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Personalized heating – Comparison of heaters and control modes

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ABSTRACT

Personalized conditioning systems represent a promising solution to two major challenges in building industry – high energy consumption of the buildings and still only mediocre thermal comfort. These systems create a microenvironment adapted for each user. Therefore, individual demands for thermal comfort can be met and energy can be saved due to higher effectiveness compared to the traditional HVAC systems. This study investigates two aspects of personalized heating – effectiveness of different heaters and impact of different control modes. Personalized heating system consisting of a heated chair, a heated desk mat, and a heated floor mat was tested with 13 test subjects in a climate chamber under operative temperature of 18 °C. The heaters were tested separately and in combination as user controlled. Furthermore, the complete system was tested with fixed setting and automatic control using hand skin temperature as a control signal. The heated chair and the heated desk mat as well as the complete system significantly improved thermal comfort, while the heated chair was found to the most effective heater. The automatic control mode could provide the same level of thermal comfort as user control in this study.

1. Introduction

Commercial buildings represent approximately 15% of the total energy consumption in EU and US [1,2], while most of this energy is spent on creating a comfortable indoor climate. However, high levels of occupants' satisfaction are often not achieved despite the substantial energy use. It has been shown that narrowing the range of conditions of indoor thermal environment does not bring higher than 80% satisfaction with thermal comfort [3].

Personalized conditioning systems (PCS) can improve both, energy performance and user comfort. While a traditional HVAC system typically creates a uniform environment for a large group of persons, PCS focuses on each single person and his or her critical body parts. This focus makes it possible to satisfy individual needs for thermal comfort and even provide more pleasant thermal environment by the non-uniformities [4]. Energy is then used more effectively by extending the indoor temperature range on a building level [5–7].

Personalized ventilation e.g. [8–11] aims to supply fresh and sometimes conditioned air directly into a breathing zone of the user. This strategy leads to improved thermal comfort in warmer conditions because of additional convective cooling and to increased indoor air quality because of higher ventilation effectiveness. Most of the studies on PCS focus rather on personalized ventilation and cooling rather than on heating [12]. However, some studies clearly show that personalized heating can improve thermal comfort [5,13–15] as well as building energy performance [5,16,17]. As pointed out by Zhang et al. [5] lowering a heating set point together with personalized heating provided allows saving energy in semi-arid climate of Fresno, California, while the saving potential increases towards colder climate zones.

It is difficult to compare the performance of different PCS in terms of both, thermal comfort as well as the energy consumption. Zhang et al. [4] reviewed available research on PCS and defined corrective power for each system as an offset of temperature or thermal sensation. Although their method disregards the energy consumption of PCS, it is a viable attempt to provide a way of comparing different systems' performance. Schiavon and Melikov [18] introduced a cooling-fan efficiency index that relates a cooling effect measured by thermal manikin to the power consumption of a fan. However, this index only shows a cooling performance relative to the power and does not take into account the effects of alliesthesia [19]. Verhaart et al. [17] proposed how to evaluate energy performance of a building equipped with PCS assuming that energy consumption of PCS can be predicted by deviation in predicted

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mean vote (PMV). Nevertheless, these methods heavily depend on the quality of input data, i.e. the characteristics of specific PCS. These characteristics should be carefully measured and completely reported in order to support a design practice.

Furthermore, a complicating factor of comparison of personalized heating systems' performance is their dependency of the applied control strategy. As Veselý and Zeiler [12] pointed out PCS are controlled predominantly by user interaction, i. e. the users control the amount of heating or cooling power themselves. Although available and perceived control over thermal environment is connected with improved thermal comfort [20], an effective automated control of personalized heating can contribute to more efficient energy use, prevent overshoots in thermal sensation, or allow users to better focus on other activities. Distal skin temperatures, such as hand or fingertip temperature, have been identified as an important factor that correlates with a risk of cold discomfort [21,22]. As a setting of personalized heating can be interpreted as a way of expressing cold discomfort, also a correlation between this setting and distal skin temperature can be expected. This relation can then be applied for an automated control of personalized heating.

This study focuses on comparison of three common methods of personalized heating and a way of controlling of the heaters. The three compared methods of personalized heating – heated chair, heated desk mat, and heated floor mat – have been previously identified as the most promising ways of mitigating cold discomfort in mild cool environment [4]. Although some studies [5,13,23–25] have demonstrated the benefits of these methods in terms of increased thermal comfort and energy savings, a comprehensive comparison of them is still lacking. This study provides data on improved comfort in relation to the energy consumption. These results are fitting into a framework that should support application of PCS in the design practice. Also a user interaction is compared to automated control with a hand skin temperature as a feedback signal in order to determine, whether an automated control can substitute the user interaction.

2. Methods

2.1. Personalized heating system

Personalized heating system as shown in Fig. 1 was tested. This system consists of a heated chair, a heated desk mat, and a heated floor mat. A heated chair has a relatively large contact area with the body and, therefore, can transfer more heat via conduction than other heating methods. It was also proved to be an effective personalized heating method by several studies [13,23–25]. As the hands and feet are usually the most thermally uncomfortable body parts under cool or cold conditions [26], it can be expected that heating applied on them will result in a pleasant alliesthesia effect [19].

Maximum power of the heaters varies from 36 to 100 W and is specified in Table 1 together with the dimensions of the heaters and their surface temperatures measured under operative temperature of 18 °C. The specified dimensions of the heated chair are the dimensions of two heated mats integrated under the fabric surface of the chair, on which the surface temperature was measured.

Personalized heating was either controlled by the user or automatically depending on the test case (see Table 3). An interface used in test cases with user control is shown in Fig. 2. Each heater could be controlled separately by a position of a slider linearly corresponding to the fraction of maximum power. The setting of personalized heating was logged with an interval of 2 s.

2.2. Subjects

Thirteen healthy college-aged test subjects (seven males and six females) volunteered for the experiments. Their height, weight, body mass index, and age are listed in Table 2. The test subjects were informed about the purpose and procedure of the experiment, but were kept blind to the exact conditions in the climate chamber. The test subjects expressed their consent with the participation in the experiments.

All test subjects participated in all 7 test cases (as specified in Section 2.3 *Procedure*). The sessions were assigned randomly within workdays between 9 a.m. and 5 p.m. with regards to test subjects' availability. The order of test cases was randomized among the test subjects in order to avoid any learning effect bias. The test subjects were instructed wear typical winter indoor clothing with insulation of 0.7 clo. In practice the average clothing insulation in all test cases ranged within 0.76 ± 0.02 clo.

2.3. Procedure

The experiments comprised seven test cases as shown in Table 3. All test subjects experienced all test cases. Three personalized heaters – a heated chair, a heated desk mat, and a heated floor mat – as well as their combination were tested. In these tests users controlled the heaters using the sliders shown in Fig. 2. Furthermore, the combination of heaters was tested using fixed setting and automatic control as described in Section 2.8 *Settings of personalized heating system*.

Each experimental session started with 30 min accustomization outside of the climate chamber, in a space conditioned to 21 °C, which correspond to approx. neutral thermal sensation. During the accustomization skin temperature loggers were attached by a medical tape. The accustomization was followed by a 90 min exposure in the climate chamber. The test subjects performed typical office work on a computer. They were allowed to drink still water during the exposure. In the tests, in which the user control

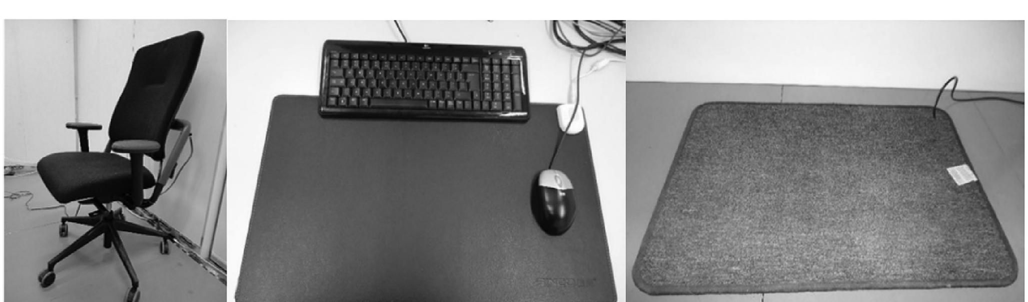

Fig. 1. Tested personalized heating system: a heated chair (left), a heated desk mat (middle), and a heated floor mat (right).

Table 1
Specification of the tested heaters.

	Max power [W]	Dimensions [cm]	Maximum surface temperature [°C]
Heated chair	36	40 × 28 (seat) and 30 × 28 (backrest)	28
Heated desk mat	80	60 × 36	35
Heated floor mat	100	70 × 50	30

Fig. 2. User control interface over personalized heating system.

Table 2
Anthropological data of the 13 test subjects.

	Height [m]	Weight [kg]	Body mass index	Age [years]
Mean	1.79	81.1	25.1	24.9
Standard deviation	0.12	26.8	5.8	3.2

was provided, the subjects were instructed to adjust personalized heating at any time in order to become thermally comfortable. Every 15 min the subjects had to fill in a questionnaire regarding their thermal comfort, thermal sensation, and well-being.

2.4. Measurements — subjective evaluation

The test subjects evaluated their thermal comfort via a computer-based app, which includes questions regarding clothing, thermal sensation, thermal comfort, and wellbeing. Thermal sensation and comfort are asked for the whole body, the neck, the head, the arms, the hands, the legs, and the feet. An ASHRAE 7-point scale is used for evaluation of thermal sensation and a comfort scale (from clearly comfortable to clearly uncomfortable with separation of just comfortable/just uncomfortable in the middle) for thermal comfort. Wellbeing questions include air quality, sick building syndrome symptoms, and self-estimated work performance. Questions regarding thermal sensation and comfort and wellbeing are shown in Fig. 3.

The acquired data regarding subjective response were first tested for normality using Shapiro-Wilk test at significance level of 0.05. Normally distributed data were tested by ANOVA Multivariate test of significance and by a *t*-test. Data not normally distributed were subjected to non-parametric Friedman ANOVA and to Wilcoxon Matched Pair test. The significance level of 0.05 is considered in the text, when p-value is not specifically reported.

2.5. Measurements — skin temperatures

Skin temperature was measured to investigate the effect of personalized heating on human physiology. It was measured using iButton wireless temperature loggers [27] on 14 locations as shown in Fig. 4 according to ISO 9886 [28]. Furthermore, hand skin temperature was measured by a contact digital thermometer DS18B20 [29] additionally to iButton.

2.6. Measurements — environmental data

Air temperature, black globe temperature, relative humidity, and air speed were continuously monitored throughout all experimental sessions. Air temperature, relative humidity, and air speed were measured at heights of 0.1, 0.7, and 1.1 m and black globe temperature at height of 0.7 m in the center of the climate chamber. All environmental data were logged with an interval of 1 min and measured in compliance with ISO 7726 [30].

2.7. Climate chamber and environmental conditions

Experiments were conducted in the climate chamber of Department of Built Environment, Eindhoven University of Technology, the Netherlands. The climate chamber is a well thermally insulated room of dimensions 3.6 × 5.7 × 2.7 m^3, which allows for a precise control of the indoor environment, namely air movement, air temperature, and temperatures of all surrounding surfaces. The air is conditioned by an air-handling unit and the air flow rate during all the test was 150 m^3/h. The air was supplied was via a slit

Table 3
Test cases.

Test case	Description
Ref	Reference case, no personalized heating applied
Chair	User controlled heated chair
Desk	User controlled heated desk mat
Floor	User controlled heated floor mat
Combi	User controlled combination of a heated chair, a heated desk mat, and a heated floor mat
Fixed	A combination of a heated chair, a heated desk mat, and a heated floor mat at fixed setting
Auto	A combination of a heated chair, a heated desk mat, and a heated floor mat with automated control

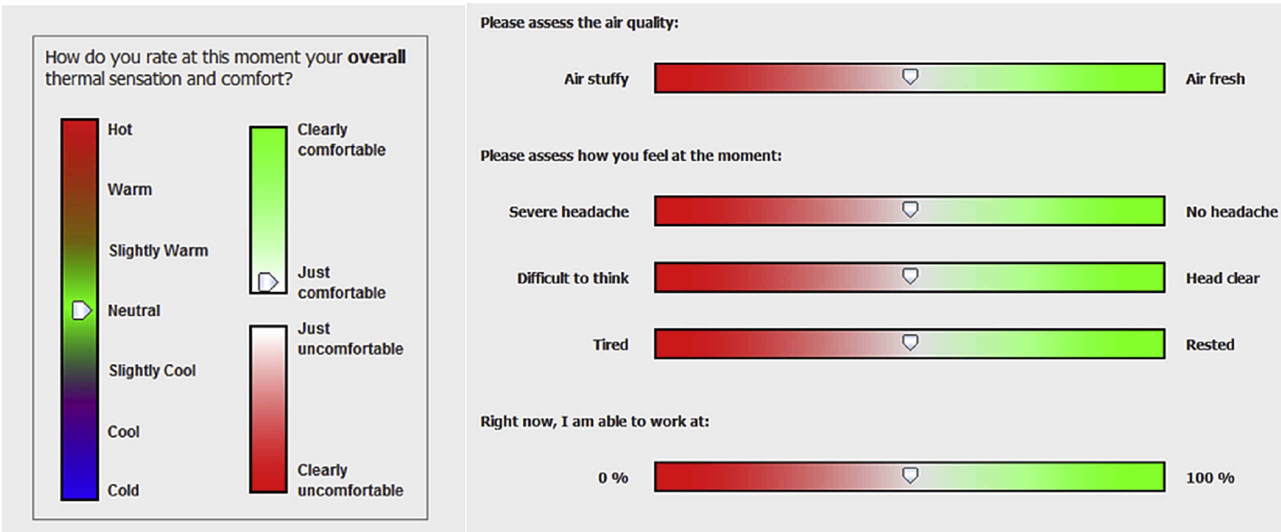

Fig. 3. The questionnaire app – Thermal sensation and comfort (left) and wellbeing (right).

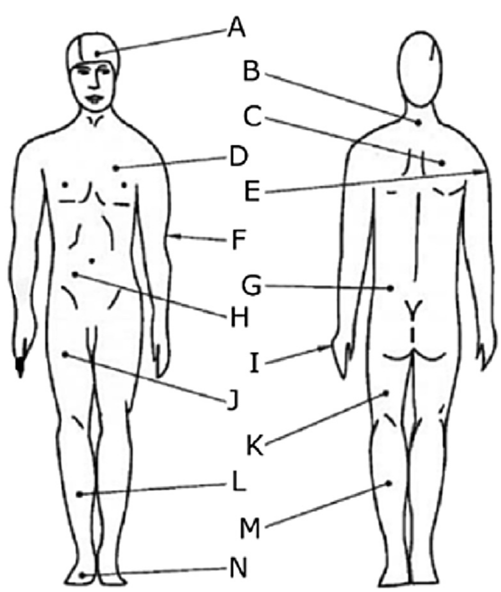

Fig. 4. Skin temperature measurement locations by ISO 9886 [28].

(height of 0.1 m) along the width of the room, integrated into a plenum box (100 × 3600 × 200 mm^3) located at the top of the shorter wall. The exhaust (height of 0.2 m) was positioned in a similar box at the top of the opposite wall. The climate chamber is located in a mechanically ventilated lab, where the cooling is provided by air conditioning and heating by a central heating system.

All described tests were conducted within a heating season. Therefore, the temperature in the lab was maintained by a central heating system at a heating set point of 21 °C.

Thermal environmental data during all tests are depicted in Table 4. The air temperature was maintained at 17.9 ± 0.3 °C, the mean radiant temperature at 17.5 ± 0.4 °C, the operative temperature at 17.7 ± 0.4 °C, and relative humidity at 48 ± 11% during all tests. Air speed was monitored in the occupied zone at heights of 0.1, 0.7, and 1.1 m. A mixing ventilation principle, which was applied, resulted in air speed in the occupied zone under 0.2 m/s. The test subjects were instructed to wear typical winter indoor clothing with insulation of 0.7 clo and they performed an office work in the climate chamber corresponding to a metabolic rate of 1.2 met. These conditions result to a PMV ranging from −1.6 to −1.9 and corresponding PPD of 55–70%.

Two office desks as shown in Fig. 5 were placed in the climate chamber. A computer screen, a keyboard, and a mouse were provided at both desks. The test subjects worked on their laptops using the provided screen, keyboard, and mouse.

2.8. Settings of personalized heating system

The settings for the control modes Fixed and Auto is derived from a pretest with 9 test subjects presented by Veselý et al. [31]. This pretest was performed according to the same procedure as the test case Combi. In the control mode Fixed the heaters were set to the average user setting from the end of the pretest. These settings are: a heated chair at 50% of its maximum power, a heated desk mat at 65% of its maximum power, and a heated floor mat at 70% of its

Table 4
Thermal environment during all tests (means ± standard deviations).

Test case	Relative humidity [%]	Air temperature [°C]	Mean radiant temperature [°C]	Operative temperature [°C]
Reference	51 ± 11	17.9 ± 0.4	17.5 ± 0.4	17.7 ± 0.4
Chair	47 ± 7	18.0 ± 0.4	17.6 ± 0.5	17.8 ± 0.5
Desk	52 ± 9	18.1 ± 0.4	17.6 ± 0.4	17.8 ± 0.4
Floor	52 ± 10	18.0 ± 0.3	17.6 ± 0.4	17.8 ± 0.3
Combi	51 ± 9	18.0 ± 0.4	17.6 ± 0.4	17.8 ± 0.4
Fixed	46 ± 11	17.8 ± 0.2	17.4 ± 0.3	17.6 ± 0.2
Auto	36 ± 7	17.8 ± 0.2	17.4 ± 0.3	17.6 ± 0.3
All test cases	48 ± 11	17.9 ± 0.3	17.5 ± 0.4	17.7 ± 0.4

Fig. 5. One of the two user desks in the climate chamber.

maximum power.

In test case Auto personalized heating was controlled proportionally to hand skin temperature as measured on its dorsal side. The setting was adjusted every 2 s. The control equations are based on linear correlation of the user setting of personalized heating and the hand skin temperature from the pretest (a heated desk mat shown in Fig. 6). The R^2 values of these correlations are as follows, 0.62 for the heated chair, 0.90 for the heated mat, and 0.86 for the heated floor mat. These correlations result in curves shown in Fig. 7.

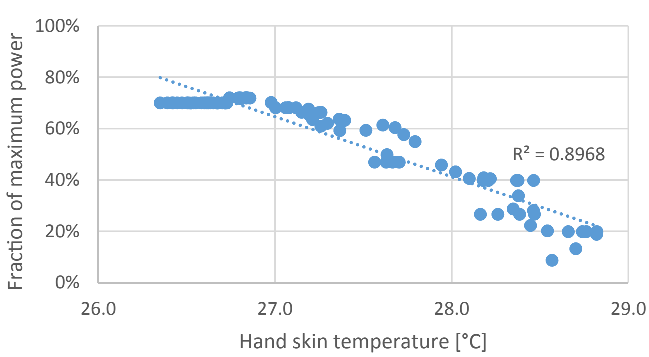

Fig. 6. User control over heated desk mat in the pretest, average of 9 test subjects [31].

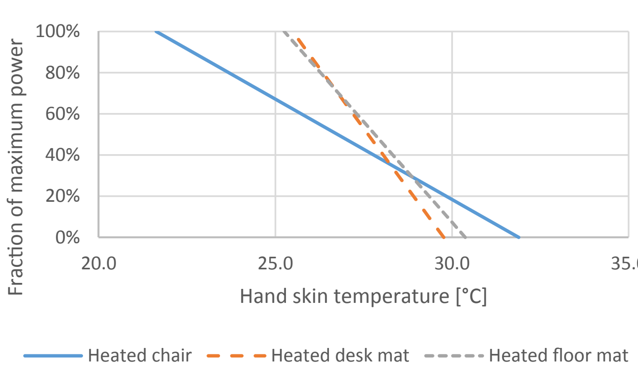

Fig. 7. Proportional control of the heaters used in test case Auto [31].

3. Results

3.1. Overall thermal sensation and comfort

Average overall thermal sensation over whole session is depicted in Fig. 8. As the test persons were accustomized outside of the climate chamber, thermal sensation at the beginning of each session was experienced as neutral without any significant differences among the test cases. At the end of the Ref session thermal sensation dropped between slightly cool and cool, which corresponds to the design conditions of PMV = −1.5.

Overall thermal sensation at the end of the session (Fig. 9) significantly increases with heated chair ($p = 0.003$), heated desk mat ($p = 0.020$), and combination of the heaters ($p = 0.000$) compared to Ref session. Moreover, the combination of three heaters provides significantly higher thermal sensation than any of the heaters ($p < 0.011$). Heated floor mat delivers about the same thermal sensation as experienced in the Ref. Similar pattern of significant differences as for overall thermal sensation applies also for overall thermal comfort (Fig. 9).

No significant differences in overall thermal sensation or comfort were observed among the three control modes. This suggest that the automatic and fixed control provided the same level of thermal comfort under given conditions.

3.2. Local thermal sensation and comfort

Local thermal sensations of the head, the hands, and the feet at the end of the session are shown in Fig. 10. Local thermal sensation of the hands significantly increases ($p < 0.001$) while using desk heating mat and the combination of all three heaters compared to the Ref. Similar but less pronounced trend as for the hands was also observed for the arms. The use of floor heating mat and heaters' combination significantly increases ($p < 0.011$) local thermal sensation of the feet. However, it has to be noted that overall thermal sensation is not increased by heated floor mat. Generally, no clear impact of personalized heating on thermal sensation of the neck and the legs was observed.

Although none of the personalized heaters was aimed at the head, its thermal sensation significantly increases ($p = 0.005$) with use of the heaters' combination. This might be connected to a higher overall satisfaction with the thermal environment.

The three control modes of personalized do not significantly differ in their impact on local thermal sensation of any investigated body part.

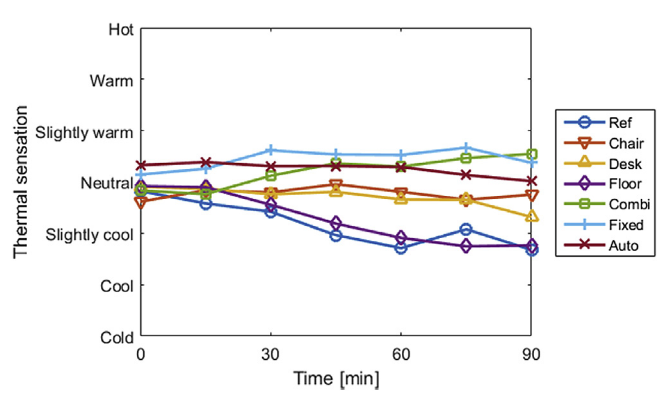

Fig. 8. Average overall thermal sensation over whole session.

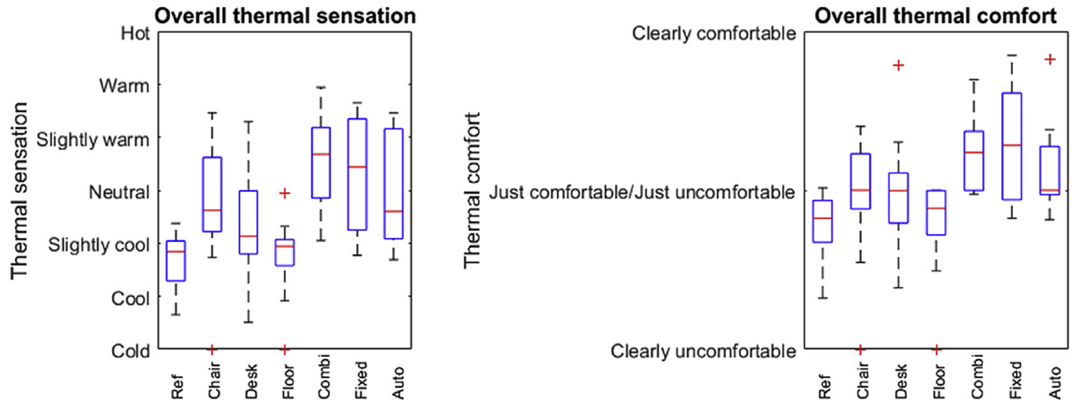

Fig. 9. Overall thermal sensation and comfort at the end of the session.

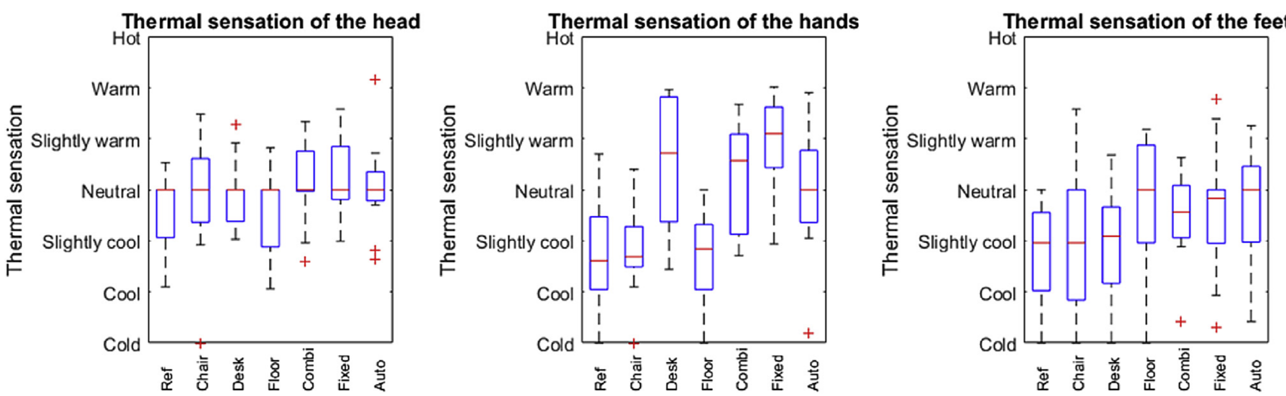

Fig. 10. Thermal sensation of the head, the hands, and the feet at the end of the session.

3.3. *Skin temperatures (vs. thermal sensation vs. settings)*

Mean skin temperature over whole session is depicted in Fig. 11. Mean skin temperature slightly rises at the beginning of the session due to increased thermal insulation after the test subjects are seated. Then it either slowly decreases – in Ref, Floor, and Desk – or remains stable – in Chair, Combi, Fixed, and Auto. No significant differences between the test cases were observed at the beginning of the session, which suggest an equal accustomization of the subjects. At the end of the session Chair, Combi, Fixed, and Auto provided significantly ($p < 0.028$) higher mean skin temperature than Ref, Floor, or Desk.

Hand skin temperature over whole session is shown in Fig. 12. Hand skin temperature decreases over the whole session in all test cases because of vasodilation induced by the mild cool conditions in the climate chamber. There is no significant difference among the test cases at the beginning of the session. At the end of the session hand skin temperature was significantly ($p < 0.081$) higher in Desk, Chair, Combi, Fixed, and Auto than in Ref and Floor.

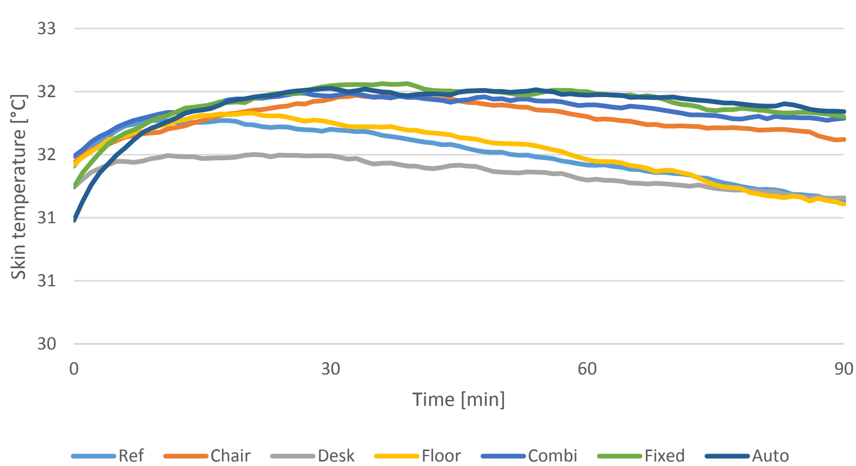

Fig. 11. Mean skin temperature over whole session.

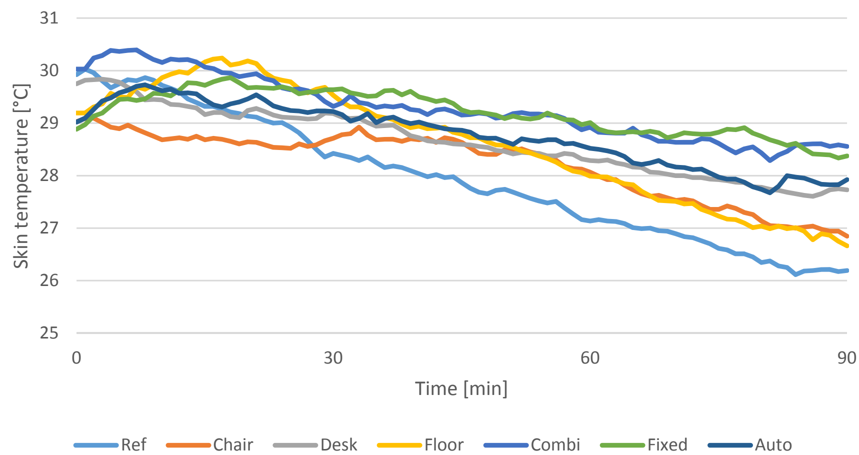

Fig. 12. Hand skin temperature over whole session.

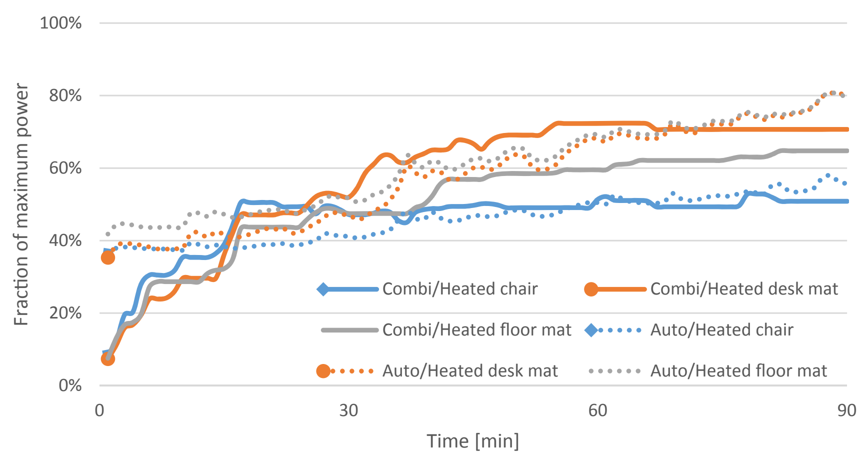

Fig. 13. Average user control input in test cases Combi and Auto.

3.4. User control

Average user control input for each heater in test cases Combi and Auto is shown in Fig. 13. When the heaters are user controlled (Combi), increases at the beginning and tends to stabilize towards the end of the session. Less than 15% of all individual control interactions took place in the last 30 min of the session. The final setting in the test case Combi are within ±6% from the settings in the test case Fixed, which were chosen based on a pretest described in Methods. The settings in the test case Auto increase during the whole session as the hand skin temperature decreases, but they remain in the same range as the user controlled settings.

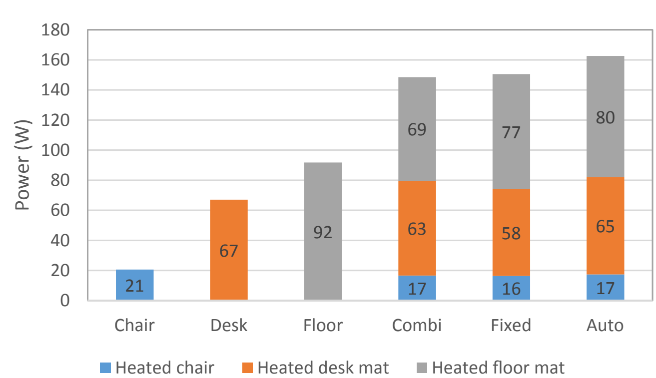

Fig. 14. Average power over last 30 min of the session.

3.5. Energy performance

In the test cases, when personalized heating was user controlled, the settings remained stable over last 30 min of the session. Therefore, the heating power in this period can be considered steady state. Power of the personalized heaters averaged over last 30 min of the session is shown in Fig. 14. The heated chair clearly needs the lowest power of the tested heaters. The three tested control modes require rather similar power ranging from 148 to 163 W, when the heaters are combined.

Table 5 lists the corrective power (sensation) and corrective power efficiency. The term of corrective power was introduced by Zhang et al. [4] and it describes the possible offset of thermal environmental conditions that (expressed in temperature, thermal sensation, or thermal comfort) can be mitigated by a PCS. In this study, corrective power is defined as a difference in average thermal sensation at the end of the exposure between the reference case and a case with a respective personalized heater. Furthermore, we define corrective power efficiency, which a power needed for a compensation of one unit of thermal sensation. It becomes clear from Table 5 that the combination of all three presented heaters has

Table 5
Corrective power and Corrective power efficiency.

	Corrective power (sensation) of tested heaters [1 point on ASHRAE scale]	Corrective power efficiency of tested heaters [W/1 point on ASHRAE scale]
Chair	1.1	20
Desk	0.6	105
Floor	–[a]	–[a]
Combi	1.9	80

[a] Difference not significant.

the highest corrective power of 1.9 on ASHRAE scale, but the heated chair is more efficient.

4. Discussion

This study focuses on comparison of three personalized heaters – a heated chair, a heated desk mat, and a heated floor. As pointed out by Zhang et al. [4], the choice of a torso, hands, and feet as most critical body parts for personalized heating is supported by recent findings that are also applied in modeling of thermal physiology. Personalized heating system presented in this study significantly improves overall as well as local thermal comfort. Comparing single components of the system shows the heated chair as a most effective and energy efficient among the tested heaters followed by the heated desk mat. The heated floor mat has generally no impact on thermal comfort. Nevertheless, as shown in Fig. 9 a combination of the tested heaters is needed to restore thermal sensation to neutral or above for a majority of the subjects under an operative temperature of 18 °C. The wellbeing aspects do not show any statistically significant difference among the test cases. This was likely caused by a relatively short exposure time, which was not enough to build up of Sick Building Syndrome symptoms.

Several recent studies have already documented improved thermal comfort with a heated chair [13,23–25,32], foot warmers [5,25,33], or hand warmers [5]. However, most of these studies focused on a single component of personalized heating system and do not provide their comparison. Only Melikov and Knudsen [13] reported that the heated chair is preferred over radiant heating panels directed to feet and legs, but this was based just on general comments by the test subjects. A review by Zhang et al. [4] lists several heated chairs with usual corrective power (sensation) of 1–2. This study shows the heated chair as the heater with the corrective power (sensation) of 1.1 compared to 0.6 of a heated desk mat and 1.9 of the three heaters combined. Although the heated floor mat improves thermal comfort of the feet, it is insufficient to have any impact on overall thermal comfort. This is likely caused by a design that differs from enclosed foot warmers [5,25,33], which heat the feet not only by conduction through the sole, but also by radiation from the sides and above the feet. The heated floor mat was chosen for this study in order to resemble a normal office environment without hindering the movement of its occupants in any way. Also personalized heaters that rely on radiation as the main heating principle were presented [13,34]. Although it is possible to improve thermal comfort using the radiant heaters, they generally require considerably higher surface temperature (up to 60 °C [34]) than conductive heaters for comparable comfort improvement. This high surface temperature would in effect lead to higher energy consumption.

Only a heated chair and a combination of heaters significantly increased mean skin temperature at the end of the session. A fact that a heated mat significantly improves thermal comfort, but does not affect mean skin temperature, suggests that comfort improves mainly due to a spatial alliesthesia effect [19], i.e. pleasant thermal stimuli counteracting the overall state of the body. Therefore, evaluation of comfort in non-uniform environment provided by personalized heating cannot rely on mean skin temperature and requires more complex modeling of local skin temperatures, such as implemented in ThermoSEM model [35], and local thermal sensation. Significant differences in hand skin temperature without personalized heating and with a heated floor mat compared to all other test cases suggest that the heating provided by heated chair and heated desk mat counteracted the vasodilation or heat loss of the body.

Beside of the corrective power [4] this study introduces corrective power efficiency, which relates corrective power to energy consumption similar to cooling fan efficiency index introduced by Schiavon and Melikov [18]. While the corrective power is defined as an offset of thermal environmental conditions that can be compensated for by personalized conditioning, corrective power efficiency takes into account also energy required for this compensation. Looking at the corrective power efficiency of the presented heaters the heated chair may seem to be a clear choice as it requires the least power per mitigated thermal discomfort. However, it is necessary to bear in mind that the combination of the heaters has higher corrective power and can thus compensate higher temperature deviation. For evaluation of the energy performance it is essential to analyze a personalized heating system together with the building, because shifting a heating set point will result in different energy savings potential, which may not correspond to the power difference between two personalized heating systems.

No clear relation between hand skin temperature and thermal sensation was observed in the reference case. However, hand skin temperature is under 30 °C and thermal sensation under neutral for all test subjects, which corresponds to the "risk of cool discomfort" area identified for fingertip temperature by Wang et al. [21]. Also, when our data are combined with a warm exposure at operative temperature of 28 °C measured by Verhaart et al. [36], a clear trend of thermal sensation increasing with hand temperature can be observed as shown in Fig. 15. As a user setting of personalized heating can be interpreted as a way of expressing thermal comfort, it can be also assumed that a relation of the user setting to a hand temperature should follow a similar trend as thermal sensation. This assumption was used for an automated control presented in this study. Personalized heating was controlled proportionally based on hand temperature in the automated mode. This is compared with a user interaction and fixed setting, which was derived from average settings used by users.

The three compared control modes – user interaction,

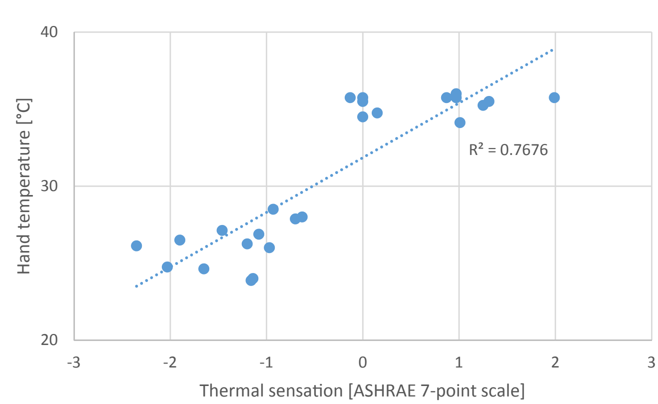

Fig. 15. Hand temperature and thermal sensation at the end of 90 min exposure, data from this study combined with data by Verhaart et al. [36] measured at operative temperature of 28 °C.

automatic, and fixed setting – do not significantly differ in provided level of thermal comfort and they result in similar power consumption. This suggest that a user interaction can be substituted by an automatic control. However, it has to be noted that the test presented in this study were performed only at background operative temperature of 18 °C, which lead to a similar power setting in different control modes. Therefore, it is recommended to further investigate the automatic control over wider range of background environmental conditions.

Majority of the test subjects indicated the user interaction as more preferable than automatic or fixed setting, because they wanted to be in charge of their own microenvironment. However, some test subjects identified in their comments a preference towards an automatic control, because it allowed them to focus more on their work. Although it was beyond a scope of this study to measure productivity, thermal comfort is widely recognized as a factor influencing it [37]. As such it is expected that thermal comfort improved by personalized heating would be also beneficial for productivity. In the study by Boerstra et al. [38] the test subjects experienced a user controlled personalized cooling in the first session and then their user profile was automatically replicated in the second session. The subjects' comfort remained the same in both sessions, but their productivity increased with automatic control, which was in contradiction with their preference for having user control. These contradictions may suggest a need for a combination of user and automatic control, which could be realized for instance by a machine learning algorithm that constantly updates a user profile based on personal control. However, the impact of such a control mode on productivity is still unclear and can be recommended for further research.

5. Conclusions

This study compares the performance of personalized heating system consisting of a heated chair, a heated desk mat, and a heated floor mat with these components used alone. The complete system significantly improves thermal comfort under mild cool conditions and can compensate up to 1.9 units of thermal sensation on ASHRAE 7-point scale. Among the single components a heated chair and a heated desk mat improve thermal comfort, while the heated chair is most energy efficient (20 W per 1 point on the 7-point scale). As the mean skin temperature is not affected, when only the heated desk mat is used, it is expected that in this case thermal comfort is improved mainly due to the spatial alliesthesia.

This study also demonstrates that control by user interaction can be substituted by automatic control or fixed setting without loss of comfort or increased energy consumption. However, further research is recommended to confirm this in a wider range of environmental conditions and to identify the effect on workers' productivity.

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