



Research Centre on  
ZERO EMISSION  
NEIGHBOURHOODS  
IN SMART CITIES

# PERSONAL HEATING AND COOLING DEVICES: INCREASING USERS' THERMAL SATISFACTION

A literature study

ZEN REPORT No. 4 – 2018



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### ZEN Report No. 4

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#### Personal Heating and Cooling Devices: Increasing User's Thermal Satisfaction

Keywords: Personal heating, personal cooling, thermal comfort, individual preference, user satisfaction

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## Abstract

This report is a part of Work Package 3 Responsive and Energy Efficient buildings. The goal for WP 3 is to create cost effective, responsive, resource and energy efficient buildings by developing low carbon technologies and construction systems based on lifecycle design strategies.

As conventional HVAC systems can only make most users satisfied with their thermal environment, there has recently been a lot of research into personal climatization systems. The aim of this literature study was to investigate whether personal heating and cooling solutions could contribute to make all users satisfied with their thermal environment. Potential energy savings are considered a bonus, but was also included in the evaluation of the literature on the subject.

Almost all of the articles reviewed in this report found that the personal climatization devices significantly improved thermal sensation and thermal comfort for the users. For both heating and cooling it was found that combining personal comfort devices resulted in higher comfort improvement and higher energy saving potential. The devices also made it possible to achieve thermal comfort outside the traditional heating and cooling setpoints, thus making it possible to extend the thermal dead-band of buildings, which could lead to substantial energy savings. There are however still some aspects of personal climatization systems where there is suggested further research, and these personal climatization systems are still not commercially available.

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# 1 Introduction

## 1.1 Background

Heating and cooling systems in buildings are traditionally designed to make *most* people satisfied with their thermal environment. A model by (Fanger, 1972) is commonly used when describing thermal comfort. Fanger`s model concludes that for large groups identically dressed and of same activity level, there will always be someone dissatisfied. This principle is illustrated in Figure 1, that shows the correlation between Predicted Percentage of Dissatisfied (PPD) and Predicted Mean Vote (PMV), where 5 % is dissatisfied even if the PMV is 0. Design of HVAC systems are based on temperature and CO<sub>2</sub> levels, not on whether the user actually is satisfied or not, which is in fact the goal of heating buildings.

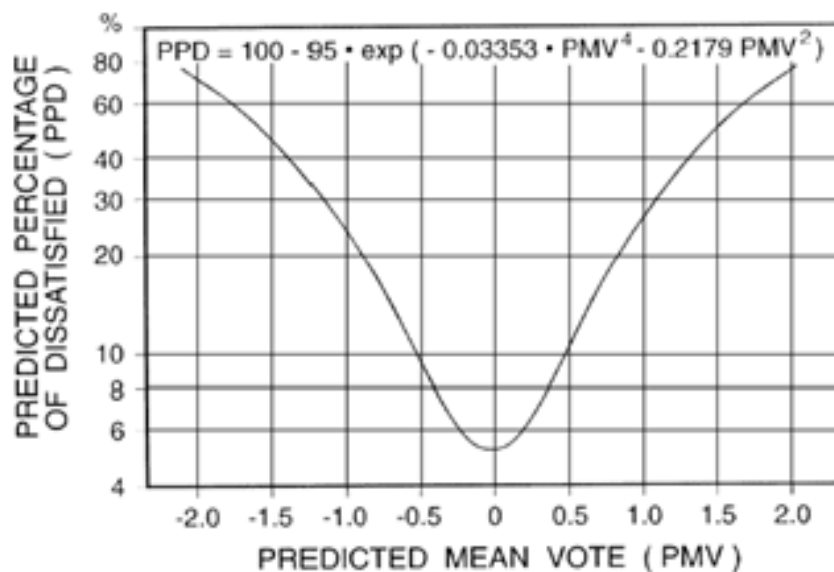


Figure 1 Correlation between Predicted Percentage of Dissatisfied (PPD) and Predicted Mean Vote (PMV). (AUTODESK Knowledge Network, 2015) [Creative Commons Attribution-NonCommercial-ShareAlike 3.0 Unported License](#)

What if it was possible to make *everybody* satisfied? Or at least a higher percentage of people than with Fanger`s approach? The idea is to use technical solutions for personal climatization in addition to the conventional heating systems, in order to enable personal control until each individual is satisfied with their thermal environment. By using personal climatization systems, the energy is deployed only where it is actually needed, and individual preferences for thermal comfort could be achieved. Personal climatization has received a lot of attention in research publications during the past years (Veselý and Zeiler, 2014). In this review, we will introduce a selection of published research since 2009-2017.

As a starting point, conventional heating systems ensure proximity to the comfort temperature. The idea is to slightly lower the setpoint compared to what is common today, and to use personal climatization systems in order to cover the rest of the individual needs. By having a slightly lower heating setpoint it will also be possible to satisfy the users that think it is too warm with today's setpoint. In addition, by implementing personal cooling solutions, the cooling setpoint could be increased, thus extending the

thermal span for central building services in both directions. This provides opportunities for substantial reductions of energy consumption in buildings (Thunshelle, 2016).

People have different preferences with regards to thermal comfort, and aside from environmental factors, it is dependent on personal factors such as clothing level, activity level and the mental state per individual (Nicol and Roaf, 2005). In addition, the stimuli of heating when one is cold and cooling when one is warm makes the occupant more satisfied. The feeling of being in control of one's own thermal environment is also satisfying and gives the user a sense of achievement (Brown and Cole, 2009). Improving thermal comfort for all users (compared to the traditional thermal comfort goal of satisfying most of them) is also expected to increase productivity in office and education buildings. The idea of satisfying all users with individual heating and cooling devices represents a new way of thinking of heating systems.

## **1.2 Aim**

The aim of this literature review is to investigate and provide an overview of technical solutions that could increase users' satisfaction with their thermal environment, and if possible reduce energy consumption as well.

## **1.3 Method**

The report is based on a literature search performed in November 2017 for articles newer than 2009 in the databases Engineering Village and ScienceDirect. The following key words were used in different combinations in Engineering Village: occupant heating, occupant control, individual heating, individual control, individual preference, temperature preference, heating, buildings, adaptive thermal comfort, personal comfort, personal control, sensory perception, thermal comfort, thermal preference, thermal sensation, thermal sensitivity, user satisfaction, user heating, user preference, user control, climate control, comfort perception, comfort sensation, indoor thermal conditions, indoor thermal environments. In ScienceDirect, there was only performed one search with the combination of the following key words: local heating, thermal comfort, individual and control. The literature was screened by only considering articles reviewing technical devices for personal climatization.

## **1.4 Scope**

The main focus of this study is to consider technical solutions for personal heating and cooling suitable for Nordic climate. Personal climatization enabled by local ventilation systems is not considered, as this is investigated in other ongoing projects, like SvalVent (<http://www.sintef.no/projectweb/svalvent/>). The technical solutions are in principle not restricted to certain building types, but the most interesting areas for this study is non-residential workspaces such as cellular offices, open space offices, meeting rooms, etc. in offices and educational buildings. Thermal comfort and individual preferences are large topics that is briefly introduced as a framework for the evaluation of the technical solutions. Communication with and control of the technical system is also considered to be adjacent topics which are not evaluated in this report. There might also be other relevant articles on the subject that were not found by the key words and time limitations used in the literature search.

## 2 Thermal comfort

### 2.1 Definitions and evaluation of thermal comfort

Thermal comfort is defined as the state of mind where one is satisfied with the thermal environment. In this condition, the user does not want it to become neither warmer nor cooler for the whole-body or for different body parts (Mysen, 2017). Thermal comfort is dependent on environmental factors such as air and radiant temperature, asymmetrical temperature differences, air velocity and relative humidity, but also cultural factors and personal factors such as clothing and activity level. People are different and have different thermal preferences. In addition, what is perceived as a comfortable thermal environment could also differ on a day-to-day basis for the same person, for example if the person is sick, stressed or tired. Other studies suggest there are differences with regards to gender, age, body weight, accustomed climate, etc. This will not be investigated specifically in this report.

There are two main principles for evaluating thermal comfort; Fanger's model and the adaptive method. Fanger's model is the traditional approach, and *"is derived from the physics of heat transfer and combined with an empirical fit to sensation. It defines constant comfort temperatures for the summer and winter period considering different clothing levels. The adaptive comfort model considers the thermal sensation of the occupants and different actions in order to adapt to the thermal environment, as well as variable expectations with respect to outdoor and indoor climate"* (Kalz and Pfafferott, 2014)

A third principle, alliesthesia, is a combination of both Fanger's method and the adaptive method, as illustrated in Figure 2. Spatial alliesthesia, or reverse instances of local discomfort, takes advantage of the positive sensation of adjusting the skin temperature of separate body parts towards neutral conditions. (Parkinson and De Dear, 2016) investigated this by heating hands and feet in a cold environment. They found that the local thermal stimulation induced a pleasant response among subjects that were dissatisfied or even indifferent to the thermal environment. Spatial alliesthesia provides a theoretical framework for thermal perceptions in environments not considered thermally neutral, and is useful for evaluating personal control and local thermal discomfort.

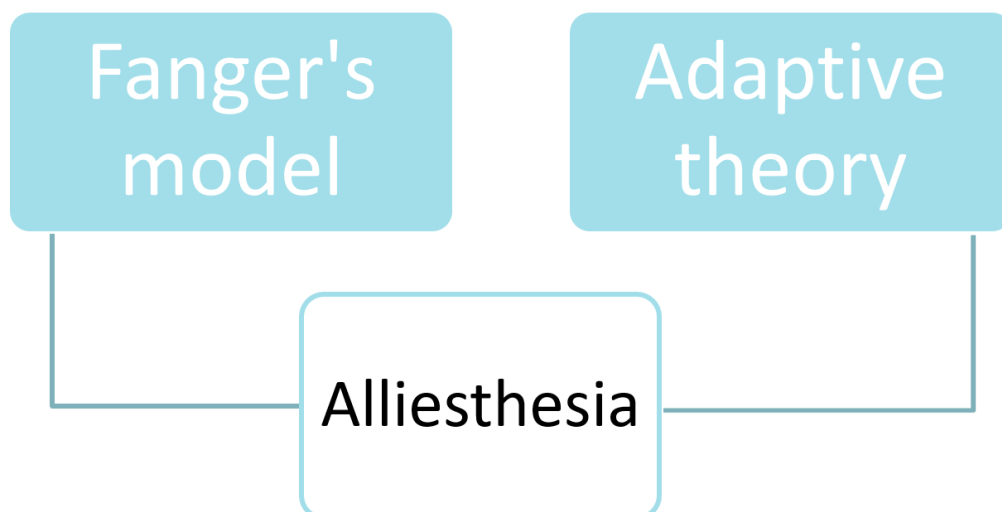


Figure 2 The two main principles for thermal comfort evaluation, Fanger's model and adaptive theory, and the alliesthesia principle which is a combination of both.

Antoniadou and Papadopoulos (2017) wrote a state of the art on occupants' thermal comfort and the prospects of personalized assessment in office buildings. They state that during the last decade, there

has been a substantial increase of research within comfort assessment in office buildings. The interest can be connected to the recognition of the impact of comfort on health, well-being and productivity, and to new European directives and standards, which objective is to improve buildings' energy and environmental performance, without diminishing the occupants' comfort. The objective of their paper is to monitor and discuss the evolution of methodological approaches regarding the determination of comfort. The research identifies a need of working towards personalized assessment of comfort based on the occupants' perspective. It also acknowledges that this is an innovative approach that needs further analysis (Antoniadou and Papadopoulos 2017).

When utilizing personal climatization systems it is important to figure out how and where the person should be heated or cooled, as overall thermal comfort is dictated by local comfort. Zhang's thermal comfort model (Zhang et al., 2010) predicts that the local comfort of feet, hands and face predominates in determining a person's overall comfort in warm and cool conditions. According to (Ciuha and Mekjavic, 2016), the sensitivity of skin regions also vary with regards to temperature stimulations. Their study investigated whether these regional variations were also evident in the perception of thermal comfort. They examined different skin areas (arms, legs, front torso and back torso) and found that the 16 test subjects (8 males and 8 females) preferred higher local skin temperature for the arms ( $35.4 \pm 2.1^{\circ}\text{C}$ ), compared to other regions (legs:  $34.4 \pm 5.4^{\circ}\text{C}$ , front torso  $34.6 \pm 2.8^{\circ}\text{C}$  and back torso:  $34.3 \pm 6.6^{\circ}\text{C}$ ), with no differences between genders. They concluded that thermal comfort of different skin regions and overall body can be accomplished at a range of temperatures, and designated this as the thermal comfort zone (TCZ) (Zhang et al. 2010).

According to (Van Craenendonck et al., 2017), there are three main procedures for improving thermal comfort in existing buildings: modelling, experiments and measurements. There is currently no standardized method regarding experiments. They therefore performed a review of human thermal comfort experiments in controlled and semi-controlled environments. In order to find the most common practice, 166 articles presenting results on 206 experiments were collected and analysed. A typical experiment was conducted in a climate chamber with a floor area of  $24 \text{ m}^2$  involving 25 subjects at three different air temperatures. Testing period was 115 min, but is executed after a preconditioning and conditioning phase. Every 15 minutes, the subject is given a questionnaire, which questions are highly dependent on the research topic, but including thermal sensation and comfort vote on a 7-level scale. Further information can be found in the article, and similar experiments will be presented in chapter 3.

## 2.2 Standards on thermal comfort

This chapter presents an overview of some of the most relevant international standards on thermal comfort, as well as research articles presenting and evaluating standards. On national levels, there can be various regulations setting further requirements that must be fulfilled. The three most acknowledged international standards on thermal comfort are considered to be:

- ISO 7730:2005 Ergonomics of the thermal environment – Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria
- EN 15251:2007+NA:2014 Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics
- ASHRAE 55-2017 Thermal Environmental Conditions for Human Occupancy



An example for a national addition is Norway's national appendix of NS-EN 15251:2007+NA:2014 (Standard Norge, 2014). As an extension of table A.1 in EN 15251, table NA.1 presents four different classes for thermal indoor environment in buildings. Class I gives the highest user satisfaction, and one of the requirements is that each user should have his own thermal zone, where it is possible to adjust the heating and cooling setpoint within a broad range (for example 19 to 26 °C). This suggests that to achieve class I, it should be implemented personal control.

Relevant articles involving standards on thermal comfort:

- Standards on thermal comfort (Kalz and Pfafferott, 2014)
- International standards related to the influence of the indoor environment on people's health, comfort and productivity (Olesen, 2012)
- Personal control in future thermal comfort standards? (Boerstra, 2010)

A study performed by (Kosmopoulos et al., 2012), challenges the PMV-PPD model used in ISO 7730, and proposes a new empirical index to quantify the overall comfort sensation of a user in an office building, the Index of Workplace Comfort (IWC). It considers both environmental and psychological weighted sensation votes and is calculated based on 13 variables found through ordered probit regression in a dataset, using a background questionnaire completed by 238 individuals working in 11 office buildings. The index was further evaluated by implementing it in a building (52 cases) and comparing it with data collected from thermal comfort measurements based on ISO 7730 (159 cases) and thermal sensation votes of the occupants (321 cases). Based on the findings, the IWC describes the overall comfort conditions better than the PMV-PPD model used in ISO 7730, and in addition supports that psychological variables affect the overall comfort sensation in workplaces.

Already in 2010, (Boerstra, 2010) suggested that personal control should be included in future thermal comfort standards, as an abundance of studies indicates that offering occupants control over their indoor climate leads to less health symptoms, higher comfort satisfaction rates and improved performance. He also proposed a solution as to how to include the aspect of personal control in the standards. With a basis in the standard thermal comfort criteria used in EN-ISO 7730:2005, the classification (from A to C) was extended to include a class called A+, which enabled a high degree of personal control at workstation level. The other classes were also modified by specifying various degrees of personal control, whereas class A and B had limited personal control at room level, while class C had no personal control. He suggested more research and discussion before implementing the proposal in the standards. Now, seven years have passed and there has been plenty of new research suggesting personal control is a good idea, so maybe it is time to reconsider the proposal?

### 3 Technical solutions for personal heating and cooling

This chapter presents a brief account of the research questions, methods and findings from the relevant articles found in the literature search. The chapter is divided in three parts, as some articles evaluated both heating and cooling solutions, while others only evaluated one or the other. The collected information is mostly based on the abstracts and conclusions of the articles.

#### 3.1 Personal heating and cooling solutions

Table 1 presents an overview of the articles that have been reviewed in this chapter, in addition to given comfort improvements and energy saving potential if applicable.

Table 1 Overview of articles on personal heating and cooling solutions, including specified improvement in comfort and energy saving potential.

<b>Title</b>	<b>Comfort improvement</b>	<b>Energy saving potential</b>
A new approach to provide thermal comfort in office buildings – a field study with heated and cooled chairs (Hoffmann and Boudier 2016)	Heating: 82 % of the subjects experienced improvement Cooling: 31 % of the subjects experienced improvement	Not quantified
Development of a wrist-band type device for low-energy consumption and personalized thermal comfort (Lopez et al. 2016)	59 % of subjects reported that heating the wrist made them feel like the whole body was warmed	Not quantified
A review of the corrective power of personal comfort systems in non-neutral ambient environments (Zhang, Arens, and Zhai 2015)	Heating CP: 2 to 10 °C Cooling CP: -1 to -6 °C (CP – Corrective Power)	Could exceed 30 %
Energy-efficient comfort with a heated/cooled chair: Results from human subject tests (Pasut et al. 2015)	Comfortable for 92 % of subjects within 18-29 °C	>50 % in many climates
Personalized conditioning and its impact on thermal comfort and energy performance – A review (Vesely and Zeiler 2014)	Thermal comfort well maintained at ambient temp. 4-5 °C higher/lower than temp. recommended by current standards	40 % in general, 60 % at highest
Comfort, perceived air quality, and work performance in a low-power task-ambient conditioning system (Zhang et al. 2010)	Good comfort levels within 18-30 °C	40 %
Design of an individually controlled system for an optimal thermal microenvironment (Watanabe, Melikov, and Knudsen 2010)	Too low heating/cooling power to satisfy most occupants in practice	Not quantified

### **A new approach to provide thermal comfort in office buildings – a field study with heated and cooled chairs (Hoffmann and Boudier, 2016)**

During the summer of 2015, a field study on office chairs with both heating and cooling functions was performed in an office building in Germany. 26 participants in single offices tested the chairs illustrated in Figure 3 and voted twice a day their thermal sensation and comfort before turning on the heating or cooling function, and while using it. Thermal sensation was reduced in close to 35 % of the cases in cooling mode, while it was increased in 85 % of the cases in heating mode, corresponding to a comfort improvement of 31 and 82 % in cooling and heating mode respectively. At high indoor temperatures (above 30 °C), the temperature difference driving the sensible convective heat transfer is reduced, thus limiting the cooling function. The personal climatization equipment makes it possible to extend the dead band for the HVAC control, especially in heating mode. However, for lower heating setpoints, additional personal heating devices (ex. foot or hand warmers) are recommended to ensure that the occupants are satisfied. The authors especially recommend using local devices in open space offices, where people with different thermal preferences work together. Heated/cooled chairs is found to improve thermal comfort for the occupants by giving them control of their thermal environment. More energy efficient control over the HVAC system provides an additional benefit. More information about the project can be found at [www.livinglab-smartofficespace.com](http://www.livinglab-smartofficespace.com).

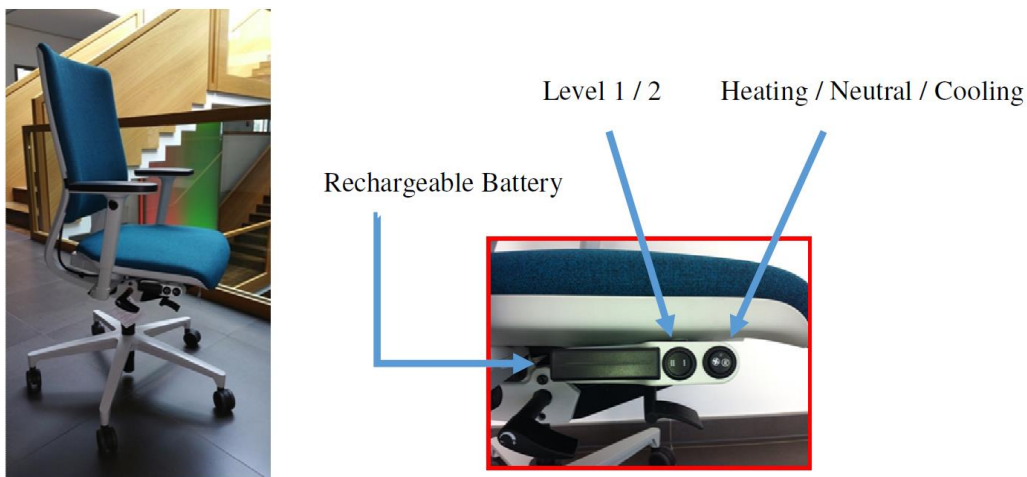


Figure 3 Left: Office chair with heating and cooling functionality, right: control unit. (Hoffmann and Boudier 2016: page 3)

### **Development of a wrist-band type device for low-energy consumption and personalized thermal comfort (Lopez et al., 2016b)**

Information has been collected both from this article and from (Lopez et al., 2016a). A Japanese research team developed a low-energy portable system using Peltier elements for both cooling and warming the neck or wrists. The cooling function gave positive effects on both physiological and psychological state in summer heat environments, while in cold climate the device only made significant difference for neck warming but not feet and hands. The device is called the PICO-band (Personal intelligent comfort control band), a wearable heating device as illustrated in Figure 4. The researchers studied how wrist warming in cold environments affects physiology, and measured temperatures at index finger, palm and back of the hand, and heat transfer toward the wrist in both normal and heating conditions. 59 % of the subjects reported that heating the wrist made them feel that the whole body was warmed. However, index finger temperature decrease was reported for two of the five test subjects in heating mode, suggesting the device does not increase finger temperatures. This could be connected to poor blood circulation and the authors plans to further investigate this phenomenon. The effect of thermal sensation with constant heating was also evaluated, and warming sensation was found to decrease after two

minutes. The authors recommended 10 seconds of cyclic heating of the wrist instead of continuous heating, as it maintains the heat sensation for longer time periods.

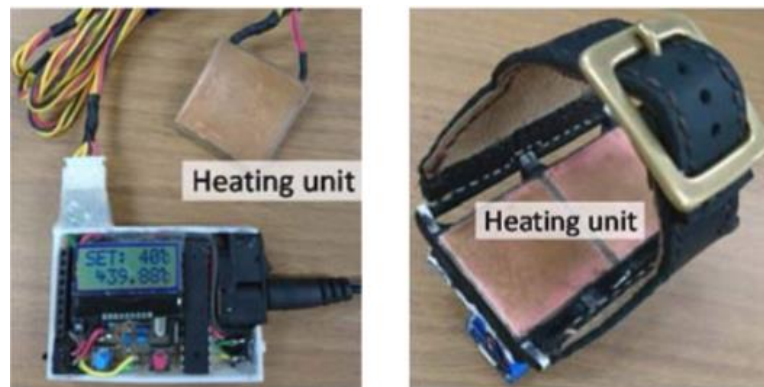


Figure 4 Left: Picture of previous prototype, right: newly developed PICO-band. (Lopez et al. 2016: page 2)

### A review of the corrective power of personal comfort systems in non-neutral ambient environments (Zhang et al., 2015b)

This paper presents a method of quantifying personal comfort systems (PCS) ability to provide comfort in ambient temperatures outside the subjects' neutral temperatures. The term "corrective power" (CP) is introduced to quantify the comfort-providing effectiveness by means of a temperature difference. "CP is defined as the difference between two ambient temperatures at which equal thermal sensation is achieved - one with no PCS (the reference condition), and one with PCS in use" (Zhang, Arens, and Zhai 2015: page 15). CP can thus quantify different PCS ability to "correct" the ambient temperature toward neutrality, but could also be a means of quantifying thermal sensation or comfort. In the reviewed studies of PCS, cooling CP was found to range between -1 to -6 °C, while heating CP ranged from 2 to 10 °C. Figure 5 presents an overview of studies with or without PCS where higher comfort rates are achieved outside the traditional heating/cooling setpoint temperatures. As further research, the authors recommend investigating spatial and temporal alliesthesia, as well as physiological and psychological information about local comfort at different body segments, to achieve a better understanding of PCS.

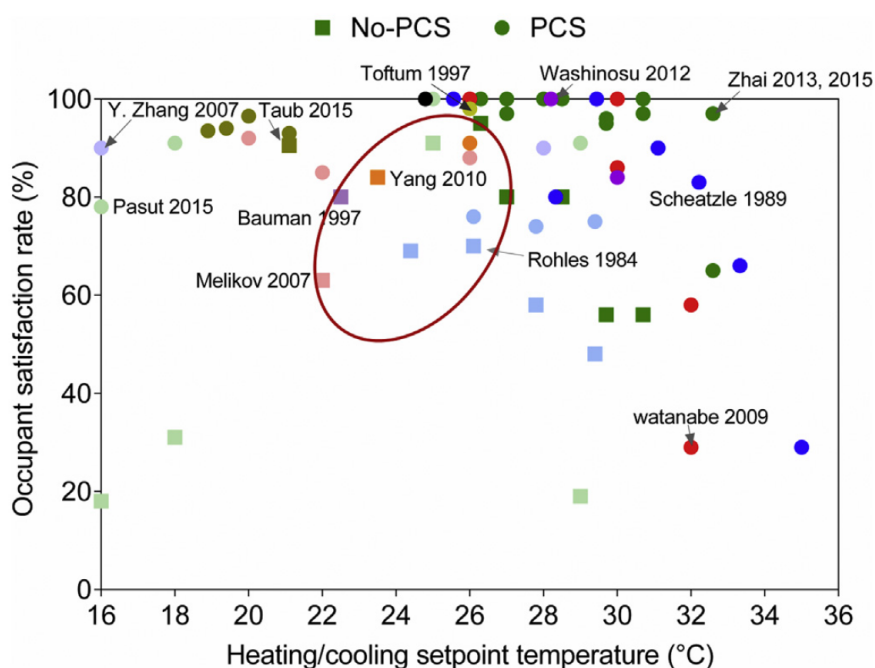


Figure 5 Higher comfort rates achieved at warmer- or cooler-than-neutral ambient conditions (neutral conditions shown as squares in the ellipse) (Zhang, Arens, and Zhai 2015: page 23).

### Energy-efficient comfort with a heated/cooled chair: Results from human subject tests (Pasut et al., 2015)

The chair evaluated in this study is considered highly efficient, and has long battery life. 23 college students tested four heated/cooled chairs in 69 2.25 h tests in an environmental chamber, where they had control of the chair power through a knob located on the chair. The tests were performed at temperatures of 16, 18 and 29 °C. Every 15 minutes, there were collected subjective responses for thermal sensation and comfort. The heated/cooled chair, illustrated in Figure 6, was found to strongly influence the subjects' thermal sensation as well as improve thermal comfort and perceived air quality. 92 % of the subjects were satisfied within the temperature range of 18-29 °C, and no significant differences were found between gender. This wider dead-band could lead to energy savings higher than 50 % in many climates. The chair energy consumption is considerably lower than that of central HVAC, so the energy saving should not be significantly offset by this. There has also been performed previous studies on this chair, where the following articles were published:

- Energy-efficient comfort with a heated/cooled chair (Pasut et al., 2014)
- Effect of a heated and cooled office chair on thermal comfort (Pasut et al., 2013)

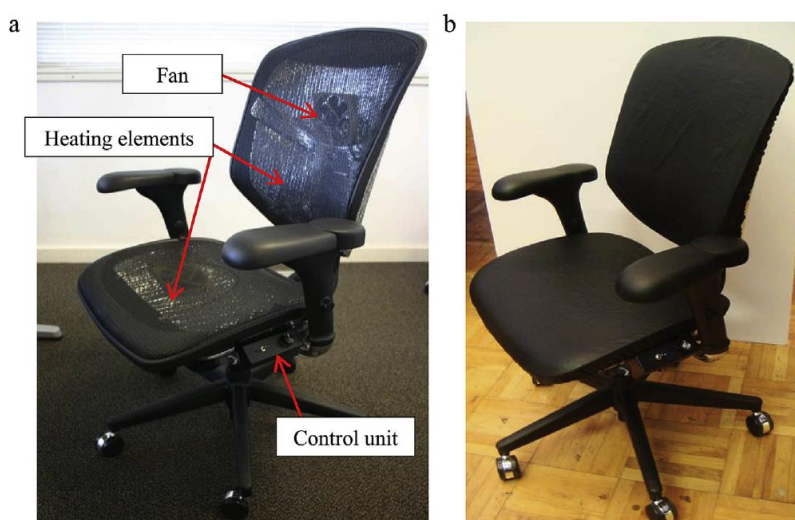


Figure 6 a: Mesh PCS chair, b: Covered PCS chair. (Pasut et al. 2015: page 11)

### Personalized conditioning and its impact on thermal comfort and energy performance – A review (Vesely and Zeiler 2014)

This paper mostly focuses on personal climatization through local ventilation units, but also mentions personal heating devices. Through a review of publications, it found that "*thermal comfort can be well maintained at ambient temperatures that are 4–5 K higher as well as lower than the temperatures recommended by current standards*" (Vesely and Zeiler 2014: page 401). This expansion of the thermal dead band will also reduce energy consumption, and simulations show that energy savings could be as high as 60 %. Annual energy savings of 40 % could be achieved by utilizing personal heating and cooling equipment and extending the temperature dead band to 18-30 °C. The reviewed studies found that elevated air movement is an effective way to provide local cooling, and that when utilizing personal convective cooling, thermal comfort can be maintained up to 30 °C and a relative humidity of 70 %. It also pointed out benefits of using personalized ventilation instead of personal fans. As personalized ventilation can condition both temperature and humidity of the supplied air, lower air velocities could provide a sufficient cooling effect compared to personal fans, which high velocities might lead to draft issues. The indoor air quality will also be improved, as the personalized ventilation systems provide fresh air to the users.



### Comfort, perceived air quality, and work performance in a low-power task-ambient conditioning system (Zhang et al., 2010)

According to Zhang's thermal comfort model (PhD thesis from 2003), local comfort of feet, hands and face are essential for determining a persons' overall comfort in warm and cool conditions. A task-ambient conditioning (TAC) system was designed to provide comfort in a broad thermal environment, by heating only the feet and hands, and cooling only the hands and face. The devices used are illustrated in Figure 7, and the energy use is less than 59 W for heating and 41 W for cooling per workstation. The system was tested on 18 subjects for a total of 90 tests, in an environmental chamber at temperatures ranging between 18-30 °C. Subjective responses about thermal comfort, perceived air quality and air movement preference were obtained, as well as measurements of the subjects' skin and core temperatures. Good comfort levels were achieved with the TAC for the entire temperature range tested. The ventilation cooling devices was deemed to be more effective at improving comfort than the heating devices. Productivity was evaluated during the test for three different types of tasks, but there were not found significant improvements for the performance with TAC compared to neutral ambient conditions. Independent on whether it was fresh or re-circulated air, the subjects' perceived any air motion provided to significantly improve the air quality. The subjects found the thermal environment acceptable, although it was judged to be slightly uncomfortable (-0.5). Simulations suggests possible annual energy savings of up to 40 % for an ambient dead-band of 18-30 °C and 30 % for the narrower 20-28 °C.

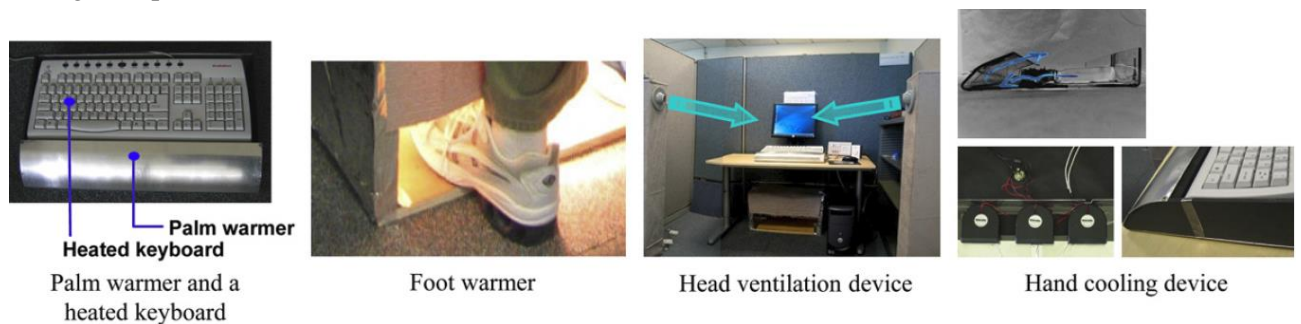


Figure 7 The four TAC devices used in this study. (Zhang et al. 2010: page 30)

### Design of an individually controlled system for an optimal thermal microenvironment (Watanabe et al., 2010)

The system evaluated in this article consist of a convection-heated chair, an under-desk radiant heating panel, a floor radiant heating panel, an under-desk air terminal device supplying cool air, and a desk-mounted personalized ventilation unit. Figure 8 provides a principle sketch of the system setup, and the performance was studied using a thermal manikin at the temperatures 20, 22 and 26 °C. At 20 °C, the effect of the heating chair, under-desk heating panel and floor heating panel corresponded to raising the room temperature by 5.2 °C, 2.8 °C and 2.1 °C, respectively. Combining all three solutions resulted in an effect of 5.9 °C. At 26 °C, the whole-body cooling effect was only -0.8 °C, while maximum local cooling effect of the face was -8.2 °C. The study also mapped the heating and cooling capacities of the systems. When analysing the results together with results from human subject experiments, it was found that both the heating and cooling capacity of the system was too low to satisfy most occupants in practice.

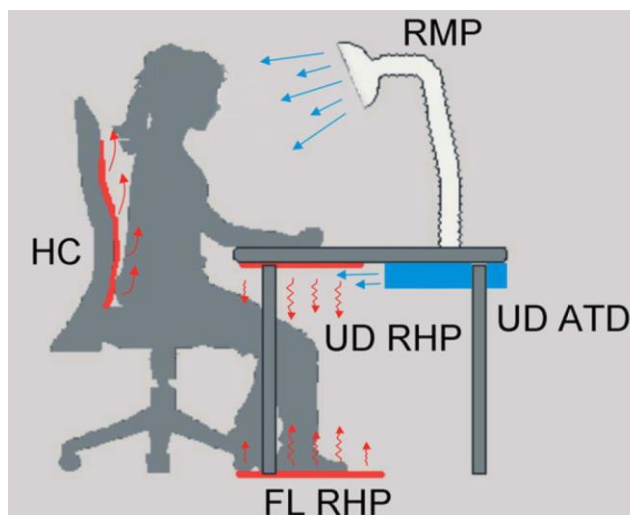


Figure 8 Sketch of the tested system consisting of a convection-heated chair (HC), an under-desk radiant heating panel (UD RHP), a floor radiant heating panel (FL RHP), an under-desk air terminal device (UD ATD) and a round movable panel air terminal device (RMP). (Watanabe, Melikov, and Knudsen 2010: page 550)

### 3.2 Personal heating solutions

Table 2 presents an overview of the articles that have been reviewed in this chapter, in addition to given comfort improvements and energy saving potential if applicable.

Table 2 Overview of articles on personal heating solutions, including specified improvement in comfort and energy saving potential.

Title	Comfort improvement	Energy saving potential
Heating chair assisted by leg-warmer: A potential way to achieve better thermal comfort and greater energy conservation in winter (He et al. 2018)	80 % comfortable down to 14 °C	61-71 %
Personalized heating – Comparison of heaters and control modes (Vesely et al. 2017)	Significantly improved	Not quantified
Computational and Field Test Analysis of Thermal Comfort Performance of User-controlled Thermal Chair in an Open Plan Office (Shahzad, Hughes, et al. 2017)	Improvement of local thermal comfort	Not quantified
A user-controlled thermal chair for an open plan workplace: CFD and field studies of thermal comfort performance (Shahzad, Calautit, et al. 2017)	Comfort: 20 %, Satisfaction: 35 %	Not quantified
Thermal comfort and energy consumption in cold environment with retrofitted Huotong (warm-barrel) (He et al. 2017)	Acceptable temp. for 90 % down to 9 °C	Not quantified
Human thermal sensation and comfort in a non-uniform environment with personalized heating (Deng et al. 2017)	Comfortable at 16 °C	Not quantified
Using footwarmers in offices for thermal comfort and energy savings (Zhang et al. 2015)	Comfortable at 18,9 °C	38-75 %
Personal heating: Is it comfortable and can it save energy? (Van Oeffelen, Jacobs, and Van Zundert 2011)	Comfortable at 20 °C	27 % for lowering room temp. to 20 °C

### Heating chair assisted by leg-warmer: A potential way to achieve better thermal comfort and greater energy conservation in winter (He et al., 2018)

This study aimed to improve comfort and energy savings by extending the comfortable temperature range in buildings, utilizing heating chairs and leg warmers, as illustrated in Figure 9. Experiments were conducted on 16 subjects (8 males and 8 females) at temperatures of 14, 16, 18 and 22 °C, and with three different heating modes: no heating devices, heating chairs and heating chairs with leg-warmers. The results indicated that heating chairs in combination with leg-warmers was by far the best solution and greatly reduced cold sensation, improving comfort and acceptability even at 14 °C. In fact, more than 80 % of the subjects voted on the acceptable side at 14 °C. The average power consumption of the heating chairs was 22.6, 15.0 and 12.4 W/person at 14, 16 and 18 °C respectively, while the corresponding values for the leg-warmers were 18.5, 19.9 and 13.0 W. When only using the heating chairs, the average power consumption was 34.1, 25.3 and 19.4 W/person at 14, 16 and 18 °C respectively. The combination of heating chairs and leg-warmers made it possible to reduce the acceptable temperature, contributing to energy savings of 71 % compared to conventional heating to 22 °C, while heating chairs alone contributed to 61 %.

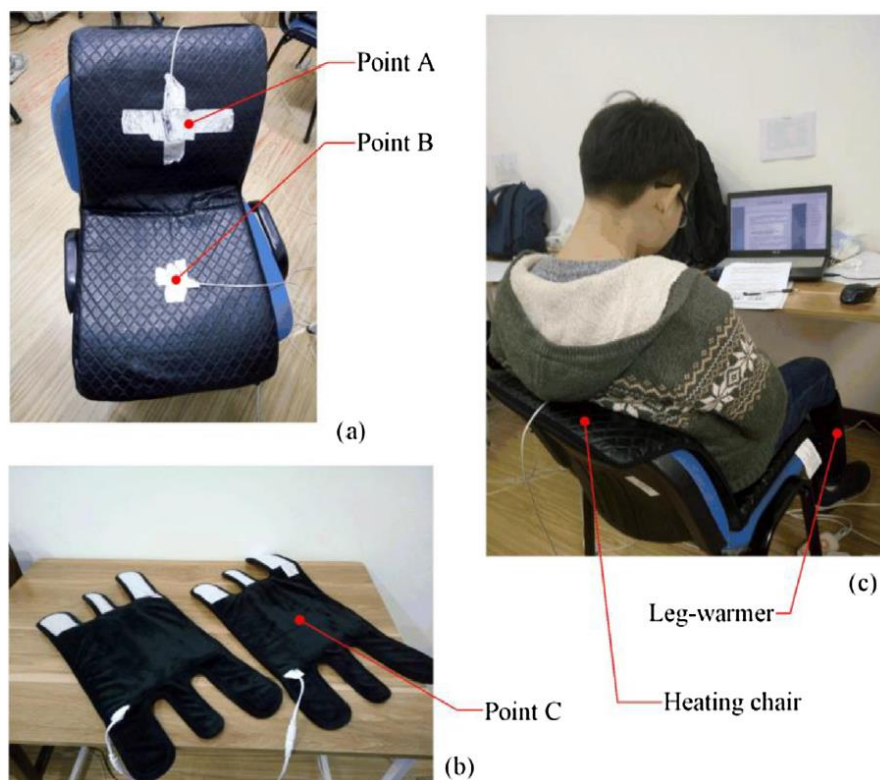


Figure 9 The personal heating devices: (a) heating chair, (b) leg-warmer and (c) a subject with devices. (He et al., 2018)

### Personalized heating – Comparison of heaters and control modes (Vesely et al., 2017)

Personal climatization systems could be a solution for reducing energy consumption in buildings while at the same time improving thermal comfort. Creating a microenvironment adapted for each user, makes it possible to satisfy individual demands for thermal comfort while at the same time saving energy, due to higher effectiveness compared to traditional HVAC systems. This study investigated heating effectiveness of different heaters and impact of different control modes. 13 subjects tested a heated chair, heated desk mat and a heated floor mat, as illustrated in Figure 10, in a climate chamber with an operative



temperature of 18 °C. The devices were tested both separately and in combination as user controlled. Fixed settings and automatic control based on hand skin temperature was also tested. The heated chair turned out to be the most effective heater, and thermal comfort was significantly improved by the heated chair and the heated desk mat as well as the complete system. No significant difference was found for the automatic control mode compared to user control with regards to thermal comfort.



Figure 10 Tested personalized heating system: heated chair (left), heated desk mat (middle) and heated floor mat (right). (Vesely et al. 2017: page 224) <https://creativecommons.org/licenses/by/4.0/>

### Computational and Field Test Analysis of Thermal Comfort Performance of User-controlled Thermal Chair in an Open Plan Office (Shahzad et al., 2017b)

Information has been collected from both the above-mentioned article and from *A user-controlled thermal chair for an open plan workplace: CFD and field studies of thermal comfort performance* (Shahzad et al., 2017a) as they are referring to the same study. The application of a user-controlled thermal chair, as illustrated in Figure 11, was investigated as to improve user comfort and satisfaction with thermal environment in an open plan office in Leeds, UK. The chair, which has both heated seat and back, was tested in a field study with 45 subjects under normal working conditions. Acceptable thermal conditions were achieved according to ASHRAE 55-2013, and surveys showed a 20 % increase in comfort and 35 % in satisfaction level through the use of the chair. Most of the occupants (86 %) set the temperature settings between 29-39 °C, and 82 % were "satisfied" or "very satisfied" with the performance of the chair. The energy consumption for the chair was around 30 W. To provide a more detailed analysis of the performance and thermal distribution around the chair, Computational Fluid Dynamics (CFD) simulations were performed, which showed that improving local thermal comfort can enhance overall thermal comfort. The authors recommended further research to optimise the thermal chair regarding thermal comfort and energy use, as well as the CFD modelling to provide better predictions.

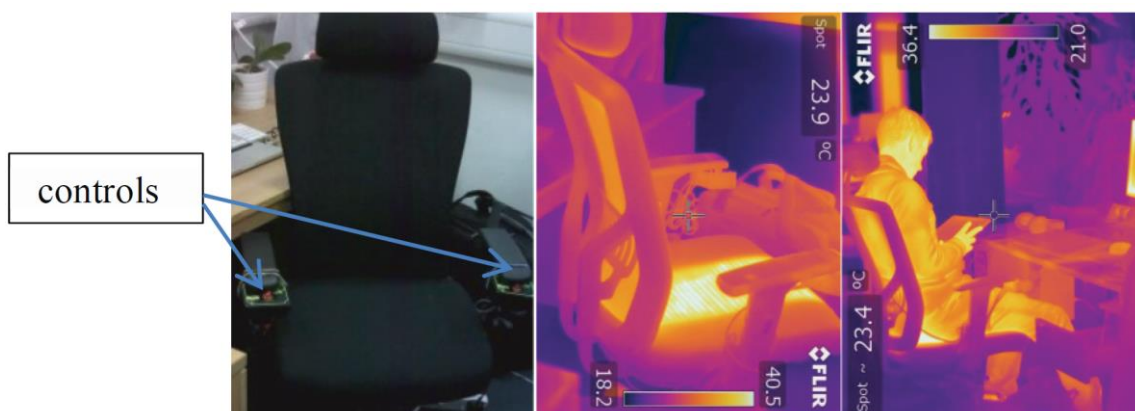


Figure 11 Thermal chair: design (left), thermal image of seat temp (FLIR T660) (middle) and in use (right). (Shahzad, Hughes, et al. 2017: page 2636)

### Thermal comfort and energy consumption in cold environment with retrofitted Huotong (warm-barrel) (He et al., 2017)

This study investigated subjective comfort and energy use in cold environment with a warm-barrel called Huotong, which is illustrated in Figure 12. Experiments were conducted at Hunan University, China, on 16 subjects using the Huotong in a room with the temperatures 9, 12, 15 and 18 °C. Subjective responses and energy measurements suggests that overall and local comfort were maintained in these cold environments. Even at 9 °C, the acceptance rate was as high as 90 %. This was better than what was found in the other articles with for example heated chairs, but the energy use for the device was also higher, rising from 50.3 to 165.6 W/person by a reduction of the air temperature from 18 to 9 °C. The authors also suggested a new index, Corrective Energy Power (CEP), based on Corrective Power (CP) introduced by Zhang, Arens, and Zhai (2015), for evaluating the performance of both comfort and energy consumption for personal comfort systems simultaneously.

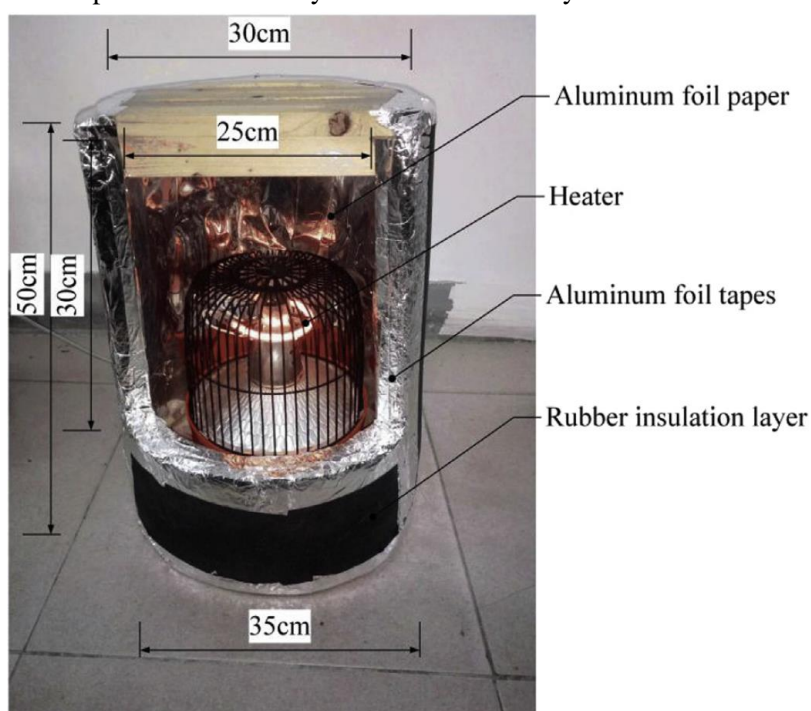


Figure 12 The retrofitted Huotong used in this study. (He et al. 2017: page 287)

### Human thermal sensation and comfort in a non-uniform environment with personalized heating (Deng et al., 2017)

This study investigated regional- and whole-body thermal sensation and comfort in cool environments with and without a heating chair, as illustrated in Figure 13. Experiments were conducted on 36 subjects (17 males and 19 females), including different age groups in a climate chamber with uniform temperatures of 18 and 16 °C. The subjects sat on a normal chair when the temperature was 18 °C and on a heated chair at 16 °C for 40 min for each of the setups. In addition to measuring skin temperature and surveying regional- and whole-body thermal sensation and comfort, these values were statistically analysed with regards to age and gender groups. The personal heating setup at 16 °C was found to provide neutral thermal conditions deemed just comfortable, which was better than for the test at 18 °C without personal heating. Thermal sensation and comfort was improved by personal heating regardless of age and gender, but adults and females felt cooler and less comfortable than children/elderly and males. As a conclusion, personal heating in non-uniform cooler environments significantly improved thermal sensation and comfort, and this is thought to be due to an elevated skin temperature. The authors

recommend further investigation of the link between thermal sensation and comfort with regards to variations of skin temperature.

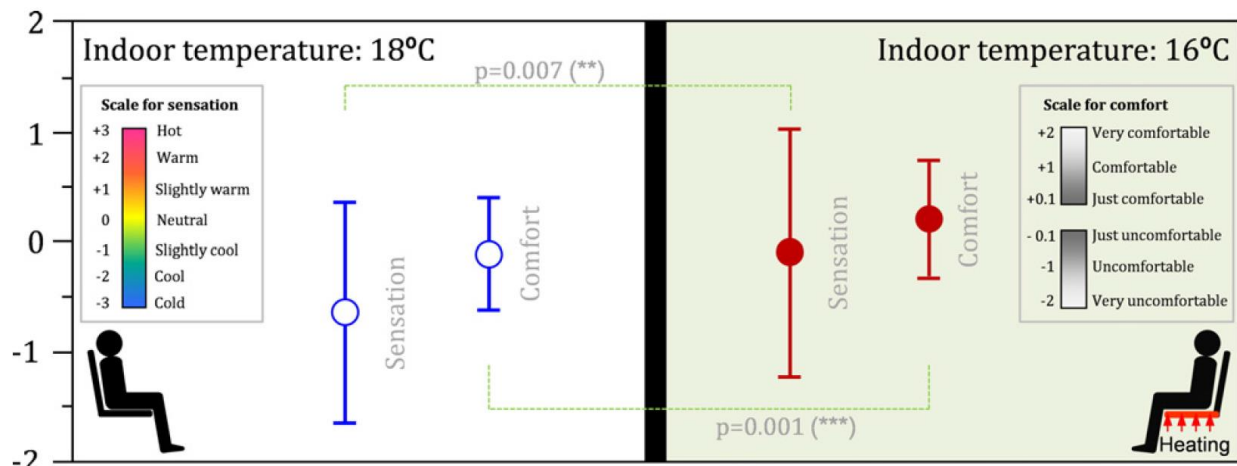


Figure 13 Graphical abstract of the article. (Deng et al. 2017: page 242)

### Using footwarmers in offices for thermal comfort and energy savings (Zhang et al., 2015a)

The feet are considered to be the body part that most strongly influences comfort perception when one is cool overall. This study evaluated the use of personal footwarmers, as illustrated in Figure 14, in cooler-than-normal indoor temperatures, for a period of six months in Berkeley, California. By making cooler indoor temperatures comfortable, the study showed that it is possible to reduce energy consumption for heating by 38-75 % depending on outdoor conditions and heating setpoint. Thermal comfort was considered to be equal for the normal heating conditions (21.1 °C) compared to the setup with footwarmers and lower heating setpoint (18.9 °C). The study did not investigate the lowest possible setpoint temperature for the footwarmers, but proved that the concept worked for long-term implementation in a real building. The footwarmers used only 3-21 W/unit as compared to 500-700 W/occupant for the central heating system, thus enabling large energy savings. A few subjects did however have ergonomic issues with the footwarmers, so the design could be improved.

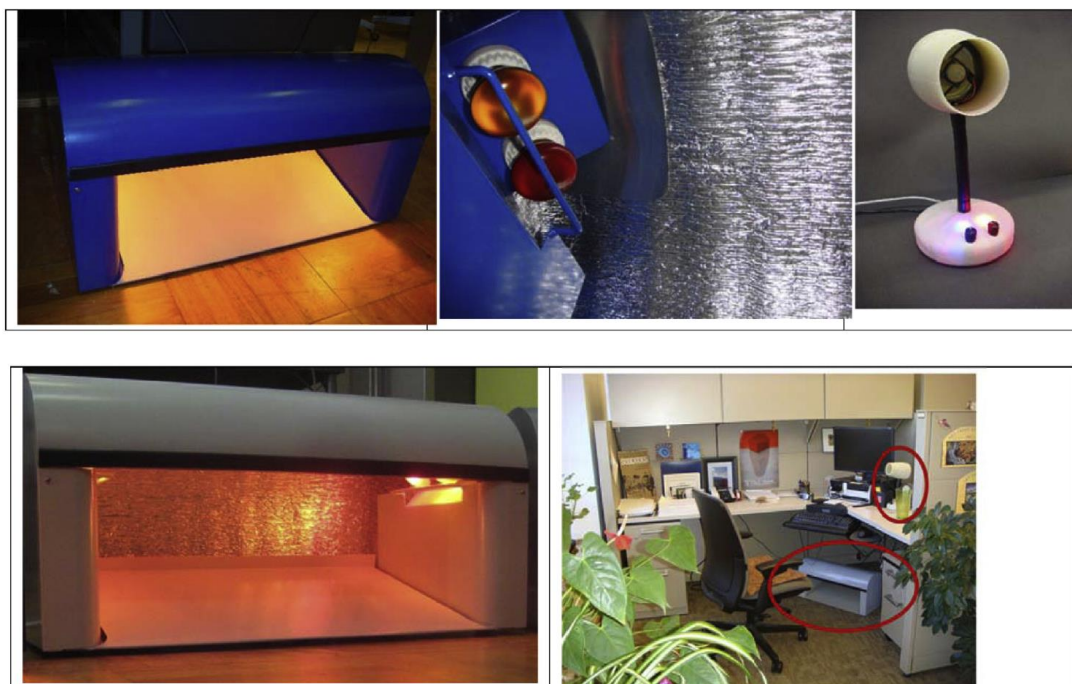


Figure 14 PCS fan and footwarmer combination. (Zhang et al. 2015: page 234)

### **Personal heating: Is it comfortable and can it save energy? (Van Oeffelen et al., 2011)**

This study evaluated a heating system consisting of four heating panels integrated in office furniture. Tests were carried out on ten subjects with control over the heating panels, in a climate chamber at the room temperatures 18, 20 and 22 °C. Objective measurements such as skin temperatures, energy use of the heating panels, air temperature and air speed were acquired, and thermal comfort was evaluated using a questionnaire. Measurements indicated that thermal comfort could be maintained at room temperatures lowered to 20 °C. Simulations show that this could lead to an energy saving of 27 % on heating energy, and it could be even higher for offices with a low and varying occupancy rate.

### **3.3 Personal cooling solutions**

Table 3 presents an overview of the articles that have been reviewed in this chapter, in addition to given comfort improvements and energy saving potential if applicable.

Table 3 Overview of articles on personal cooling solutions, including specified improvement in comfort and energy saving potential.

<b>Title</b>	<b>Comfort improvement</b>	<b>Energy saving potential</b>
Preliminary study of thermal comfort in buildings with PV-powered thermoelectric surfaces for radiative cooling (Kimmling and Hoffmann 2017)	Early-phase prototype, conceptual proof of the function of the device.	Not quantified
Local cooling in a warm environment (Pallubinsky et al. 2016)	Significantly improved thermal sensation and comfort	Not quantified
Adaptive effect to thermal comfort of cool chair in ZEB office (Suzuki, Washinosu, and Nobe 2012)	Users felt more comfortable than with standard office chair	Not quantified
Thermal evaluation of a chair with fans as an individually controlled system (Watanabe, Shimomura, and Miyazaki 2009)	Acceptable up to 30 °C	Not quantified

#### **Preliminary study of thermal comfort in buildings with PV-powered thermoelectric surfaces for radiative cooling (Kimmling and Hoffmann, 2017)**

Temperature levels are rising due to climate change, resulting in a serious challenge to maintain healthy and comfortable indoor environmental conditions in many regions of the world. Space cooling has already become one of the main causes of electric energy consumption in the built environment, making it interesting to investigate more energy efficient cooling solutions. This study presents a novel thermoelectric cooling partition called Thecla, that is now being developed and tested. It is a local device based on Peltier elements which provides a cool surface. Direct and individual cooling is achieved through longwave radiation transmitted from the user's skin and clothing. The setup is illustrated and described in Figure 15. The article contains results from the first field study, but the results of the study can only be considered as a conceptual proof. There are suggested technical improvements for the device, in addition to further work evaluating energy efficiency, system costs and profitability as well



as correlation between PMV and thermal sensations. More information about the project can be found at [www.livinglab-smartofficespace.com](http://www.livinglab-smartofficespace.com).

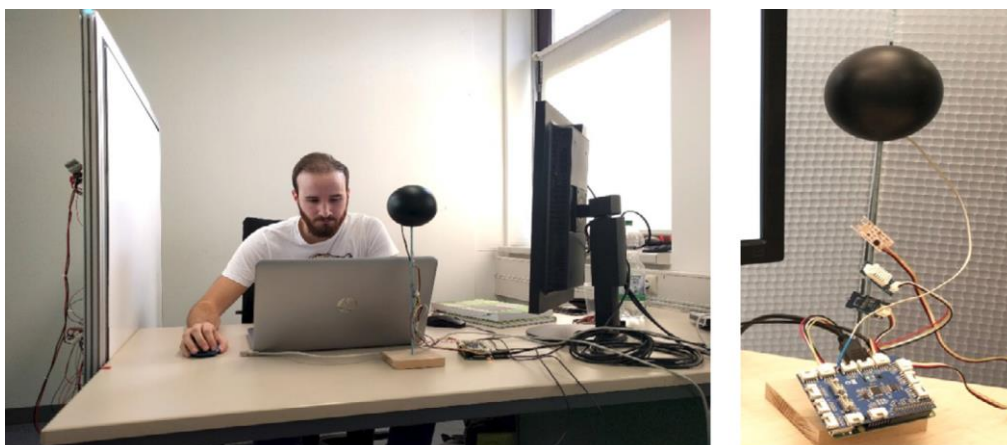


Figure 15 Left: Overall test setup and environment including Thecla, workplace and environment sensors. Right: Detail of environment sensor setup including Raspberry Pi and GrovePi+, air temperature and humidity sensors, air velocity sensor and MRT sensor. (Kimmling and Hoffmann, 2017)

### **Hybrid cooling clothing to improve thermal comfort of office workers in a hot indoor environment (Song et al., 2016)**

A hybrid cooling clothing was developed to improve thermal comfort of office workers in hot indoor environments. (Song et al., 2016) examined its effect through trials with eleven male subjects performed through two 90-min sessions in a climate chamber with and without the hybrid personal cooling garment (PCG). At an air temperature of  $34.0 \pm 0.5$  °C, it was found that for most of the time the hybrid PCG significantly improved the whole-body thermal sensations, skin wetness sensations and comfort sensations compared to the normal clothes without cooling. Mean skin temperatures and the total sweat production were also significantly reduced by wearing the cooling clothing.

### **Local cooling in a warm environment (Pallubinsky et al., 2016)**

The effect of local cooling on thermal sensation, thermal comfort and skin temperatures were investigated in this study, as well as differences between genders. 16 healthy young men and women underwent measurements in a climate chamber in Priva, Netherlands, with an ambient temperature of  $32.3 \pm 0.3$  °C. The setup is illustrated in Figure 16. They were exposed to local cooling of separate body parts: face, back, underarm and foot sole for 45 min and 30 min of combined face-underarm cooling. It was found that "Face cooling" and the combination of face and underarm cooling were the most effective measures, and significantly improved thermal sensation and comfort for both genders. Measurements of skin temperatures (26 sites) also indicated that women had significantly higher skin temperatures than men.



Figure 16 Experimental setup. The white arrows indicate the outlet of the fan. The outlet position was adjustable in height and angle to individually direct the airflow onto the participant's face. (Pallubinsky et al. 2016: page 17)

### Adaptive effect to thermal comfort of cool chair in ZEB office (Suzuki et al., 2012)

As each worker has different preferences for thermal environmental conditions and comfort, it is not possible to satisfy all the individual preferences by the conditions in the office building. The "Cool Chair" has been developed since 2003 to provide a solution to this problem, and the operational status with regards to thermal environmental conditions and use has been evaluated in this article. As illustrated in Figure 17, the airflow is coming from both the armrests and seat of the chair. It is also possible to move the armrests and adjust the flow and direction of the air. 33 chairs were introduced to the building, and the workers tended to use the Cool Chair the most when they returned to the office and with increasing ambient temperatures. Not all workers were given a Cool Chair, and the workers with the Cool Chairs were more comfortable than those with standard chairs. Frequent use of the chairs also led to higher satisfaction, and the office workers were positive about the option of personal climatization.

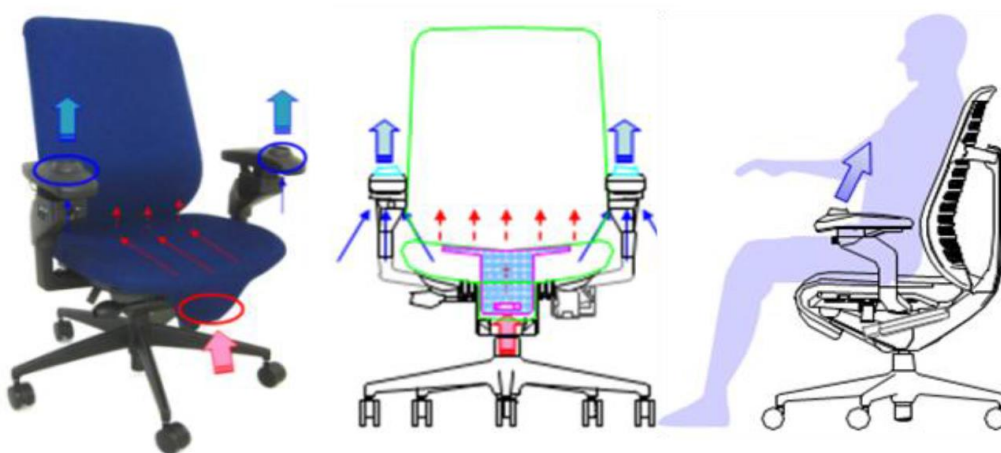


Figure 17 Principle sketch of the office chair with cooling effect. (Suzuki et al., 2012)

### Thermal evaluation of a chair with fans as an individually controlled system (Watanabe et al., 2009)

Already in 2009, the authors of this study stated that individually controlled systems are needed to create a comfortable thermal environment for each worker. There were developed two chairs with two fans each, positioned under the seat and behind the backrest, as illustrated in Figure 18, to provide isothermal

forced airflow to the user of the chair. The size of the fans was different for the two chairs. Experiments were conducted in a climate chamber among seven healthy male college students, which were in control over the two built-in fans. The subjects tested the chairs with fans in addition to a normal chair at room air temperatures of 26, 28, 30 and 32 °C. Whole-body thermal sensations were found to be close to thermally neutral for both chairs at 28 °C, while at 30 °C, the chairs with fans made it possible to create acceptable thermal environments with regards to whole-body thermal sensation and comfort. The isothermal airflows greatly improved local discomfort rates at the back and lower back at 30 °C. At 32 °C however, the chairs were not able to provide acceptable thermal environments, and additional local systems to cool the heads, arms and hands are recommended. The article did however not mention anything about sound levels/noise from the fans, which could be an issue with a solution like this.



Figure 18 Left: Test chair with fans installed under the seat and behind the backrest. Right: Fan and open fabric of the chair. (Watanabe, Shimomura, and Miyazaki 2009: page 1394)

## 4 Discussion

There are many studies confirming that personal heating devices potentially increases comfort at a lower ambient temperature. However, lowering the heating setpoint to save energy would probably introduce some challenges and it would not be possible in all types of buildings. Many of the individual heating and cooling devices presented depend on that the users are situated at their workstations, as for example the heating chairs. If the users are moving around in the office, and are not using a portable device, like heated clothing or the heated wrist-band, they are more likely to feel cold. Although they would have an increased activity level, and thus could prefer a lower heating setpoint. Another issue to consider is the investment costs of the devices, which has not been evaluated in this report. If the heating setpoint is lowered for all the rooms in the building, personal heating devices should be applied in all rooms, for example heating chairs at every workstation, meeting rooms, canteen, etc. In that case the heating devices should not be too expensive per unit.

Another issue could be users' acceptance of lowering the indoor air temperature and using personal heating devices to compensate for this. As an example, when people get into a cold car, most of them turn on the heating system at around 20 °C and the seat warmer simultaneously. When the air temperature in the car is sufficiently heated and the driver feels comfortable, the seat warmer is turned off. The alternative corresponding to the proposed solution of reducing indoor air temperature and introducing personal comfort systems would be to keep the seat warmer on, and rather reduce the setpoint temperature in the air conditioning system. It is not clear whether this choice is made for comfort reasons, or if it is just because it is more convenient to regulate the seat warmer button on/off than to regulate the temperature setpoint on the air conditioning system. Many studies have however confirmed that people with greater personal control tend to accept wider ranges of indoor thermal environment.

Clothing insulates and reduces the heat loss from the human body. The most energy efficient method for thermal climatization is thus to dress according to the thermal environment and activity level. In addition to adjusting the clothing level for insulation purposes, there is also the possibility to utilize advanced clothing that provides heating and cooling, which is commercially available. Examples are heated sweaters, socks, gloves, insoles for shoes, etc. Heated/cooled clothes can represent technical solutions for personal climatization, but there was only found one scientific article evaluating its performance.

Although these solutions are most relevant for office and education buildings, they could be implemented in other building types as well. For residential buildings, people are freer to adapt by changing the clothing level, but many occupants would probably still be interested in such solutions.

The personal comfort systems are based on electricity. If the personal comfort systems were to cover a large share of the total heating demand, it is not guaranteed to save energy compared to more effective central heating solutions as for example heat pumps. As the devices demonstrated from the articles in this report are low-power solutions compared to the central HVAC systems, it is however likely that they will contribute to energy savings, provided that the heating setpoint is kept at a reasonable level. Which heating setpoints are considered reasonable will depend on building type, heat loss and heating system for each specific building, as well as how the building is used. Either way, there will still be a benefit of making the users more satisfied. In office and education buildings, this may also lead to improved productivity.



Some of the articles also suggested new indexes to evaluate thermal comfort and possibilities for extending the thermal dead-band, as for example Corrective Power (CP). This concept was further developed by another study to Corrective Energy Power (CEP) which includes energy efficiency. These indexes could prove useful for comparing different personal climatization systems.

## 5 Conclusion

Almost all of the articles reviewed found that the personal climatization systems significantly improved thermal sensation and thermal comfort for the users. In the studies that evaluated different personal heating equipment, the heated chairs were found to be most effective. For both heating and cooling it was found that combining the personal comfort devices resulted in higher comfort improvement and higher energy saving potential.

The devices also made it possible to achieve thermal comfort outside the traditional heating and cooling setpoints, thus making it possible to extend the thermal dead-band of buildings. Applying the energy only where it is actually needed with low-power solutions, could lead to substantial energy savings compared to traditional HVAC systems operated around 21-22 °C. How the heating and cooling setpoints could be set depends on the number of devices applied by each user. In addition, the combination of different devices, for example heating chair and footwarmer, makes it possible to further extend the dead-band. Another review of personalized conditioning systems by Veselý and Zeiler (2014) found that thermal comfort can be well maintained at ambient temperatures that are 4-5 K higher as well as lower than the temperatures recommended by current standards. Thus, personal climatization technologies has a potential to significantly reduce energy use.

To conclude, personal climatization systems can make more, if not all, users satisfied with their thermal environment, while at the same time reducing energy consumption. As for now however, there seems to be mainly smaller devices available, for instance heated chair pads and clothing. Some of the studies evaluated in this report also suggested further development and optimization of their devices.

## 6 Further research

Users' acceptance of utilizing personal climatization devices in combination with lowering the heating setpoint or increasing the cooling setpoint has not been considered in the presented articles. This and other aspects could be tested in the planned ZEB Flexible Lab in Trondheim, as it will have two identical rooms for such research purposes.

Heated and cooled clothes also represent a type of personal climatization systems. Although many products are commercially available, there were only found one study evaluating its performance. This is a topic that would be interesting for further investigations, although there might be limitations for offices with dress codes.

The study by Lopez et al. (2016) on the wrist-band heating device found that 10 seconds cyclic heating of the wrist makes it possible to maintain heat sensation for longer periods than by continuous heating. This is something that should be considered for other devices as well, as it is in line with the alliesthesia principle of a positive stimulation and in addition will lead to energy savings. It should be further investigated if 10 second cycles are the optimum heating intervals and if it applies for other body segments as well.

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