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Personalized Heating – Heaters’ effectiveness

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SUMMARY
Personalized conditioning systems create just a small thermal microenvironment for every user unlike the traditional HVAC systems that condition even an unoccupied space and create uniform environment for every user. Therefore, personalized conditioning system can satisfy individual needs for thermal comfort and energy can be saved due to higher effectiveness. A number of different personalized ventilation, cooling, and heating systems has been tested by different research groups. However, a comprehensive comparison and a way of benchmarking of different systems is still missing.

This paper provides a comparison of personalized heating by a heated chair, heated desk mat, a heated floor mat, and a combination of these three options. These heating options were tested with 13 human subjects in a climate chamber under operative temperature of 18 °C and exposure time of 90 minutes. The test subjects evaluated their thermal comfort every 15 minutes via a computer based questionnaire. Their local skin temperatures as well as the thermal conditions in the climate chamber and energy use of the personalized heaters were also recorded.

A comparison of thermal comfort and energy consumption of different heaters and their combination is provided in the results section. The heated chair and the heated desk mat perform better than the heated floor mat and improve thermal comfort. However, a combination of these heaters is needed in order to increase thermal sensation above neutral.

PRACTICAL IMPLICATIONS
This paper compares different heaters of a personalized heating system. The results aim to form a guideline for application of such system in a building practice.

KEYWORDS
Energy reductions, Personalized heating, Thermal comfort

1 INTRODUCTION
Personalized conditioning systems (PCS) can provide a solution for two major problems that the building industry is facing nowadays – high energy consumption and still often unsatisfactory indoor climate (Veselý & Zeiler 2014). Considerable amount of energy is being used in the buildings in order to ensure indoor environmental conditions prescribed by standards such as ISO EN 15251 (2007). It is usually assumed that narrower range of indoor environmental conditions translates into better thermal comfort. However, it has been shown that in practice even the wider ranges of conditions prescribed by relevant standards deliver the same comfort as the narrower ones (Arens et al. 2010).

PCS brings heating, cooling, and ventilation in a close proximity of its user. This allows to create a microenvironment adjusted to individual needs for comfort. At the same time the energy is used in an effective way and the range of allowed conditions in the surrounding space can be extended. This way energy can be saved on a whole building level due to higher effectiveness of PCS (Verhaart et al. 2015; Schiavon & Melikov 2008).
Although research on PCS focuses more on personalized ventilation and cooling, some studies investigated personalized heating as well (Veselý & Zeiler 2014). These studies clearly showed the potential of personalized heating in terms of thermal comfort improvements (Melikov & Knudsen 2007; Watanabe et al. 2010; Zhang et al. 2010; Pasut et al. 2014) as well as in the overall heating demand reductions (Zhang et al. 2010; Foda & Sirén 2012; Verhaart et al. 2015).

However, the up-to-date tested personalized heating systems focused mostly on single components or overall system. A comprehensive comparison of the components under same conditions was still missing and is thus provided in this study. Three following heaters have been identified to have a good potential for energy effective comfort improvement – 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 (Pasut et al. 2015; Zhang et al. 2007; Oi et al. 2011; Melikov & Knudsen 2007). As the hands and feet are usually the most thermally uncomfortable body parts under cool or cold conditions (Arens & Zhang 2006), it can be expected that heating applied on them will result in a pleasant alliesthesia effect (de Dear 2011). Results of this study should support a possible deployment of personalized heating in practice.

2 METHODS

Personalized Heating System
The tested personalized heating system consists of a heated chair, a heated desk mat, and a heated floor mat (Figure 1). Table 1 specifies maximum power, maximum surface temperature (measured in a room at operative temperature of 18 °C), and dimensions of the heaters. The heated chair is an ordinary office chair with two heating mats integrated under the fabric surface of the chair. The heated chair dimensions given in Table 1 are dimensions of the integrated heated mat and the surface temperature was measured on the fabric surface of the chair.

<table>
<thead>
<tr>
<th></th>
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<th></th>
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</thead>
<tbody>
<tr>
<td>Heated chair</td>
<td>36</td>
<td>40x28 (seat) and 30x28 (backrest)</td>
<td>28</td>
</tr>
<tr>
<td>Heated desk mat</td>
<td>80</td>
<td>60x36</td>
<td>35</td>
</tr>
<tr>
<td>Heated floor mat</td>
<td>100</td>
<td>70x50</td>
<td>30</td>
</tr>
</tbody>
</table>

Figure 1 Heated chair (left), heated desk mat (middle) and heated floor mat (right)
Personalized heating system was user controlled (user interface shown in Figure 2) and the settings were logged with an interval of 2 seconds. Different control strategies were tested alongside with the user interaction in another yet unpublished study (Veselý et al. 2016).

Figure 2 User control over personalized heating system

**Climate Chamber and Environmental Conditions**

Experiments were conducted in a climate chamber of Unit of Building Physics and Services, Eindhoven University of Technology, The Netherlands. The climate chamber is a well thermally insulated room of dimensions 3.6 x 5.7 x 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.

During this experimental phase the climate chamber was set to maintain both air and mean radiant temperature at 18 °C. As mixing ventilation was used the air movement in the occupied zone was negligible. The subjects performed an office work resulting in metabolic rate of 1.2 met and they were instructed to wear clothing ensemble with insulation of 0.7 clo (common winter indoor clothing). These background conditions result in PMV of -1.5 and corresponding PPD of 50 %.

Two user desks (Figure 3) were set up in the climate chamber. Both user desks were equipped with a computer screen, a keyboard, and a mouse. The test subjects connected their laptops to the provided equipment at the beginning of each session.

Figure 3 One of the two user desks in the climate chamber
Subjects
Thirteen healthy university students (seven males and six females) volunteered as test subjects. Their anthropological data are listed in Table 2.

Table 2 Anthropological data of the 13 test subjects

<table>
<thead>
<tr>
<th></th>
<th>Height [m]</th>
<th>Weight [kg]</th>
<th>Body mass index</th>
<th>Age [years]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>1.79</td>
<td>81.1</td>
<td>25.1</td>
<td>24.9</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.12</td>
<td>26.8</td>
<td>5.8</td>
<td>3.2</td>
</tr>
</tbody>
</table>

Procedure
Five test cases as shown in Table 3 were tested and all test subjects experienced all test cases. The test comprised three distinct personalized heaters (heated chair, heated desk mat, heated floor mat) as well as a combination of these three heaters. The personalized heating system was user controlled in all test cases. All three heaters could be controlled separately in test case ‘Combi’.

Table 3 Test cases

<table>
<thead>
<tr>
<th>Test case code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ref</td>
<td>Reference case (i.e. no personalized heating applied)</td>
</tr>
<tr>
<td>Chair</td>
<td>Only heated chair applied</td>
</tr>
<tr>
<td>Desk</td>
<td>Only heated desk mat applied</td>
</tr>
<tr>
<td>Floor</td>
<td>Only heated floor mat applied</td>
</tr>
<tr>
<td>Combi</td>
<td>Heated chair, heated desk mat, and heated floor mat applied</td>
</tr>
</tbody>
</table>

Each session comprised 30 minutes of warm accustomization (i.e. just outside of the climate chamber) and 90 minutes of exposure. During the accustomization period the skin temperature loggers were attached. During the exposure the subjects performed ordinary office work on a computer. The subjects were asked to fill in a questionnaire regarding their thermal comfort every 15 minutes within the exposure.

Measurements – Subjective Evaluation
During the experimental sessions the subjects evaluated their thermal comfort via a java-based app (sample screenshots shown in Figure 4). This app includes questions regarding the subjects’ clothing, thermal sensation, thermal comfort, and wellbeing. Thermal sensation and comfort was evaluated as overall and in particular for neck, head, arms, hands, legs, and 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.
Measurements – Environmental Data
The thermal environment in the climate chamber was continuously monitored during all experimental sessions. This includes measurements of air speed and air temperature at the heights of 0.1, 0.7, and 1.1 m (standard heights for a sitting person) as well as the relative humidity and globe temperature in the occupied zone of the room. All environmental data were logged with an interval of one minute and measured in compliance with ISO 7726 (ISO 1998).

Measurements – Physiology
In order to investigate the effect of personalized heating on human physiology, skin temperature was measured on 14 locations on the body by iButtons (van Marken Lichtenbelt et al. 2006). Digital thermometer DS18B20 was used to measure the hand temperature additionally to iButton.

3 RESULTS
Thermal sensation and comfort
The average thermal sensation over the whole exposure is shown in Figure 5. Figure 6 shows boxplots of thermal sensation and comfort at the end of the exposure. The thermal sensation starts at about neutral in all test cases due to neutral accustomization. In the ‘Ref’ test case thermal sensation drops under slightly cool. The heated floor follows a similar tendency, while the heated chair and heated desk mat can maintain thermal comfort between neutral and slightly cool. The combination of these three heaters then even increases thermal sensation towards slightly warm. The test case ‘Combi’ significantly (p < 0.05) increased thermal sensation and improved thermal comfort over the other test cases. The test cases ‘Chair’ and ‘Desk’ significantly (p < 0.05) increased thermal sensation and ‘Desk’ also improved thermal comfort over the ‘Ref’.
Energy consumption of personalized heating

Figure 7 depicts energy consumption of the three personalized heaters in the test cases when personalized heating was used. Clearly, the lowest energy consumption was observed for the heated chair and the highest for the combination of all three heaters.

Figure 7 Energy consumption of personalized heating averaged per person over the whole exposure (90 minutes)
4 DISCUSSION
As expected the personalized heating system significantly improves thermal comfort under mild cool conditions. Melikov and Knudsen (2007) reported the heated chair as a more preferred heater than a heater focused on legs (floor and under-desk radiant panels). In our test, we observed the heated desk mat and the heated chair as more preferred heating options than the heated floor mat. The fact that the gain in thermal comfort with heated chair compared to a reference case was not significant is likely to be caused by a single outlying value. The cause of this requires further investigation.

The heated chair performed the best among the heaters presented in this study in terms of energy consumption. However, only the heated chair was not sufficient to bring average thermal sensation above neutral and a combination with other heaters was needed for this. It also has to be noted that a reduction of the surface area of the heated desk mat would result in considerable energy reduction. This would, of course, require a careful ergonomic design. The gains in thermal sensation and comfort can also be directly related to energy consumption of the heaters in order to establish a benchmark similar to Cooling-Fan Efficiency Index introduced by Schiavon and Melikov (2009).

The presented experiments also included yet unreported measurements of local skin temperatures. The upcoming analysis of the skin temperatures is expected to give an insight into how much of the thermal sensation gain is caused by recovering the whole body heat balance and how much accounts for an alliesthesia effect (de Dear 2011).

5 CONCLUSIONS
The personalized heating system presented in this paper significantly increases thermal sensation and comfort. The heated chair and the heated desk mat are more effective heaters than the heated floor mat in terms of thermal comfort. The heated chair performs the best in terms of the energy consumption.

The following issues are recommended for further research:

- Establishing a benchmarking index from the direct relation of thermal comfort gain and energy consumption of personalized heating.
- Impact of personalized heating on local skin temperatures and thermal physiology.

ACKNOWLEDGEMENT
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6 REFERENCES


