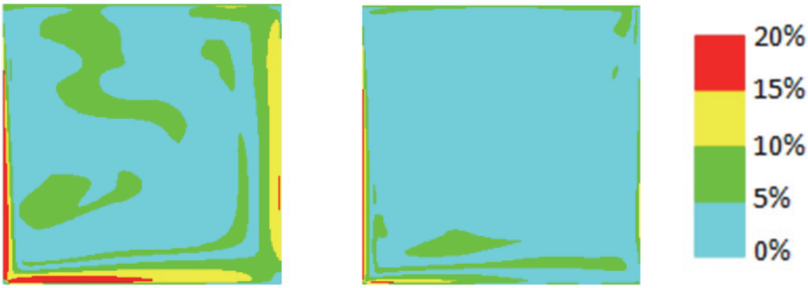

Figure 6.12 Draught rates on cross section AA'; left: V4 (floor temperature 26°C) and right: V5 (floor temperature 21°C)

Applicability rule of thumb

Whether the variants are allowed according to the rule of thumb of Olesen[1] is presented in Table 6.6, the variants are assessed for a maximum allowed air velocity of 0.18 m/s. The U-value of the glass (U_{glass}) is calculated according to equation 6.3. Based on the rule of thumb, only variant V1 (with a window temperature of 19°C) will not present a downdraught risk. Furthermore, the rule of thumb assumes lower values for the variants with floor heating. This indicates less risk on downdraught compared to variants without floor heating. The air velocity and draught rate in the variants with floor heating however are higher.

Table 6.6 Assessment of variants using the rule of thumb of Olesen[1]

Variant	U_{glass}*h [-]	Allowed
C1	4.9	No
C2	5.3	No
V1	2.7	Yes
V2	6.0	No
V3	6.6	No
V4	9.5	No
V5	10.4	No
V6	9.7	No
V7	15.6	No

Discussion on variant study

The numerical results show fluctuations in air temperature and air velocity, indicated by the error bars in the results, due to a time-dependent flow pattern. These fluctuations were observed in both cases (C1 and C2) and all variants (V1-V7). According to Rees et al. complex quasi periodic fluctuations can occur under stationary boundary conditions[36]. However, the measurement period per measurement position (5 minutes) for the calibration measurements was too short to capture one whole period of the fluctuation. Nevertheless, as the trend is predicted well and mean deviations are limited it is concluded that the model is valid to perform a variant study.

The results from the variant study confirm the results of previous studies on downdraught (e.g. Manz et al.[37] and Jurelionis and Isevicius[35]) that window height and window temperature significantly influence downdraught. Although Huizenga et al.[4] concluded that cold radiant asymmetry can cause discomfort, based on the presented numerical results discomfort due to radiant asymmetry was assessed low in the variant study when applying EN-ISO 7730[14] (Table 6.5).

To the best of our knowledge, no studies on downdraught have included floor temperature as significant influencing parameter. Yet, the numerical results show that floor temperature influences the air flow pattern negatively with respect to downdraught. The warmer floor (+5°C) caused the maximum air velocity to increase by a factor two close to the floor due to buoyant forces. It should be marked that the floor heating variants have wall temperatures lower than room air temperature (max. ΔT of 0.9°C) and the variants with a floor of 21.0°C have warmer walls compared to the room air (max. ΔT = 2.5°C). This was necessary to achieve and maintain similar operative temperatures. In spite of this difference, the colder walls (compared to the air temperature) did not result in additional downdraught, the air flow near these walls is still upwards. However, the wall temperature can influence the air flow in the rest of the room. The effect of floor heating on air flow was confirmed by the measurement results. However, during the measurements these differences were relatively small but significant (23.0°C versus 24.3°C for case S1 and S2 respectively). It is recommended to validate these results further with experimental measurements.

6.6 Discussion on applicability of a rule of thumb to prevent downdraught

Compared to the EN-ISO 7730[14] guidelines, as applied to the investigated numerical variant, the rule of thumb is conservative. All but one case (variant V1) are regarded as downdraught risk, based on the rule of thumb of Olesen[1]. This is because the maximum occurring air velocity is higher than 0.15 m/s in most variants. However, this maximum value occurs within one meter from the window at floor level (i.e. outside the living area, Fig. 6.1d) and decreases rapidly. When the maximum occurring Draught Rate (DR) is considered, the same design conclusions are obtained as with the rule of thumb. Only Numerical variant 1 (V1) with 19°C window temperature is assessed as acceptable (maximum DR<20%). When including the obtained results from the subject experiments in the discussion (S1 and S2 in line with M1 and M2), the rule of thumb and DR seem to be too conservative since according to the rule of thumb the conditions would not be allowed. However, the subjective responses indicate no thermal discomfort.

It should be noticed that DR is developed for draught at neck level and, based on the results obtained, overestimates the Percentage Dissatisfied (PD) due to draught at foot level. DR should differentiate in the location where draught is expected.

Finally, the rule of thumb and the maximum DR show a different trend. Considering the rule of thumb, the temperature difference between the room air and window decreases with floor heating (for the variants) which assumed a lower maximum air velocity and thus more comfortable conditions. However, DR predicts a higher PD for the floor heating variants as a result of the increased velocity at floor level. Therefore the authors recommend to further study the effect of floor heating on downdraught and perhaps include the floor temperature as influencing parameter in the rule of thumb.

6.7 Conclusions

Based on both experimental and numerical results the rule of thumb for assessing the risk of downdraught[1], often used by engineers in practice, is conservative for the investigated experimental cases. This results in unnecessary measures to prevent the expected downdraught. Furthermore, the numerical results reveal that an increased floor temperature (i.e. floor heating) can negatively influence the air flow pattern, which results in more downdraught. Therefore, it is recommenced to implement the floor temperature as influencing parameter in the rule of thumb and to study the allowed comfort limits.

Further research should focus on comfort assessment at ankle level under downdraught configurations, for example a Percentage Dissatisfied due to draught at ankle level instead of a PD at neck level.

Finally, more research is needed regarding the instability which can occur in the indoor air velocity pattern and the influence on thermal comfort.

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PART III

DISCUSSION

Chapter

7

The use of a thermophysiological model in the built environment to predict thermal sensation

coupling with the indoor environment and thermal sensation

This chapter has been published as L. Schellen, M. Loomans, B. Kingma, M. de Wit, A. Frijns, W. van Marken Lichtenbelt, *The use of a thermophysiological model in the built environment to predict thermal sensation - Coupling with the indoor environment and thermal sensation*, Building and Environment 2012; doi: http://dx.doi.org/10.1016/j.buildenv.2012.07.010.
The lay-out has been adjusted to fit the style of this thesis.

Abstract

Thermal comfort, influenced by thermal sensation is an important building performance indicator. In this study we discuss the use of a thermophysiological model in the built environment to assess thermal sensation. In the context of this work, the use of CFD to simulate the thermal environmental conditions around a human is analyzed. Experimental data from two independent studies, covering both genders, are used to validate three different, currently available, thermal sensation models: (1) the Predicted Mean Vote index (PMV), (2) the UC Berkeley thermal sensation model and (3) the EN-ISO 14505 standard. Use of such a model is required to link physiological responses to thermal sensation. In this study they have been evaluated for two different steady-state non-uniform thermal environments. The results confirm that the PMV is not capable of predicting whole body thermal sensation when local effects (local skin temperatures and thermal sensation) have a significant influence. The results furthermore indicate that the use of a thermophysiological model (ThermoSEM) in combination with the UC Berkeley model or EN-ISO 14505 standard seems to be promising regarding the prediction of thermal sensation of local body parts and overall thermal sensation under steady-state non-uniform environments. The advantage of using a thermophysiological model in combination with a thermal sensation model is that thermal comfort can be assessed on a more individualized level under complex, daily encountered, thermal environments where local effects play an important role. However, both thermal sensation models need more research before they can be used in daily building design practice.

7.1 Introduction

Thermal comfort is regarded as one of the important building performance indicators[1]. Therefore, accurate models for predicting thermal comfort during the design phase of a building can be beneficial in avoiding malperformance in the use phase. In addition to the satisfaction of the occupant, reduction of the energy-use is an important aspect in building design, since one-third of the primary energy use in developed countries is consumed by heating, ventilating and air conditioning in residential, commercial and public buildings[2]. Non-uniform and transient thermal environments may reduce the amount of energy needed to realize an acceptable thermal environment compared to a uniform and steady-state thermal environment[3-5]. However, these kinds of thermal environments can cause thermal discomfort[6 7]. On the other hand, some combinations of local and general discomfort factors, for example draught under warm conditions, can be comfortable. Moreover, under asymmetrical thermal environments higher levels of thermal comfort can be achieved compared to uniform environments[3 4].

Thermal comfort and satisfaction with the thermal environment is a complex phenomenon, and therefore complicated to predict in the design phase. This paper discusses, based on two case studies, the use of a thermophysiological model to support and improve the comfort assessment compared to existing, more simplified, thermal comfort models.

Context

Thermal comfort can be defined in different ways. In ASHRAE[8] thermal comfort is defined as 'that expression of mind which expresses satisfaction with the thermal environment'. This statement is widely accepted and most used as definition for thermal comfort. Due to the large differences between persons, both psychological and physiological, it is difficult to satisfy everyone in the same room even if the individuals are allowed to change their personal behavior accordingly. In the past many researchers carried out laboratory and field studies to investigate the parameters which affect thermal comfort. The objective was, by using the results, to define conditions which are comfortable and/or acceptable for a major part of the occupants. One of the first studies related to this field was conducted by ASHVE (nowadays ASHRAE) in 1925, resulting in an index for the effective temperature (ET)[9]. In another study conducted by Vernon and Warner[10], the corrected effective temperature (CET) was developed. The purpose of the study of Vernon and Warner was to take the effect of radiation into account. Both methods were used worldwide as an index for thermal comfort[9].

The PMV model

The most well-known and probably most referred research in the field of thermal comfort was carried out by Fanger in the 1970s[11]. He developed an empirical model which was capable of predicting the overall thermal comfort (whole-body) for a group of occupants. This model was based on regression equations that were derived from subjective responses. Fanger developed a method that could be used by HVAC engineers to determine the optimum environmental conditions (combination of air temperature, mean radiant temperature, relative humidity and mean air velocity) under given boundary conditions (activity level and clothing) to satisfy most persons of a given group of occupants. He defined that if a person is in a thermal neutral condition, that this is also the most comfortable condition. A thermal neutral condition was assumed as the condition wherein a person does not prefer either a colder or warmer environment. In physiology the thermoneutral zone is defined as the range of ambient temperatures without regulatory changes in metabolic heat production or evaporative heat loss[12].

For practical use Fanger composed comfort diagrams; two examples are shown in Figure 7.1. The comfort lines are represented by the lines in the diagrams, each point on these lines corresponds with the conditions which are necessary to achieve thermal comfort.

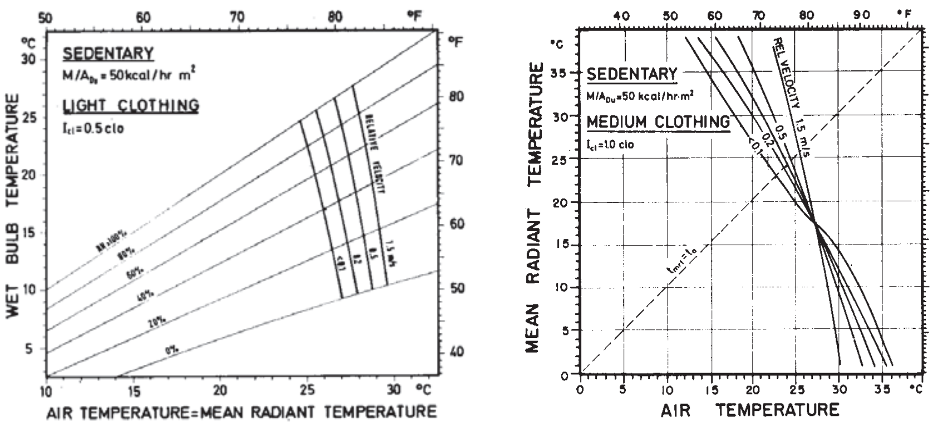


Figure 7.1 Comfort lines as derived by Fanger[10]

Fanger developed a model that predicts the mean thermal sensation vote (PMV, predicted mean vote), and linked this vote to thermal comfort through the percentage of people who will be dissatisfied with the thermal environment (PPD, predicted percentage dissatisfied). Results of the PMV model are expressed on the 7-point ASHRAE thermal sensation scale (Table 7.1), consisting of a range from -3 to +3, where negative values correspond to a cold sensation and positive values to a warm sensation. Currently, this scale is widely accepted and used. The PMV model is nowadays the most commonly used model in practice to predict thermal comfort in the design process of a building. Furthermore, the model is often used to evaluate discomfort in an existing situation.

Table 7.1 7-point ASHRAE thermal sensation scale[8]

Thermal sensation	Corresponding term
-3	Cold
-2	Cool
-1	Slightly cool
0	Neutral
+1	Slightly warm
+2	Warm
+3	Hot

Limitations of the PMV model

Several studies show a good agreement between the predicted mean vote (PMV) and actual mean vote (AMV), where the actual mean vote is the subjective response regarding thermal sensation expressed on the 7-point thermal sensation scale (Table 7.1). The good agreement is, particularly, found for uniform and steady-state environmental conditions (typical HVAC conditions)[13 14]. Other studies, however, found discrepancies between PMV and AMV due to limitations of the model regarding differences in different subpopulations (e.g. young versus elderly, males versus females)[6 9 15 16]. Since preferences for non-neutral thermal sensations are common and can change over the season, the optimal thermal condition is not necessarily equal to thermal neutrality[17-19]. At the same time, low and high PMV values do not always represent discomfort[15]. Van Hoof et al.[20] conducted an extensive literature survey on the validity of the PMV/PPD model. They compared the PMV/PPD model relation to the actual percentage of dissatisfied. In Figure 7.2 the outcomes are presented. They found for naturally ventilated buildings and air-conditioned buildings and in climate chamber settings relations between PMV and PPD that were different from the ones derived by Fanger. One of the deviations found concerns the symmetrical distribution of the model; on the warmer side fewer dissatisfied subjects were found than based on Fanger's model.

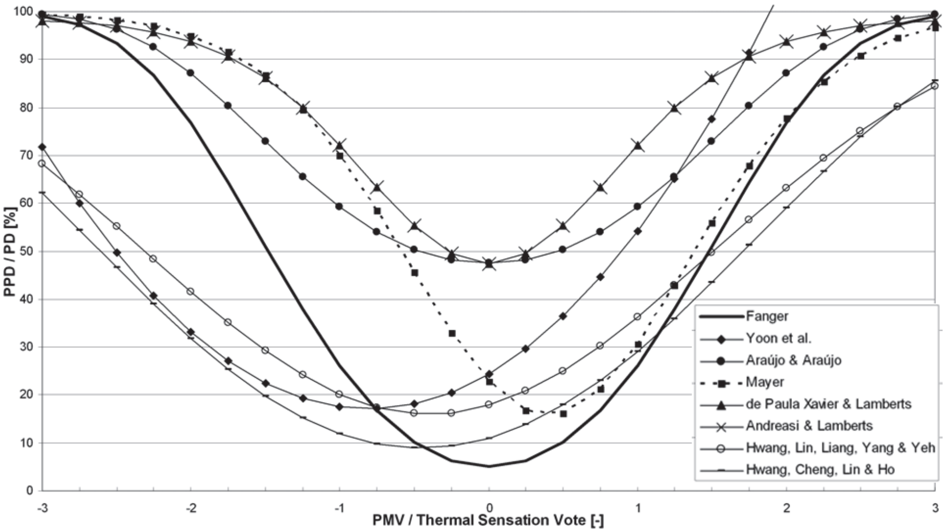


Figure 7.2 Relation between PMV and PPD based on several studies[18]

Furthermore, van Hoof et al.[20] compared the outcomes of the PMV model with the AMV of test subjects in several different studies. Due to inter-individual differences the optimal thermal sensation differs up to 1.0 scale unit (approximately 3K), between anthropomorphically (age, gender, body composition) equal subjects. Based on their literature review they suggest that the PMV model undervalues thermal sensations and overestimates the swings of these sensations. Explanations are found in the steady-state laboratory conditions from which the model was derived, an oversimplification of metabolic rates, and the sensitivity of PMV to clo-values.

In addition to inter-individual differences (of anthropomorphically comparable individuals), differences exist regarding the thermal preferences and optimal conditions between sub-populations. Several studies indicate that the thermal neutral temperature and optimum thermal condition of elderly differ from the thermal neutral temperature and optimum condition of young adults, due to differences in health (e.g. an increased systolic blood pressure in elderly). An impaired cold-induced thermogenesis causes elderly to be more sensitive to mild cold conditions compared to young adults[21]. Furthermore, the range of the thermal neutral zone of elderly is smaller in comparison to the thermal neutral range of their younger counterparts[12]. Therefore, elderly might require a higher ambient temperature to achieve thermal comfort when compared to younger adults at equal clothing and activity levels[6]. As, in the next 20 years, in the western world, the number of people aged 60 or older will increase from 15.4% in 1996 to 25.3% in 2030[22], it is relevant to study possible differences in thermal comfort, thermal preferences and physiological responses.

Also gender can play a role in perceiving the indoor climate; in general females are more sensitive for cold conditions and deviations from the optimum conditions than males. Females also frequently prefer higher temperatures[9 23-25].

Furthermore, due to the characteristics of the input variables, the PMV model is not able to predict thermal comfort under non-uniform environmental parameters (i.e. vertical air temperature stratification cannot be included because the ambient air temperature is assumed to be uniform). Therefore additional relations have been developed to assess local discomfort caused by draught, asymmetrical radiation and/or vertical temperature differences. However, in some cases these standards may be conservative. For example draught under warm conditions, is not always regarded as uncomfortable[26].

The effect of body mass on thermal comfort is also of great interest since obesity is becoming an issue of concern in the Western countries[27]. In literature little is reported on the differences in thermal comfort between lean and obese people.

Regarding more complex thermal environments (i.e. non-uniform and/or transient environments), local effects can play an important role as well; whole body thermal comfort depends on the thermal sensations of local body parts[4 7 28-31].

Given the fact that PMV/PPD assumes little effect of physiological conditions and local effects on whole body thermal sensation and comfort, whereas research shows that this is not always valid, including more detailed physiological information in the thermal comfort assessment might be beneficial for a more accurate assessment in specific design situations.

In conclusion, the PMV/PPD-model is applicable in situations where the indoor climate conditions are uniform, steady-state, close to neutral and where the individual occupants do not differ too much from each other. But how are conditions assessed adequately which are non-uniform, not-neutral, or in buildings where the occupants significantly vary in age, gender or body composition?

Thermophysiological models

In response to the known requirements for valid application of the PMV/PPD model and its assumptions, another way to predict thermal comfort is by using thermophysiological models. A thermophysiological model provides a mathematical description of physiological responses to thermal environments. A thermophysiological model can be used to model the dynamic physiological responses (i.e. local skin temperatures and body core temperature). The interest in thermophysiological models increased towards the end of the previous century. Initially, these models were developed for application in extreme conditions (e.g. military). Significant developments of these models and improved computer resources caused the attention for application in non-military conditions, including the thermal comfort area[9]. For more complex thermal environmental conditions (e.g. transient or non-uniform) the empirical models (e.g. PMV-index) may become less suitable. For such conditions a dynamic thermoregulation model might be required to simulate the skin and core temperature, and from that predict the thermal sensation. In addition, a thermoregulatory simulation model allows taking into account the individual body characteristics that influence the thermal state of the body. For the majority of such thermoregulatory models (e.g. the model of Stolwijk and Hardy[32 33], Wissler[34], Fiala (UTCI)[35 36], Huizenga et al. (UC Berkeley model)[37], van Marken Lichtenbelt et al. (ThermoSEM model)[38-40]) the thermoregulatory system is divided in a passive and an active (controlling) system. The basis for these models was formed by the work of Stolwijk[33].

ThermoSEM

The ThermoSEM model[38-40] will be used in this paper to simulate physiological responses and to discuss the influence of boundary conditions. ThermoSEM is based on the model of Fiala[35]. Van Marken Lichtenbelt et al.[39] concluded that the composition of the body is an important factor for differences which occur in physiological responses. In comparison to the most existing models, ThermoSEM is able to take non-uniform environmental conditions and individual characteristics (height, weight and fat percentage) into account. Therefore, ThermoSEM was included in this study. In the model, the human body is subdivided into 18 cylinders and 1 sphere (Figure 7.3). Every cylinder and sphere consists of layers that represent different tissue materials such as: brain, lung viscera, bone, muscle, fat and outer and inner skin. Additionally, the cylinders are spatially subdivided into three sectors, the anterior, posterior and interior (Figure 7.3). These sectors allow modelling of asymmetric boundary conditions. For individualization purposes, each element (except the head) can be scaled by a factor *f*; *f* is the ratio of the height of the individual person to the height of the average person. For example, if the individual person is 1.80m, the factor *f* will be 1.80/1.73=1.04. The head is scaled by $\sqrt{f}$. With scaling, the thickness of the tissue layers remains unchanged. Heat exchange between the elements takes place through arterial blood delivered from a virtual central blood pool. After counter-current heat exchange, heat is delivered to local tissues through blood perfusion[39]. Compared to Fiala's model, ThermoSEM mainly differs in the controlling active part; the skin blood flow is modeled based on neurophysiological concepts[40].

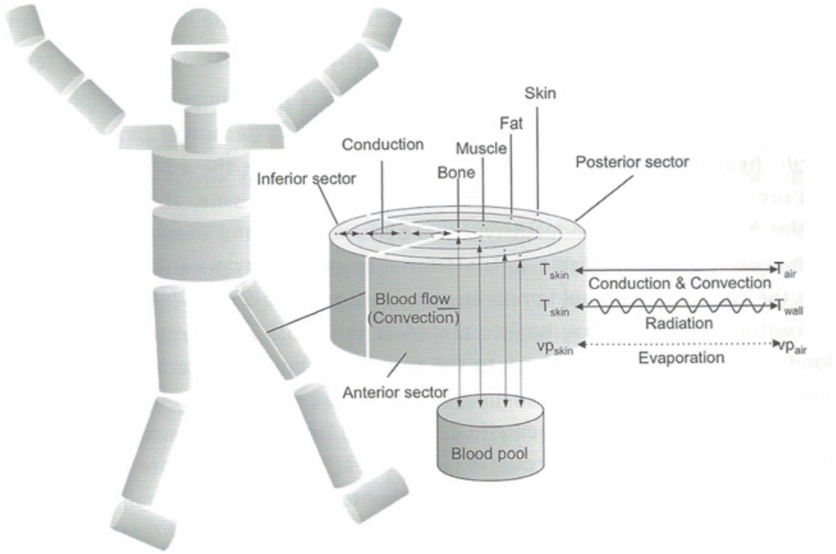


Figure 7.3 Schematic view of the ThermoSEM model[36]

Coupling thermal comfort

The output of the model (core temperature and skin temperatures) as such is not sufficient to predict thermal sensation and thermal comfort. For that, a coupling between skin temperatures and/or core temperatures and thermal sensation and/or thermal comfort is indispensible.

Different approaches have been conducted by several researchers. A comparison between the different methods, for both local and overall thermal sensation, has been made by Foda et al.[41]. For local thermal sensations, the UC Berkeley model of Zhang et al. (UCB-model)[4] and the model of Nilsson which is implemented in the EN-ISO 14505 standard (Nilsson model)[42 43], were included in the study of Foda et al.[41]. The UCB-model is based on physiological responses (i.e. mean skin temperature, local skin temperatures, core temperature and rate of change in these parameters), where the model of Nilsson defines clothing independent comfort zones for the different body parts as function of the equivalent temperature (T_{eq}). In the study of Foda et al.[41], data from Cheong et al.[31] and Nilsson and Holmer[44] were used to validate the model results for whole-body thermal sensation and local thermal sensations; both males and females participated in the experiments; unfortunately no distinction in gender was made in the results presented in the study of Foda et al. The predictions of the local thermal sensations (LTS) with both models were nearly in agreement with the actual local mean votes (LMV), especially at higher temperature levels (T_{eq}>24°C). However, for the extremities (head, hand and foot) the LTS showed large discrepancies with the LMV. Furthermore, significant discrepancies were found for lower equivalent temperatures (T_{eq}<22°C).

For the prediction of the overall thermal sensation (OTS, whole-body thermal sensation), the PMV-index[11], Fiala's DTS[35], the Nilsson model and the UCB model were used. The models were validated using the same data as mentioned above. The best agreement between the predicted and actual OTS was found for the UCB model[45], in which the actual LMV was used. The other models showed a discrepancy of on average 1 scale unit on the 7-point ASHRAE thermal sensation scale; the predicted OTS was for all models higher than the actual OTS which indicates that the subjects were feeling significant colder than predicted.

Another comparison between different thermal sensation models was made by Cheng et al.[46]. In this study the UCB-model is compared with the EN-ISO 14505 index[43], which is based on the Nilsson model. From this comparison it can be concluded that the EN-ISO 14505 index is more sensitive to warm environments, while being less sensitive to the cold environment. Furthermore the EN-ISO 14505 index seems to be less suitable for a thermal neutral situation. However, in this study the results are not validated against human subject experiments and therefore it is not possible to draw conclusions from this study regarding the reliability of both models.

In conclusion, the UCB-model seems to be promising for the prediction of thermal sensation under non-uniform environments. However, the data used for the development of the model was mainly conducted under warm conditions focusing on cooling a specific body part. It is not yet clear how the model would perform under more daily encountered conditions (as found in the built environment), and conditions close to neutral and colder than neutral.

Following the above, the objective of the research presented in this paper is to investigate whether a thermophysiological model can be used in the built environment for the prediction of (local) thermal sensation under non-uniform environmental conditions at the cold side of neutral. In the context of this objective, the simulation of the boundary conditions for the thermophysiological model using Computational Fluid Dynamics (CFD) will be discussed as well, addressing the convective heat transfer coefficient as one of the input parameters for the thermophysiological model.

7.2 Methods

Experimental data

The thermophysiological model results will be validated using two independent datasets. Both datasets include measurements of physiological (i.e. skin temperature and core temperature) and physical parameters. Skin temperatures were measured on 24 sites by wireless iButtons (Thermochron iButton DS1291H, Dallas Maxim) (Figure 7.4a), including the 14 points as proposed by EN-ISO 9886[47] to calculate the mean skin temperature. Core temperature was measured with an ingested telemetric pill (CoreTemp, USA). Air temperature (NTC Thermistor, type SC95, accuracy ±0.1°C), relative humidity (RH)

(Humidity Sensors, Honeywell HIH- 4000 series), air velocity (hot sphere anemometer, Dantec, estimated accuracy 15%[48], and surface temperature (NTC Thermistor, U-type EU-UU-10-PTFE, accuracy ±0.1°C) were measured according to EN-ISO 7726[49]. Air temperature, RH, and air velocity were measured on two comfort stands at 0.1, 0.6, 1.1 and 1.7 m height. The average surface temperature for each surface was derived from nine measurement points on each surface (at a grid of 3x3). The mean radiant temperature was determined according to the surface temperatures and view factors related to the position of the subject. Turbulence-intensity was calculated as the ratio of the root-mean-square of the velocity fluctuations and the mean velocity, therefore air velocity was measured at an interval of 10Hz.

Thermal sensation votes were asked on the continuous 7-point ASHRAE thermal sensation interval scale (table 7.1), where each point on the line could be marked[8]. As a result, the thermal sensation could be assessed within ±0.05 scale unit of accuracy.
During both experiments for which the datasets were retrieved subjects were sedentary and performing office tasks (metabolic rate was approximated at 1.2 met).

a **b**

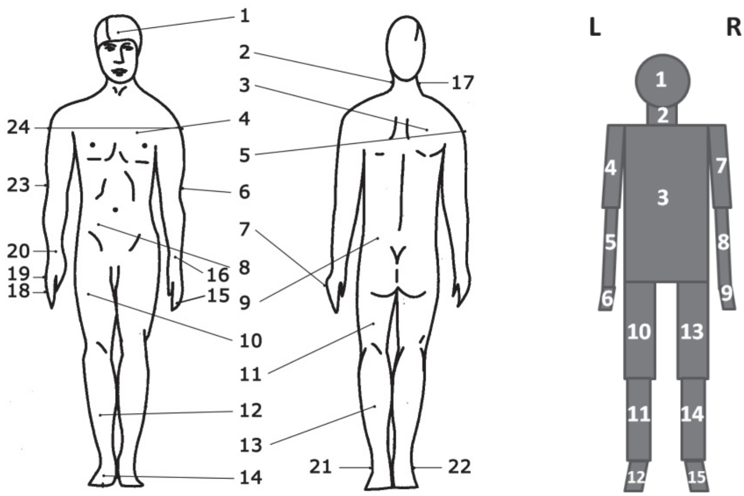


Figure 7.4 (a) Measurement sites skin temperature; **(b)** Schematic representation of body parts to assess local thermal sensation and comfort

In the first dataset (D1, details are given in Table 7.2) 10 healthy male subjects (Table 7.3) were exposed to a heating case were downdraught occurred at a cold wall (duration 2h) combined with floor heating. The subjects were positioned at one meter from the cold wall. Subjects wore standardized clothing, consisting of a cardigan, jogging pants, thin T-shirt, underpants, socks and shoes (1.0 clo, including desk chair).

In the second dataset (D2, Table 7.2) 20 healthy subjects (10 males and 10 females; Table 7.3) were exposed to a cooling case where cooling occurred through radiation by the ceiling (duration 2h). To enlarge the non-uniformity (i.e. the radiant asymmetry) the floor was heated. The applied conditions remained within the PD<10% criteria with respect to local discomfort for non-uniform conditions as provided in EN-ISO 7730[50]. The subjects were positioned in the middle of the climate chamber. The subjects wore standardized clothing as well, consisting of a jogging pants, polo shirt, underpants, socks and low shoes (0.6clo, including desk chair). The subject characteristics of both datasets are listed in Table 7.3.

Table 7.2 Dataset details of both datasets applied

	Dataset D1 M (n=10)	Dataset D2 M (n=10)	Dataset D2 F (n=10)
Mean operative temperature [°C]	21.8 ± 0.16	24.4±0.1	24.3±0.1
Mean air temperature [°C]	22.2 ± 0.15	24.2±0.1	24.1±0.1
Surface temperature cold wall [°C]	13.7 ± 0.56	-	-
Surface temperature floor [°C]	24.3 ± 0.10	28.9±0.1	28.9±0.0
Surface temperature ceiling [°C]	-	18.0±0.2	17.9±0.1
Surface temperature remaining surfaces [°C]	22.7 ± 0.12	23.6±0.0	23.2±0.1
Mean radiant temperature [°C]	21.3 ± 0.15	24.7±0.0	24.5±0.1
Mean air velocity [m/s]	0.09 ± 0.02	0.14±0.01	0.13±0.00
Mean turbulence intensity [%]	25.9 ± 1.28	-	-
Mean relative humidity [%]	47.7 ± 6.00	33.3±1.0	32.7±0.1

Values are presented as mean ± standard deviation (SD)
M males, *F* females

Table 7.3 Subject characteristics

	Dataset D1 M (n=10)	Dataset D2 M (n=10)	Dataset D2 F (n=10)
Age (yr)	23.5±1.7	24.7±2.0	24.0±1.6
Height (cm)	185.0±6.1	181.8±8.34	169.6±8.68
Weight (kg)	77.7±8.8	77.3±8.5	64.7±9.2
Body fat% (%)	16.8±3.9	16.3±4.7	18.3±6.3
BMI (kg/m^2)	22.6±1.6	23.5±3.4	22.5±2.5

Values are presented as mean ± SD
M males, *F* females, *BMI* body mass index. The BMI is calculated as the ratio of the mass (kg) and the squared height (m).

Numerical approach

To study the sensitivity of ThermoSEM and the related thermal comfort prediction to the environmental conditions, dataset D1 is used. For that purpose a detailed numerical model is developed to predict the environmental boundary conditions. This model is also used to study the heat transfer coefficients near the human body, as a result of the environmental conditions. Whether a thermophysiological model together with a thermal sensation model is capable to cover gender effects, is investigated using dataset D2.

The model geometry was adopted from the climate chamber geometry, resulting in a computational domain with dimensions 5.4 x 3.6 x 2.7m^3 (LxWxH, Fig. 7.5a). Furthermore a humanoid, positioned at 1.0m from the wall was modelled (Fig. 7.5a).
A hybrid grid (1.4 million cells), containing both tetrahedral and hexahedral cells, has been developed using the commercially available software Gambit 2.4.6 (Ansys Inc, Canonsburg, USA) for the discretisation (Fig. 7.5b).

a **b**

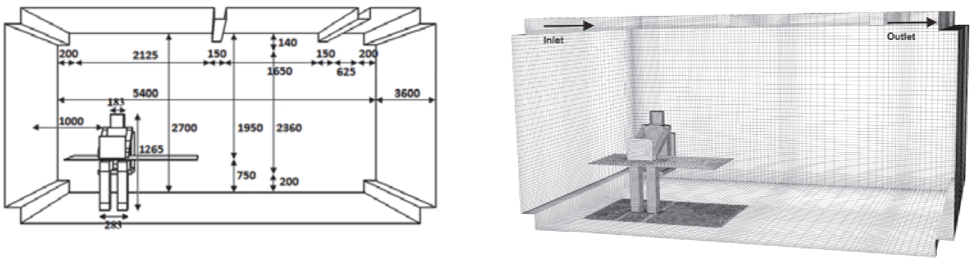


Figure 7.5 (a) Perspective view of computational domain; **(b)** View of the computational grid

The transient 3D Reynolds-averaged Navier Stokes (RANS) equations, combined with the Renormalisation Group (RNG) k-ε turbulence model using enhanced wall treatment[51], are solved using the commercially available software package Ansys Fluent 12.1.4 (Ansys Inc., Canonsburg, USA). Buoyancy forces are modeled through the Boussinesq approximation. Pressure-velocity coupling is conducted by the SIMPLE algorithm, for pressure interpolation the body force weighted discretisation scheme is used and second order discretisation schemes are used for the convection and viscous terms of the governing equations following the best practice guidelines[52]. Simulations have been executed with a time step of 1 second; per time step 10 iterations were conducted. Convergence criterion for the scaled residuals was 10^{-5}. The achievement of a heat balance was an important criterion for acceptance of the solution as well. In total 2700 time steps (45 minutes real time) were simulated.
In the CFD simulations radiation was not taken into account. To compensate for the radiation part, only the convective part of the heat emission of the human was included (52% of 112W[48]). The heat emission of the local body parts was determined proportional according to the specific body part surface. Furthermore, the air inlet conditions and surface temperatures of the room were adopted from the subject conditions (Table 7.2, dataset D1) and measured for a room with a thermal manikin to obtain data for validation purposes. For the boundary conditions the averaged measurement results of the case with thermal manikin have been used. They are provided in Table 7.4.

Table 7.4 Boundary conditions for numerical model

	Boundary conditions D1
Inlet – Air temperature [°C]	22.0
Inlet – Air velocity [m/s]	1.0
Inlet – Turbulence Intensity [%]	7
Inlet – Turbulence length scale [m]	0.0014
Surface temperature East wall [°C]	13.4
Surface temperature North wall [°C]	22.7
Surface temperature South wall [°C]	22.7
Surface temperature West wall [°C]	22.8
Surface temperature Floor [°C]	24.3
Surface temperature Ceiling [°C]	22.9

To validate the numerical model, a comparison for the air temperature and air velocity was made between measurement and simulation results (Fig 7.6). The results are validated for three different heights (0.1, 1.1 and 1.6m), these heights are the representative heights for a sitting person according to EN-ISO 7726[49]. For both air velocity and air temperature the mean deviation is not larger than 20% and 1K, respectively, between experimental and numerical data. A further discussion on the grid sensitivity analysis is provided in Schellen et al.[53].

In the results section, data from the last 900 seconds are averaged and completed with the standard deviation over that period. The latter was chosen as flow instability was identified, despite the stationary boundary conditions provided. Further details on the modelling are described in Schellen et al.[53].

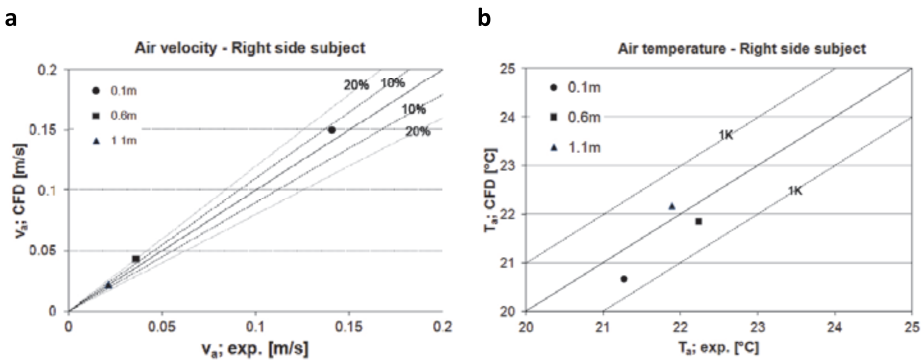


Figure 7.6 Comparison between measured [exp.] and numerical simulated [CFD] **(a)** mean air velocity and **(b)** mean air temperature on three representative heights

7.3 Results

Prediction of boundary conditions using CFD (Dataset D1)

To use the results of the CFD model, a coupling between ThermoSEM and the obtained numerical results is needed. In the study reviewed by Cheng et al.[46] the coupling between a thermophysiological model and the simulated boundary conditions is done by calculating the required environmental parameters (i.e. air temperature and air velocity), based on the initial boundary conditions, using a detailed CFD model. Subsequently, these parameters are input into the thermophysiological model. In our study the physiological responses were simulated using the environmental conditions calculated by CFD as well. A manual coupling was applied for this. However, our numerical model (CFD) is less detailed and therefore requires less computational time compared to models using a higher level of detail.

To compare the influence of the humanoid on the local predicted boundary conditions, the physiological responses were simulated applying environmental boundary conditions from two different positions: (1) close to the humanoid, just outside the free convection boundary layer at the manikin (0.1m from humanoid) and (2) at the position were the environmental conditions were measured in the climate chamber using comfort stands (approximately 0.4m away from the humanoid)[53]. In Figure 7.7 the predicted air velocity and temperature pattern are shown around the humanoid.

Different values in literature can be found for the convective heat transfer coefficients per body part[35 54]. In addition, we also simulated the physiological responses using the heat transfer obtained with the CFD model described. An overview of the convective heat transfer coefficients found in this study and the coefficients of Fiala[35] used in the ThermoSEM model are given in Table 7.5. The convective heat transfer coefficients h_c are calculated through equation 7.1, where Q_i is the heat emission (only convective) of body part (i) [W/m^2], $T_{sk;i}$ is the area averaged surface temperature of body part (i) [K] and T_{ref} is the averaged ambient temperature just outside the boundary layer (distance 0.1m) of the specific body part (i) of thehumanoid [K].

$$h_c = \frac{Q_i}{\bar{T}_{sk;i} - \bar{T}_{ref}} \qquad (7.1)$$

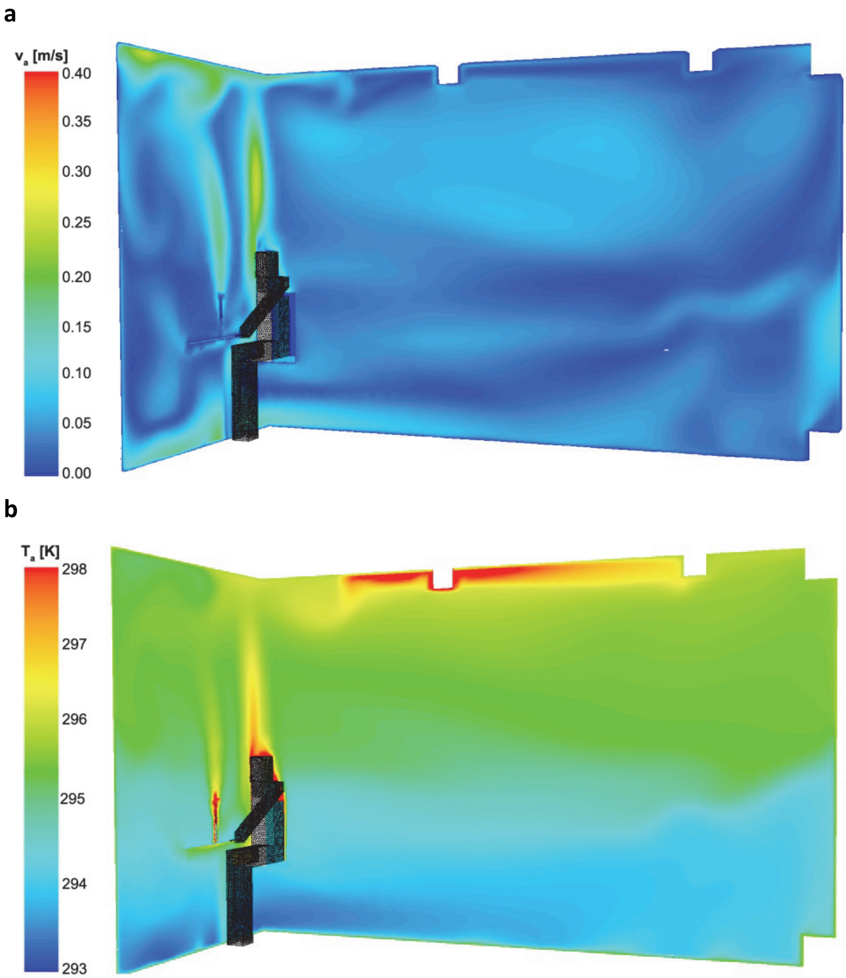


Figure 7.7 (a) Simulated velocity field around thermal manikin colored by velocity [m/s] and **(b)** simulated temperature field around thermal manikin colored by temperature [K]

The simulated physiological responses, at a time interval of 60s, are represented in Figure 7.8. The humanoid used for the simulations was based on Fiala[35] (height = 1.73m; Dubois area = 1.85m^2, weight = 73.4kg, fat percentage = 14.4%). The presented measured mean skin temperature is the averaged mean skin temperature of all subjects (n=10). The results of the acclimatization period (t=0 – t=30 min) are not presented. The simulated responses, for both positions regarding the environmental boundary conditions, were in good agreement with the measured responses; root mean squared error (RMSE) for both results was 0.09°C. The RMSE of the simulation results using the computed convective heat transfer coefficients was 0.38°C; the results were in less good agreement with measurements but still within the standard deviation of the measured skin temperatures. These deviations are caused by the differences in convective heat transfer coefficients.

Table 7.5 Convective heat transfer coefficients (mixed) found in this study and Fiala[32]

Body part	This study $h_{c;mix}$ [W/m^2K^{-1}]	Fiala[32] $h_{c;mix}$ [W/m^2K^{-1}]
Foot	9.4	10.5
Underleg	6.6	11
Upperleg	6.9	11
Hand	6.7	10.8
Lower arm	6.6	10.8
Upperarm	4.1	10.8
Head	7.4	5.7
Chest	6.9	7.4
Abdomen	6.6	9

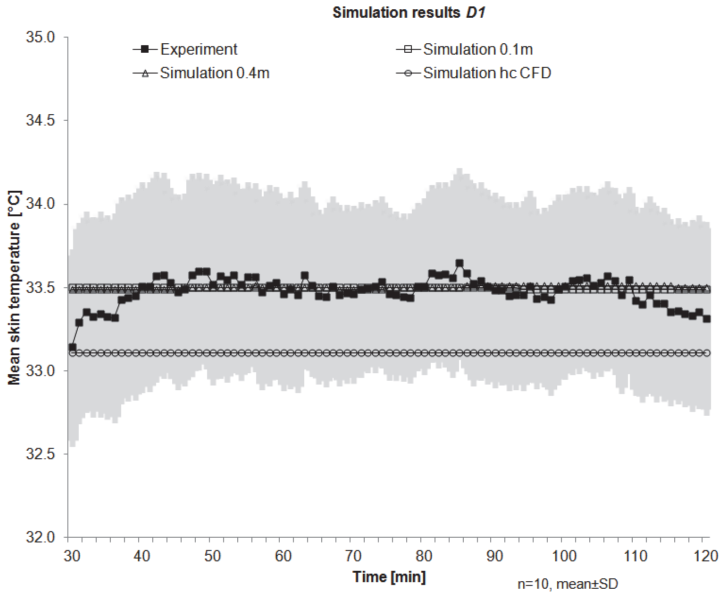


Figure 7.8 Measured and simulated mean skin temperatures of dataset D1. Simulation results are presented for two environmental positions: (1) close to the manikin, just outside the boundary layer of the manikin (0.1m from manikin) and (2) at the position were the environmental conditions were measured using comfort stands (approximately 0.4m away from the manikin) and for using the computed convective heat transfer coefficients obtained with CFD.

Coupling thermal sensation of dataset D1

The next step is to couple the simulated environmental conditions and/or physiological responses to a thermal sensation assessment. Three different models have been tested in this study and compared with the actual mean votes (AMV). Only steady-state models are taken into account because the measured and simulated responses show no clear transient trend. The following models were considered: (1) the PMV-index[11], (2) the UCB-model[45], and (3) the model of Nilsson[43].

Within dataset D1 no local effects were observed in the local thermal sensation votes (Figure 7.9). Therefore, the results of the actual mean votes were compared with the simulated responses on whole-body level. For the input variables in all methods, the simulated results (both environmental boundary conditions obtained with CFD [distance to subject 0.1m] and physiological [ThermoSEM]) were used. As input for the UCB-model, the local sensations were calculated using Zhang et al.[4]; only the static part is considered within our study because no transient conditions were observed. The neutral skin temperature set-points, needed as reference in the UCB-model, were calculated using ThermoSEM for a thermal environment which would result in a neutral PMV (0) under the given boundary conditions of dataset D1 for clothing insulation and metabolic rate in an environment with still air (v_a<0.05 m/s). Since, no local sensations were observed lower than -1 or higher than +1, the 'No-opposite-sensation' model was used to calculate whole-body thermal sensation[45].

The equivalent temperatures, needed for the Nilsson model, are calculated based on the heat emissions obtained with ThermoSEM. The results are presented in Table 7.6.

The PMV-index shows a slight overestimation of the thermal sensation compared to the averaged actual mean vote. However, the difference between AMV and PMV is within the accuracy (±0.5) of the PMV-index. The prediction with the UCB-model, based on the predicted local thermal sensations (Figure 7.9), shows a good agreement with the AMV. With respect to the predicted local thermal sensations, predicted according to the simulated local and neutral skin temperatures (ThermoSEM), differences (<1 scale unit) can be observed for the back and the upper arms. The other body parts are in good agreement (<0.5 scale unit) with the measured local sensations (Figure 7.9).

The whole body thermal comfort level is assessed as neutral by the Nilsson comfort zone method. A direct comparison between the AMV and Nilsson is not possible, because of the different terms used. If an AMV of 0 is regarded as neutral than one could conclude that the prediction is in agreement with the AMV.

Table 7.6 Measured and predicted whole-body thermal sensation using four different methods (n=10)

AMV [-] (n=10)	PMV [-] [11]	UCB-model [-] [45]	Nilsson [-] [43]
0.07±0.47	0.2*	0.02	Neutral

AMV values are presented as mean ± SD, the other values as mean

*p<0.001 versus AMV

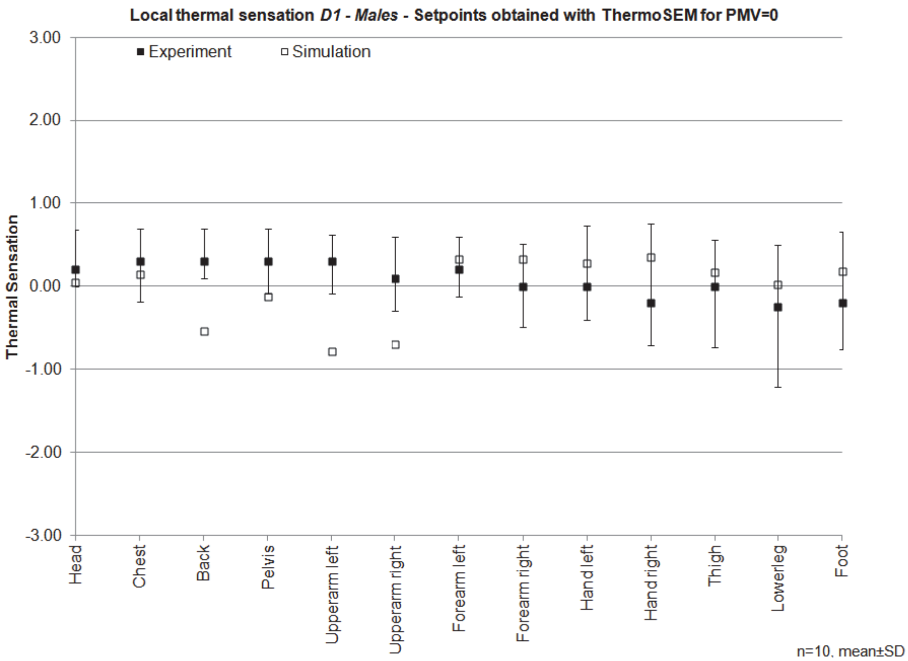
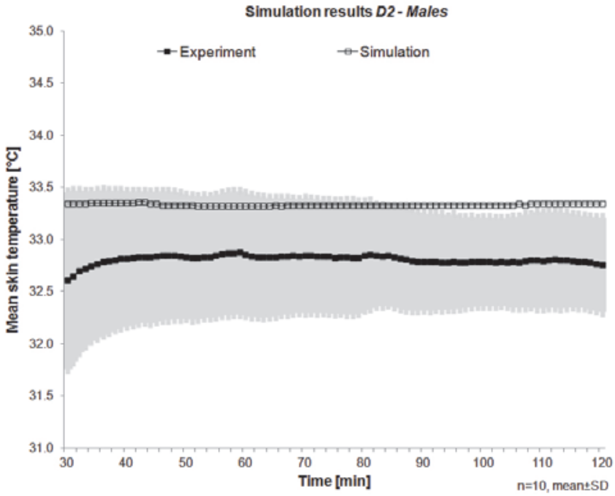


Figure 7.9 Local thermal sensation, measured and predicted using Zhang et al.[4].

Prediction of physiological responses for different genders (Dataset D2)

The physiological responses of dataset D2, for both males and females, were simulated using the measured environmental conditions. For both genders the simulated mean skin temperature, using ThermoSEM, is slightly higher than the measured mean skin temperature (Figure 7.10, RMSE males: 0.53°C; RMSE females: 0.86°C). The slight decreasing trend in mean skin temperature of the females is not predicted by the model. However, both results are considered to be in good agreement with the experimental results.

a



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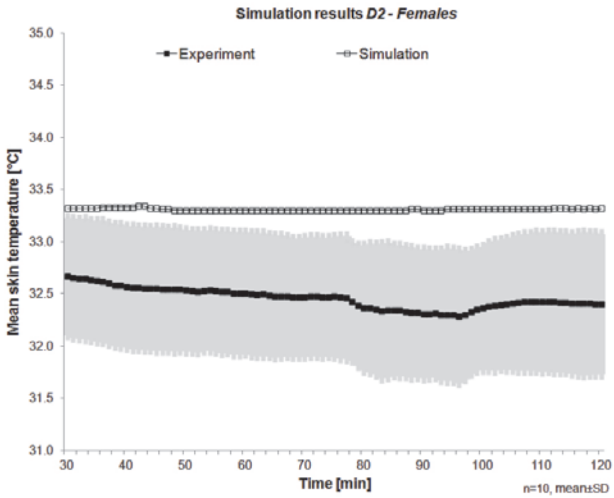


Figure 7.10 Measured and simulated mean skin temperatures of dataset D2 for **(a)** male subjects and **(b)** female subjects.

Coupling thermal sensation of dataset D2

In the results of dataset D2, no clear transient trends were observed. Therefore, the same static thermal sensation models (i.e. PMV, UCB-model and Nilsson) as for dataset D1 have been taken into account to predict thermal sensation. In Table 7.7 the results, separately for males and females, are presented for the whole-body thermal sensation assessment. The PMV[11] is predicted using the measured environmental conditions. As input for the UCB-model[45], the simulated local and neutral skin temperatures are used. The neutral skin temperatures are simulated using ThermoSEM for the environmental conditions which would achieve a neutral PMV for the given boundary conditions of dataset D2 with respect to clothing insulation and metabolic rate. The whole-body thermal sensation for both the males and females, is calculated, based on the predicted local sensations (Figure 7.11), according to the 'No-opposite' sensation model[45]. For the Nilsson model[43], the equivalent temperatures are calculated based on the measured skin temperatures and the heat transfer coefficients obtained with ThermoSEM. For the clo-value the summer clothing level within the model is selected. The Nilsson model generates a thermal sensation assessment based on five different comfort zones, therefore the thermal sensation (TS) votes need to be recalculated according to these comfort zones; the following classification is applied: neutral (-0.5<TS<0.5), cold but comfortable (-1.0<TS<-0.5), warm but comfortable (0.5<TS<1.0), too cold (TS<-1.0) and too hot (TS>1.0).

Table 7.7 Measured and predicted whole-body thermal sensation using four different methods (Males: n=10; Females: n=10)

	AMV [-]	PMV[11] [-]	UCB-model[45] [-]	Nilsson[43] [-]
Males (n=10)	-0.3±0.41	0.1*	-0.4*	Neutral
Females (n=10)	-0.6±0.69	0.0*	-0.4*	Cold but comfortable

AMV values are presented as mean ± SD, the other values as mean
*p<0.05 versus AMV

The results show for both genders a significant discrepancy between the averaged actual thermal sensation (AMV) and the predicted thermal sensation with the PMV and UCB-model. However, the differences, except PMV for the females, are within 0.5 scale units and therefore the predictions are considered as in good agreement. With respect to the local thermal sensation data for the UCB model (Figure 7.11), the actual local thermal sensation votes of the males are higher than the predicted ones (Figure 7.11a), while the actual local thermal sensation votes of the females (Figure 7.11b) are lower than predicted. For the back and feet large differences can be observed for both genders. For the females, also significant differences can be observed for the upper arms and hands.

Significant and relatively high correlations were found between whole body thermal sensation (AMV) and local TS of these extremities and AMV and local skin temperatures of these extremities[55]. Therefore, the authors assume that the discrepancy between the AMV and PMV of the females is caused by local discomfort of the hands and arms. However, this relation was not found for the male subjects. For the male subjects no clear explanation can be found for the difference in AMV and PMV, but note that the difference is still within the accuracy of the PMV (±0.5).

The predicted local and whole body thermal sensation for the females using the Nilsson model shows a relative good agreement, although it is difficult to quantify the differences (Figure 7.12b). With respect to comfort zone and trend level, the predictions are in good agreement with the experimental results. For the male subjects the majority of the local sensations are predicted well when compared to the measured results (Figure 7.12a). However, for the hands the equivalent temperature is underestimated and therefore the sensation there is predicted colder than actually voted.

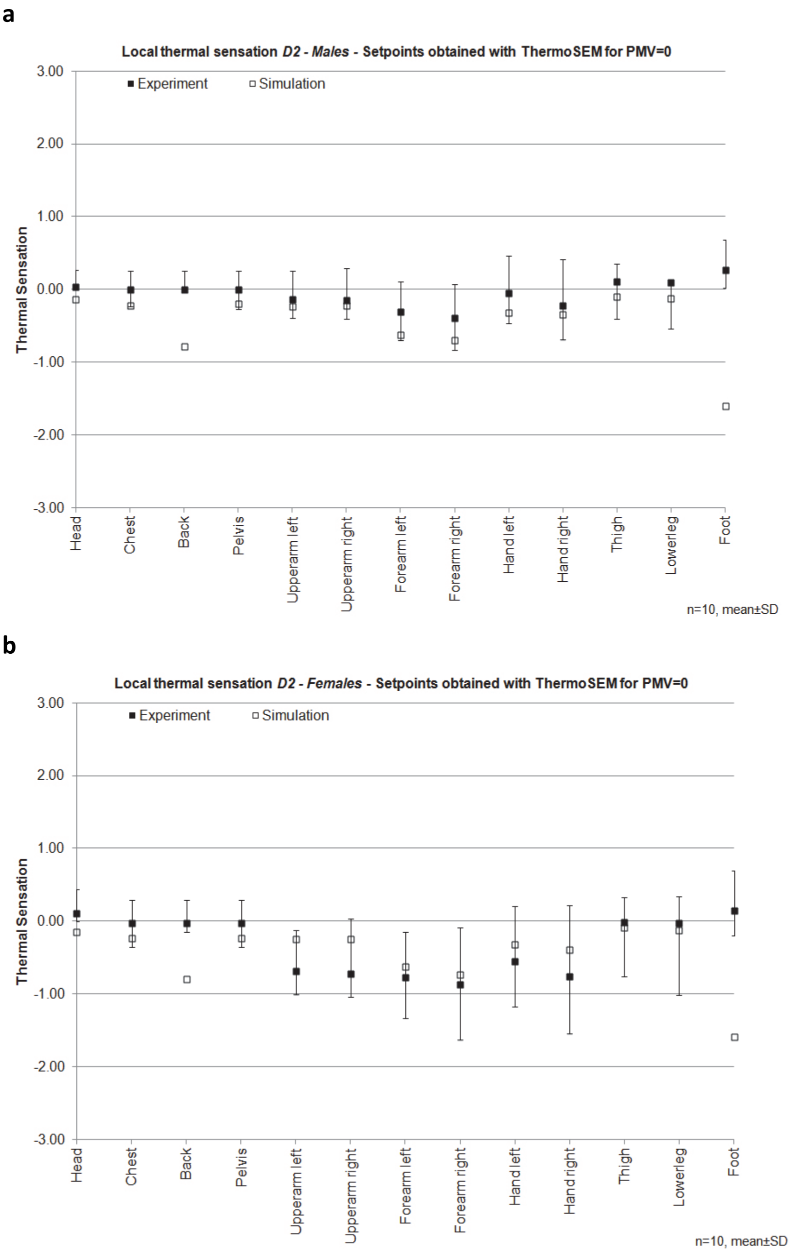
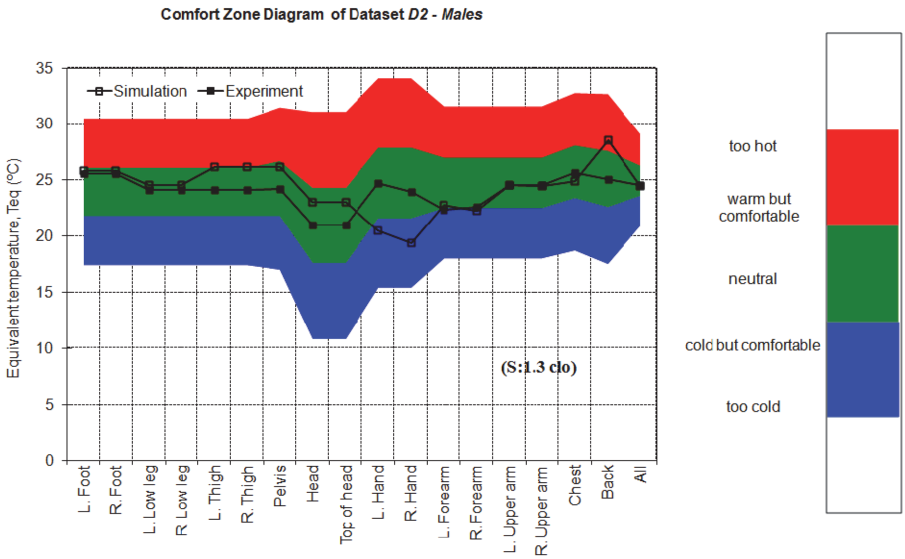


Figure 7.11 Measured and simulated local thermal sensation according to Zhang et al.[4] of dataset D2 for **(a)** male subjects and **(b)** female subjects.

a



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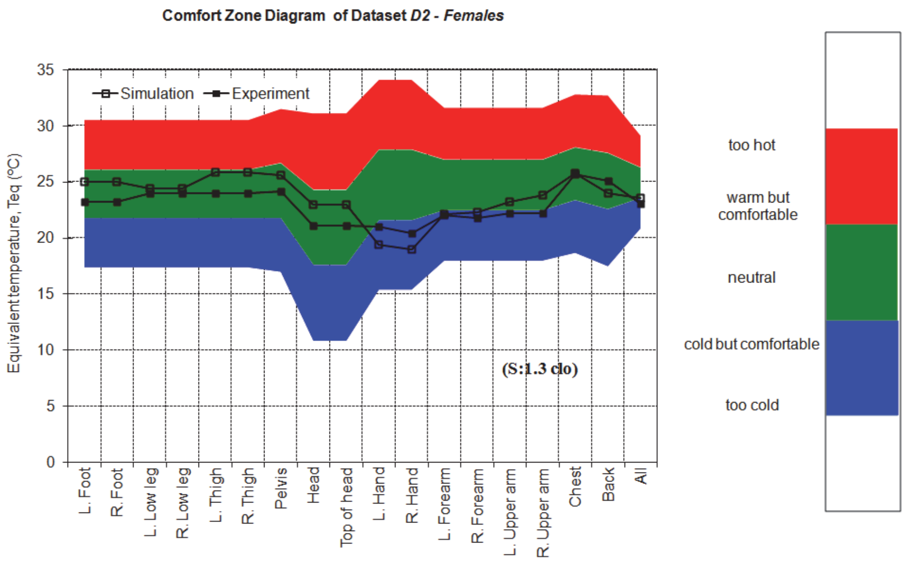

Figure 7.12 Measured and simulated local and whole body thermal sensation according to Nilsson[40] of dataset D2 for **(a)** male subjects and **(b)** female subjects. The red zone indicates the warm but comfortable to hot zone, green the neutral zone and blue the cold but comfortable to cold zone, all represents whole-body.

7.4 Discussion

The objective of this paper was to discuss the use of a thermophysiological model in the built environment to predict thermal sensation. First, the use of Computational Fluid Dynamics (CFD) to determine the environmental conditions, needed as input for the thermophysiological model, was analyzed. Literature presents several examples of detailed CFD-models to predict the environmental conditions around a realistic human body. Also results are available that couple these models with thermophysiological models[56 57]. Compared to for example the model of Gao en Niu[58], the model used in our study (Figure 7.5) to predict the environmental conditions around the human body is less detailed in terms of geometry and number of cells numbers. In our model the total number of cells is 1.4 million (total room dimension 3.6x5.4x2.7= 52.5m^3), in the study by Gao and Niu the total number of cells was 1.8 million for a smaller room geometry, resulting in a larger number (over 3 times more) of cells per m^3 (total room dimension 2.6x2.2x2.7=15.4m^3). Regarding the geometry significant differences exist as well. In our study the humanoid within the CFD model consisted of blocks, while the humanoid modeled by Gao and Niu is a real representation of a seated occupant, obtained by using a 3D laser scanning technique. With respect to the effect of the human body on the environmental conditions good agreement was found with experimental results, indicating that the level of detail in our study was sufficient for thermal comfort purposes, which is in line with previous results[56 59]. Furthermore, radiation was not taken into account in the thermophysiological model. In the CFD model only the convective part is calculated. With respect to the results applied this does not seem to be a problem. The physiological responses were simulated subsequently using the environmental conditions predicted by the CFD model. No differences in physiological responses were found for the two different positions that were applied to retrieve the environmental boundary conditions from the CFD-results (Figure 7.8). These results indicate a limited sensitivity of the physiological responses to the environmental conditions as part of the convective heat transfer in this case. It also indicates that the results of the numerical model, with a coarse geometry for the humanoid, can be accurate enough to predict the physiological responses. The obtained heat transfer coefficients may be used to calculate the convective heat transfer within the thermophysiological (ThermoSEM) model. However, various assumptions have been made to calculate these coefficients in this specific case; the heat emission (convective) of the humanoid was fixed in CFD, and the heat emission per body part was proportionally calculated according to the surface area while in real life the convective fraction of the total heat emission differs per body part. More research is needed regarding the influence of this heat emission on the obtained surface (skin) temperatures of the humanoid, and subsequently on the flow patterns. Furthermore, the influence of clothing is not taken into account. In literature significantly different values can be found for the convective heat transfer coefficients[35 60 61]. Zhang et al.[62] speculate that the possible differences are caused by the divergence in measurement results between the different studies. These differences include the selected surface air temperature setting, the control mechanism and accuracy of the mannequin used in the different experiments, the uncertainty of the used equipment, and the impact of size, shape and position of the different mannequins. However, this is only generic speculation and more research and a more in-depth analysis is needed on this topic. The results obtained in our study assume that the sensitivity to the convective heat transfer coefficients is limited for the studied condition. More research is needed on this topic as well.

An important topic in this study was the coupling of physiological responses to thermal sensation as this is an important performance indicator that is applied to assess design solutions. From both datasets that were applied in the assessment it can be concluded that physiological responses can be predicted well using a thermophysiological model (ThermoSEM, maximum RMSE 0.86°C). For dataset D2, the predicted skin temperatures were slightly higher (maximum difference males: 0.73°C and females: 1.03°C) than the experimental results. Mainly for skin temperatures obtained at higher air velocities (>0.05 m/s), the actual skin temperatures were lower than predicted. This is probably caused by the modeling of the air layer between skin and clothing. At air velocities higher than 0.05 m/s ThermoSEM applies an emperically based relation to determine the air velocity at this layer for body parts covered with clothing; this relation reduces the maximum occurring air velocity in the layer by an emperically based damping factor of 4. Probably this factor is overestimated which causes slightly higher skin temperatures (Figure 7.10), for instance a damping factor of 1 results in a RMSE 0.15°C. Therefore more research is needed to validate the damping of the air velocity by clothing.

The coupling of the physiological responses to thermal sensation was investigated through two case studies for three different static thermal sensation models to assess whole-body TS. Two of them were also suitable to predict local TS.

For the first dataset (D1) (cold wall and slightly elevated floor temperature), the whole-body thermal sensation could be predicted well using the PMV[11], UCB-model[4] and Nilsson[43] model; the predictions were within an accuracy of 0.5 scale units.

Though the PMV model showed a good agreement for dataset D1 (difference <0.2 scale units) with the experimental results, the discrepancies between AMV and PMV for dataset D2 (cooled ceiling, heated floor) were significant. The largest deviation was found for the female group (0.6 scale units). This difference is explained by local effects (i.e. local skin temperatures and local TS), which are not taken into account in the PMV model.

The UCB-model appears to be very sensitive for the set-point skin temperatures. Since, the boundary conditions in the original experiments of Zhang[63] significantly deviate from the boundary conditions in our experiments it was required to simulate the neutral skin temperatures, as the measured neutral skin temperatures are dependent on the environmental conditions. In our approach, we simulated the neutral skin temperatures using ThermoSEM for boundary conditions (ambient conditions, clothing insulation and metabolic rate) which would achieve a neutral PMV. Therefore, the simulated neutral skin temperatures are dependent on the boundary conditions needed as input for the PMV-index: the ambient conditions, clothing insulation and metabolic rate. When the local thermal sensations are determined using the measured skin temperatures and neutral skin temperatures as provided in Zhang[63], large differences can be observed between the predicted and actual local thermal sensations (Figure 7.13). For comparison, in Figure 7.13 another data set for neutral skin temperatures is presented (Olesen and Fanger[63]) and the effect on the local thermal sensations if these set points are lowered with 1K (Olesen and Fanger -1K). In that case an average increase of >0.5 scale units in thermal sensation is derived. Especially the head, chest and back are strongly influenced by this decrease in set point values.

As, the subjects were not exposed to neutral uniform conditions, it was not possible to determine the neutral skin temperatures of the subjects for the investigated specific experimental boundary conditions. The simulated physiological responses were in good agreement with the measured physiological responses (RMSE < 1.0°C). Therefore, the local sensations were predicted using the simulated physiological responses and simulated neutral skin temperatures using ThermoSEM. Following this approach, the predicted and actual local thermal sensation were in good agreement (differences <0.5 scale units). Given the sensitivity towards the neutral skin temperatures, however, care should be given to the simulated physiological responses. The results for the examined cases indicated a difference of approximately 1K with the experimental data. Furthermore, as the PMV model is used to determine the boundary conditions for the neutral skin temperatures care should be given to identified discrepancies[15].

For the UCB-model[4], the chest, back and pelvis were found to be dominant for whole-body thermal sensation. In our study, especially for the females of dataset D2, the extremities were observed as significant influencing parameter for whole-body thermal sensation. Probably, these discrepancies are caused by the difference in measurement set-up that was used for the development of the model. In our study the imposed environmental conditions were intended to represent conditions as encountered in the built environment, wherein all body parts are exposed at the same time to the environmental conditions. In the study of Zhang et al. (UCB-model) a specific body part was cooled or warmed using an attached air-sleeve, subsequently the influence was studied on whole-body level.

Following the above, more research is needed on the determination of the neutral skin temperatures.

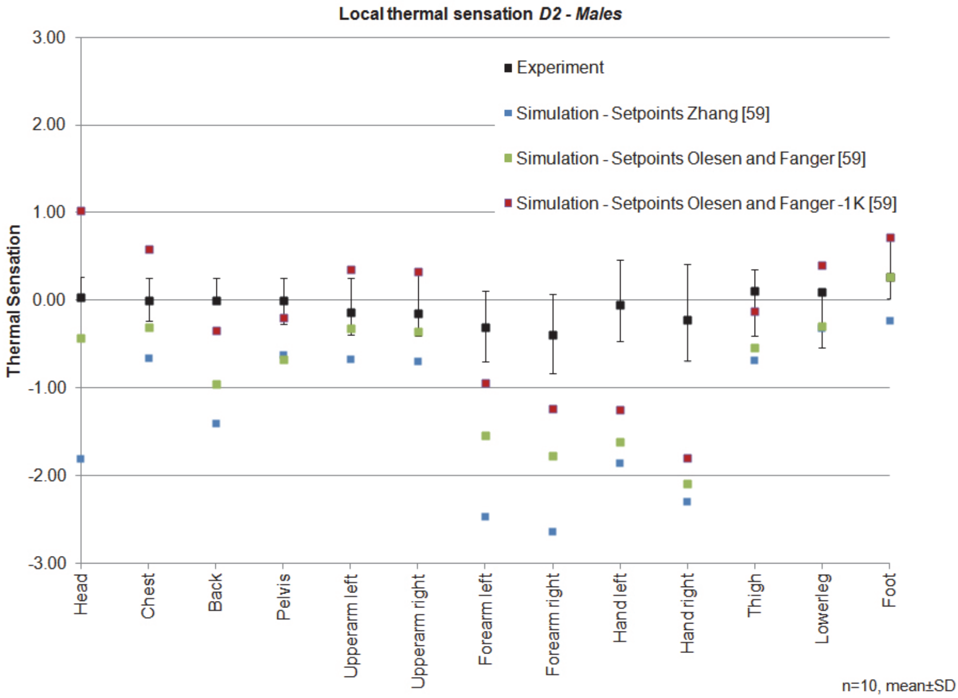

Figure 7.13 Predicted local thermal sensations using measured skin temperature and set points obtained from Zhang et al.[63].

The Nilsson model showed good agreement for both datasets, also the trends in local thermal sensation were predicted well. However, the translation of the actual mean votes, expressed on a 7-point scale, to the comfort zones as defined by Nilsson can be argued; for example is thermal sensation equal to thermal comfort[64]? More research is needed to elaborate on this. Besides, the definition of the equivalent temperature (T_{eq}) is not easy to use in practice since a thermophysiological model is needed to calculate the heat flux and heat transfer coefficients. Cheng et al.[46] furthermore concluded, that more research is needed for application of the Nilsson model at thermal environments away from neutral.

A limitation of the methods presented within this paper is that it is not suitable for use under transient conditions. However, Schellen et al.[6] showed that under transient conditions the thermal sensation can be predicted well by using the PMV-index.

A recent approach of predicting thermal sensation proposed by Kingma et al.[16], may provide a further alternative for predicting thermal sensation under transient conditions.

7.5 Conclusion

In this study, the use of a thermophysiological model to predict thermal sensation in the built environment was discussed. In general, ThermoSEM (thermal physiological model) is able to predict the physiological responses for different subpopulations (male, female) under close to neutral thermal environments. A CFD model can be used to derive the environmental conditions close to the human as input (boundary conditions) for such models. Geometry and modeling requirements for the investigated cases did not indicate the necessity for a high modeling detail of the human body. However, prudence is required with respect to generalization of these results to other room conditioning systems, e.g. local climatization systems.

Based on the results, the PMV model can be suitable to predict thermal sensation. However, care should be taken regarding application under non-uniform environments and when different sub-populations are considered. Under non-uniform conditions both the UCB-model and Nilsson model seem to be very promising to predict the thermal sensation of local body parts and overall thermal sensation. However, both models need more research before they can be used in daily design practice. With respect to the UCB-model more research is needed on the determination of the neutral skin temperatures and dominant (regarding whole-body thermal sensation assessment) body parts. Regarding the Nilsson model, more research is needed on the use of the equivalent temperatures within the presented method, the used terminology and the use of the model under thermal conditions away from neutral.

The added value of the presented approach, with respect to the built environment, is that thermal comfort can be assessed at a more individualized level under complex, daily encountered, thermal environments where local effects play an important role. Furthermore, more insight can be obtained in the actual physiological responses and related thermal assessment.

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Chapter

8

Closure

a general overview and conclusions

8.1 Introduction

Thermal comfort dictates satisfaction of persons with their (thermal) environment, and is therefore regarded as an important performance requirement in the building design process[1]. Subsequently, for successful application of novel low energy and low exergy HVAC (heating, ventilating and air conditioning) systems the achievement of thermal satisfaction is indispensible.

In current building practice standards are available to assess whole-body thermal comfort of the future occupants during the design phase based on the Predicted Mean Vote (PMV)[2 3]. Although several studies found a good agreement between the PMV and actual mean votes[4 5], other studies found discrepancies[6 7]. The PMV model is based on human thermal neutrality as optimum thermal condition. However, thermal neutrality does not necessarily correspond to the ideal thermal condition[1 7]. The thermal neutral zone, from a physiological point of view, differs among subpopulations and individuals. Mild thermal challenges can cause an individual to move further away from its thermal neutral zone compared to another individual[8]. Furthermore, thermoregulatory responses (e.g. skin blood flow and non-shivering thermogenesis) vary on individual and subpopulation level[9-13]. These variations may explain the deviations which occur in thermal perception. Improvements with respect to existing thermal comfort models may benefit from a better understanding of the physiology behind thermal perception and the relation between physiological responses and thermal comfort[14]. By using a thermophysiological model (e.g. ThermoSEM) it is possible to model the dynamic thermoregulatory responses. An important aspect, however, is the coupling to thermal perception and the required level of detail with respect to the prediction of the boundary conditions[1 14].

This thesis aims to explore *thermal comfort beyond uniformity*. Focus is on the effects of non-uniform and transient thermal environments on thermal comfort, physiological responses and productivity with an emphasis on the effects for different subpopulations (i.e. young vs. elderly and males vs. females). Finally, the use of ThermoSEM to predict thermal sensation and comfort is discussed.

8.2 Summary of results

Transient environments

The effects of a moderate transient environment are studied using human volunteers, for two different subpopulations: young males (age 18-30 years) and older male adults (age 68-78 years). The results of the studied moderate temperature drift in Chapter 2 show that a temperature drift up to ±2 K/h in the range of 17–25°C is assessed as acceptable and will not lead to unacceptable conditions with respect to thermal comfort. The thermal sensation of the elderly was in general 0.5 scale units (on the 7-point ASHRAE thermal

sensation scale) lower compared to the younger adults. Consequently, the elderly preferred higher ambient temperature levels. The PMV model was capable of predicting the thermal sensation of young adults in response to a moderate temperature drift. For elderly, the model was capable to predict the trends in thermal sensation, but the absolute thermal sensation is overestimated with on average 0.5 scale units (neutral instead of slightly cool).
In Chapter 3 a novel approach to predict thermal sensation under transient conditions, based on neurophysiological modelling, is presented. The thermal sensation model is developed and validated using two independent datasets obtained from human experiments. In contrast to the PMV model which is suitable to predict thermal sensation for a large uniform group of persons, the neurophysiological approach can be applied for the prediction of thermal sensation of individuals under transient thermal environments.

Non-uniform environments
Under non-uniform conditions, the operative temperature on its own is not sufficient for the prediction of thermal sensation. For the majority of the experimental cases the actual mean votes (AMV, whole-body thermal sensation) significantly differed from the PMV (Chapter 4 and 5). The differences were mainly caused by the presence of combined local discomfort factors, even if the individual discomfort factors were within their limits (predicted percentage dissatisfied < 10%) according to EN-ISO 7730 and ASHRAE[2 3]. Furthermore, local effects (i.e. skin temperature and thermal sensation of individual body parts) play an important role in the whole body thermal sensation and comfort assessment under non-uniform thermal conditions; this especially applies for females (Chapter 4). Mainly, the skin temperatures and coupled thermal sensations of the extremities (i.e. hands and arms) are of high importance for whole body thermal sensation and thermal comfort. However, more research is needed to identify the relations between these local effects, local discomfort factors and whole body thermal assessment.
With respect to the differences in gender, Chapter 4 reveals significant differences in thermal sensation and comfort. Females are more uncomfortable and dissatisfied under the same environmental conditions compared to males. The results are applicable for thermal sensations colder than predicted. For thermal sensations warmer than predicted, this should be investigated further. In terms of cooling, the ambient temperatures for females need to be increased (i.e. less cooling should be provided) to improve satisfaction with thermal environment and focus should be on local effects to achieve whole-body thermal comfort.
In Chapter 6 thermal comfort is discussed for a non-uniform heating situation. In current building practice, large glass façades are popular architectural features. However, these façades can result in interior downdraught during periods with low outdoor temperatures. The focus was on the validity of a rule of thumb[15] to assess the risk on downdraught from a thermal comfort point of view. Both the experimental and numerical modelling results indicate that the existing rule of thumb is conservative regarding the downdraught risk.

Furthermore, the numerical modelling results reveal that an increased floor temperature (i.e. floor heating), which is often regarded as a measure to prevent downdraught, can increase the downdraught risk. Therefore, it is recommended to modify the rule of thumb by implementing the floor temperature as a parameter.

The experimental results (Chapter 2 through Chapter 6) indicate significant differences in thermal sensation and thermal comfort between subpopulations (i.e. males vs. females and young adults vs. elderly). The effects of local skin temperatures and thermal sensations strongly influence whole-body thermal sensation and comfort under non-uniform conditions, especially for females. The results of Chapter 7 reveal that the PMV is not capable of predicting whole body thermal sensation when local effects (local skin temperatures and thermal sensation) have a significant influence. The use of a thermophysiological model (ThermoSEM) in combination with the EN-ISO 14505 standard[16] or UC Berkeley model[17-19] seems to be promising for the prediction of thermal sensation of local body parts and overall thermal sensation and comfort for individuals under steady-state non-uniform environments. However, both thermal sensation models need more research before they can be used in daily building design practice.

8.3 Implications for the application of low energy/exergy HVAC systems

General

In current, most important, thermal comfort standards no attention is paid to the differences in thermal perception between subpopulations[2 3]. Also in recently developed thermal comfort models these differences are neglected[17-19]. Following Karjalainen[20 21], we should not longer ignore the differences in gender when designing the indoor climate. Moreover, the differences between young adults and elderly should not longer be neglected. Both for females and elderly the same trend can be observed in thermal perception compared to young male adults; under the same thermal conditions (mainly at the cold side of neutral) they are feeling significant colder and more uncomfortable in comparison to the young male adults (Chapter 2 and 4). Especially for the design of more individualized HVAC systems this should be taken into consideration.

Temperature drifts

In general, temperature drifts are regarded as an interesting energy-saving measure[22]. However, mild thermal challenges can cause significant physiological responses. For the elderly, mild cold temperature exposures result in a larger increase in systolic blood pressure compared to their younger counterparts, even after rewarming. Since, long-term increased systolic blood pressure levels are related to an increased risk for coronary diseases and mortality[23 24], it is advisable to protect our elderly from even mild thermal disturbances[12]. Contrary, younger adults may benefit from moderate temperature drifts, as

mild temperature challenges could increase the energy expenditure, and may have a positive influence on reducing obesity[12 25]. In general, the indoor climate can have an influence on the health of occupants. Therefore emphasis, with respect to the thermal environment, should be on individual level.
Following the above and from the results (Chapter 2), moderate temperature drifts (up to 2K/h) are allowable as energy-saving strategy in buildings occupied by younger adults.

High temperature cooling systems
Radiant cooling systems are regarded as interesting alternative to classic all-air conditioning systems with respect to thermal comfort, since all-air systems are associated with draught risks[26-28]. In this study no preferences, based on the subjective votes (Chapter 5), were found for radiant cooling (both ceiling and floor systems) compared to conventional all-air systems. However, with respect to the ventilation strategy a clear preference was found for displacement ventilation. In older literature, displacement ventilation is often related to large vertical temperature differences (up to 6°C) and low temperatures near the floor (as low as 18°C) which may result in local discomfort due to draught and vertical temperature differences[29-31]. However, from a more recent study[32] and from the results, we can conclude that vertical temperature gradients (in this study up to 4°C/m) and lower temperatures near the floor, even in combination with floor cooling, can result in acceptable thermal conditions. In addition, the condition where displacement ventilation was combined with a floor cooling systems was assessed as most comfortable. This latter is an interesting application from an energy point of view[32 33]. Additionally, the ventilation effectiveness of displacement ventilation is higher compared to mixing ventilation[32].

Low temperature heating to prevent downdraught
Finally, low temperature floor heating is not advisable as measure to prevent downdraught near large glazed façades and in atria. The increased floor temperatures, which can occur due to the application of a floor heating system, have a negative influence on the air flow patterns and may increase downdraught. This effect was also indicated by Schellen[34].

8.4 Concluding remarks and future directions

As mentioned in the introduction, thermal comfort is indeed a complex phenomenon and difficult to predict due to the great number of influencing factors. Many researchers have tried to indentify the link between the thermal environment, physiology and the perception of the thermal environment. From literature we know that persons do not sense temperature directly, the information is coded into neural fire rates[35 36]. With respect to the modeling of thermal comfort, a novel approach for the prediction of thermal sensation based on neurophysiology is presented in Chapter 3. While this approach performs very well under dynamic conditions, it is not yet suitable for the prediction of thermal sensation under steady-state non-uniform conditions where skin temperatures remain nearly constant. Furthermore the results showed that the operative temperature only is not sufficient for the prediction of thermal sensation and thermal comfort under non-uniform conditions due to the influence of local effects. Non-uniform environments can achieve a comparable or even a more comfortable assessment compared to uniform environments, as was also found by Arens et al.[37]. However, a combination of local discomfort factors can also result in an uncomfortable thermal condition, although the individual discomfort factors are within their individual limits according to thermal comfort standards[2 3]. Non-uniform environmental conditions can achieve significant different thermal sensation votes as predicted in advance. These differences can be enlarged in case the environmental conditions tend away from neutral. The differences are most probably caused by local effects (local thermal sensations and local skin temperatures) and the presence of combined local discomfort factors. Future research should elucidate on the relations between these local effects, local discomfort factors and whole body thermal assessment. The focus should be on the physiology behind thermal perception rather than identifying skin temperature set-points. The physiological approach is now proven to be successful for application under dynamic thermal environments and may explain the differences on subpopulation level. Moreover, one could argue whether set-points are a good representation of the physiology behind thermoregulation or thermal sensation[38 39].

Another important aspect regarding thermal comfort is the psychology behind thermal perception. Little is known about the perceptual mechanisms; what constitutes thermal pleasure and behavioral responses[6 14]. According to de Dear (following Cabanac)[14] 'for each individual, pleasure and displeasure merge into indifference in the centre, along a pleasure gradient that ranges from extremely negative (distress) to extremely positive (delight)'.For example, 'one man's breeze is another man's draft'.

It is generally accepted that skin thermoreceptors play an important role in the neural drive of thermal pleasure[6 14 40]. In Chapter 3, a method based on the latter is presented for the prediction of thermal sensation. However, for non-uniform environments the presented method was not applicable. Furthermore, the differences in gender regarding the influence

of local skin temperatures on whole-body thermal assessment could not be explained. The females tend to be more sensitive to deviations from the optimum. In clinical research often the pain threshold differences in gender are discussed. It is often discussed that females have a lower pain threshold compared to males, but that their pain tolerance is much higher[41]. For future research it could be relevant to investigate whether this applies for thermal sensation as well in order to be able to explain the existing differences in thermal perception between genders.
Another aspect regarding the satisfaction with the thermal environment from a psychological point of view is the perceived extent of personal control. Results from literature show that an increased level of personal control over the physical workspace is correlated to higher levels of thermal comfort and general satisfaction[42 43]. Regarding future work this should be investigated further with an emphasis on the associated energy consumption.

With respect to future improvements of current thermal comfort standards, e.g. EN-ISO 7730 and ASHRAE Standard 55[2 3], focus should be on a more individualized thermal assessment with attention for different sub-populations. The EN-ISO 14505[16] provides a method to evaluate the thermal comfort under complex thermal environments which occur in vehicle environments where local effects play an important role. It should be investigated further whether this method could be suitable for application in the built environment (Chapter 7). An advantage of using a method wherein the influence of local effects on whole-body thermal comfort is taken into consideration, is that no additional limits with respect to local discomfort factors are needed. Since, current standards seem to be conservative on this aspect (Chapter 2, 5 and 6).

In conclusion, based on the presented work, no *uniform* thermal comfort exists as thermal environments are often *non-uniform* and humans are *non-uniform*. With respect to the prediction of thermal comfort under non-uniform conditions the method presented in Chapter 7 seems to be very promising to evaluate different design variants. However, more research is needed to further confirm these results.
Following the above, prudence is still required when designing thermal comfortable conditions in general, and when low exergy/energy systems (e.g. high temperature cooling by means of radiation) are applied.

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Nomenclature

Symbol	Description	Unit
A	Surface area	[m^2]
c	Heat capacitance	[J kg^{-1} K^{-1}]
D	Sign operator for direction of response	[-]
f	Neuron fire rate	[$pulse^{-1}$]
h	Surface heat transfer coefficient	[W m^{-2} K^{-1}]
H	Hypothalamic neuron fire rate	[pulse s^{-1}]
k	Conductivity	[W m^{-1} K^{-1}]
K	Gain factor for dynamic part of neuron fire rate	[-]
m	Mass	[kg]
n	Number of subjects	[-]
p	Probability of obtaining a test-statistic at least as extreme as the one observed	[-]
P	Peripheral afferent neural drive	[pulse s^{-1}]
Q	Representing the moment of questionnaire	[-]
Q_i	Heat emission of body part i	[W/m^2]
r	Radius	[m]
r^2	Squared correlation coefficient	[-]
S	Steady state neuron fire rate	[-]
t	Time	[s]
T	Temperature	[K]
T_{ref}	Ambient temperature just outside the boundary layer	[K]
$T_{sk;i}$	Area averaged surface temperature of body part i	[K]
U_{glass}	Overall heat transfer coefficient of glass	[W m^{-2} K^{-1}]
v	Velocity	[m/s]
v_{air}	Maximum accepted air velocity	[m/s]
w	Warm sensitive neurons	[-]
X_j	j-th order coefficient	[-]
Z	Value of the standard normal distribution	[-]
Z_y	Value of the standard normal distribution corresponding to the type II error rate	[-]

Greek symbols	Description	Unit
α	Error rate	[-]
β	Heat equivalent of blood flow	[W m^{-3}]
γ	Model constants for neurophysiological thermal sensation model	[s $pulse^{-1}$]
ε	Emissivity	[-]
δ	Prediction-error	[-]
σ	Standard deviation	[-]

Subscripts and superscripts	
a	Arterial
air	Air
c	Convective
cold	Cold
e	Evaporative
eq	Equivalent
i	Index
j	Index
max	Maximum
mean	Mean
mix	Mixed
neutral	Neutral
sk	Skin
t	Time
warm	Warm

Abbreviations and acronyms	
AC-C-D	Active Cooling through Convection by Displacement ventilation
AC-C-M	Active Cooling through Convection by Mixing ventilation
AC-R-D-F	Active Cooling through Radiation by the Floor and Displacement ventilation
AC-R-M-C	Active Cooling through Radiation by the Ceiling and Mixing ventilation
AC-R-M-F	Active Cooling through Radiation by the Floor and Mixing ventilation
AMV	Actual Mean Vote
ANOVA	Analysis Of Variance between groups
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BMI	Body Mass Index
C	Cold
CBS	Centraal Bureau voor de Statistiek | Statistics Netherlands

CC	Cooling through convection
CET	Corrective Effective Temperature
CFD	Computational Fluid Dynamics
D1	First dataset
D2	Second dataset
DR	Draught Rate
DTS	Dynamic Thermal Sensation
DV	Displacement Ventilation
E	Elderly
ET	Effective Temperature
F	Female
HVAC	Heating Ventilation and Air Conditioning
IEA	International Energy Agency
ISO	International Standards Organisation
IQR	Interquartile Range
LME	Linear Mixed Effectmodel
LMM	Linear Mixed Model
LMV	Local Mean Votes
S	Local Thermal Sensations
M	Male
NTC	Negative Temperature Coefficient
OTS	Overall Thermal Sensation
PC	Passive Cooling
PC-C-M	Passive Cooling through Convection by Mixing ventilation
PD	Percentage Dissatisfied
PID	Proportional Integral Derivative
PPD	Predicted Percentage of Dissatisfied
PMV	Predicted Mean Vote
RANS	Reynolds-Averaged Navier Stokes
RC	Cooling through radiation by the ceiling
RH	Relative Humidity
RMSE	Root Mean Squared Error
RMSR	(Square) Root of Mean Squared Residual
RNG	ReNormalisation Group
RPM	Remote Performance Measurement
S1	Session 1
S2	Session 2
SD	Standard Deviation
SIMPLE	Semi-Implicit Method for Pressure Linked Equations
TC	Thermal Comfort

TS	Thermal Sensation
TSV	Thermal Sensation Vote (Whole Body)
UCB	University of California Berkeley
UDF	User Defined Function
VAS	Visual Analog Scales
VC	VasoConstriction
VD	VasoDilatation
W	Warm
WB TS	Whole-Body Thermal Sensation
Y	Young

List of publications

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Curriculum Vitae

Lisje Schellen was born on the 23rd of June 1984 in Roermond. In 2001 she finished secondary school at the Stedelijk Lyceum in Roermond. In the same year she started a bachelor study in both Building and Civil engineering at the Zuyd University of Applied Sciences. She completed the foundation course in 2002. Consecutively she followed the Bachelor Architecture, Building and Planning at the Eindhoven University of Technology. After graduating for her bachelor in 2005 she started the master Architecture, Building and Planning, with a specialization in Physics of the Built Environment, at the same university. For her master thesis she studied the differences in thermal perception and thermophysiology between young adults and elderly in response to a transient and steady-state thermal environment. During her master study she was student member of the Faculty Management Board. Furthermore, as student-assistant she was actively involved in the improvement of the portfolio program of the master Architecture, Building and Planning and the educational program of the bachelor Architecture, Building and Planning. She graduated for her master of science in 2007 and started her PhD study, which is described in this thesis, directly afterwards at the unit Building Physics and Systems of the department of the Built Environment at the Eindhoven University of Technology. The PhD study has been performed in close cooperation with the department of Human Biology of Maastricht University. During her PhD study she was also involved in education in the bachelor and master program of Architecture, Building and Planning.
In 2010, next to her PhD study, she started to work as lecturer Building Physics at the department of the Built Environment at the Avans University of Applied Sciences at Tilburg and Den Bosch. In 2011 she became a board member of the Dutch chapter of the International Society for Indoor Air Quality and Climate (ISIAQ).

After finishing her PhD she will continue working at the Avans University of Applied Sciences as lecturer and researcher.

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behorende bij het proefschrift

Beyond Uniform Thermal Comfort

on the effects of non-uniformity and individual physiology

1. Vrouwen zijn moeilijker te behagen dan mannen, in ieder geval thermisch. *(Hoofdstuk 4)*
2. Lokale effecten spelen een belangrijke rol in de algemene comfortbeleving, en zouden in een comfortmodel niet mogen ontbreken . *(Hoofdstuk 4 en 5)*
3. Het vinden van gezonde ouderen (boven de 67 jaar) voor een proefpersonenonderzoek is een lastig gegeven: m.a.w. gezonde ouderen blijken niet representatief te zijn. *(Hoofdstuk 2)*
4. Traditionele radiatorenverwarming vervangen door vloerverwarming uit het oogpunt van energiebesparing (Lage Temperatuur Verwarming), is geen verstandige keuze uit het oogpunt van koudevalcompensatie. *(Hoofdstuk 6)*
5. Het realiseren van een experimentele faciliteit vergt meer dan het ontwerpen ervan.
6. ‘Elk mens is anders’, echter in de normen worden we in eerste instantie allemaal behandeld als hetzelfde. Met de huidige stand van computertechniek zou hier wel verandering in gebracht kunnen worden.
7. Wanneer de TUe het ambieert om zo min mogelijk nakomelingen van hoogopgeleide vrouwen na te streven, dan is het Women in Science traject een goede zet.
8. Het hebben van een Facebook-account is ideaal wanneer je promoveert; het geeft een invulling aan je werkontwijkend gedrag en je hebt het idee niet in een sociaal isolement te raken.
9. Bij aanstellingen is het goed om eens te kijken wat voor kwaliteiten er al in huis zijn; het gras is immers niet altijd groener bij de buren.
10. Als kind leer je ‘kinderen die vragen worden overgeslagen’, echter voor volwassenen lijkt te gelden ‘wie het hardst roept krijgt het meest’.
11. Zien is de kunst van het kijken, maar je moet wel weten waar je naar kijkt.
12. Niet kennis, maar verstandig omgaan met wat je niet weet: dat is wijsheid. (*Bas Haring, 2009*)

Lisje Schellen, 18 september 2012

Propositions

belonging to the thesis

Beyond Uniform Thermal Comfort

on the effects of non-uniformity and individual physiology

1. Compared to men, it is more difficult to satisfy women, at least thermally. *(Chapter 4)*
2. Local effects play a significant role in whole-body thermal comfort and should therefore be included in thermal comfort models. *(Chapter 4 en 5)*
3. It is difficult to find older healthy subjects (above 67 years) to participate in experiments: so healthy elderly seem to be not representative. *(Chapter 2)*
4. The replacement of a traditional radiator with a floor heating system for energy reasons (Low Temperature Heating), is not an intelligent choice from a downdraught point of view. *(Chapter 6)*
5. The realization of an experimental test set-up implies more than the design of it.
6. ‘Every human being is different’, however in standards we are all treated as one and the same on first instance. Regarding the current computer technology, this should be changed in future.
7. In case the TUe has the aspiration to aim for as less as possible descendants of highly-educated women, the Women in Science track is a good strategy.
8. Having a Facebook-account is perfect when doing a PhD; it gives meaning to your work avoiding behaviour and you have the idea that you are not getting into a social isolation.
9. In case of vacancies it is good to look at the quality of your own employers, since ‘the grass of the neighbours is not always greener’.
10. The Dutch proverbial phrase ‘kinderen die vragen worden overgeslagen’ teach us as child that if you ask for something you will be skipped, however for adults the rule ‘the ones who call louder get the most’ seems to apply.
11. Seeing something is the art of looking, however you have to know where you are looking at.
12. Not knowledge, but wisely managing the things you do not know, that is wisdom. *(Free translated from Bas Haring, 2009)*

Lisje Schellen, 18 September 2012

Thermal comfort dictates satisfaction of persons with their (thermal) environment, and is therefore regarded as an important performance requirement in the building design process. Subsequently, satisfaction of the occupants with their thermal environment is one of the most important parameters for successful application of novel low energy and low exergy HVAC (heating, ventilating and air conditioning) systems. To adequately design optimal environmental conditions in the future, both in an energy-friendly and comfortable way, more knowledge on the interaction between the system, indoor climate and the human body is indispensable.
Thermal comfort is a complex phenomenon and it is therefore difficult to satisfy everyone in the same room if no individual correction measures can be taken. This is due to the large differences between persons, both psychological and physiological. Furthermore, the optimal thermal condition is not necessarily equal to thermal neutrality since preferences for non-neutral thermal sensations are common.
This thesis aims to explore thermal comfort of occupants beyond uniformity. Focus is on the effects of non-uniform and transient thermal environments on thermal comfort, physiological responses and productivity with an emphasis on the effects for different subpopulations (i.e. young vs. elderly and males vs. females).

/ Department of the Built Environment

Technische Universiteit
Eindhoven
University of Technology