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Comfort of cooling by personal air movement

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SUMMARY
Personalized cooling is a promising solution to reduce the energy use of a building cooling system, while satisfying a person’s individual thermal comfort. In this study, the effect of the air supply temperature on user selected airspeed was investigated. This can be used to design more comfortable personal cooling systems (PCS).

Climate chamber tests were conducted at a slightly warm environment with human subjects. Twelve test subjects were recruited, seven females and five males. The airspeed was controlled by the test subjects using a slider. Each subject performed four tests: two with different supply temperatures (23°C and 26°C), one reference without cooling and one training session.

In this study, the most comfortable supply temperature was 23°C. The thermal sensation votes for the relevant body parts and the perceived air quality all showed improvement in both cases, however, the comfort was only showed a significant improvement at the lower supply temperature.

PRACTICAL IMPLICATIONS
The outcome of this work can contribute to the design and development of a personal cooling systems for application in the office environment. The relatively low supply temperature is preferable.

KEYWORDS
Personal cooling, thermal comfort, climate chamber test, personal ventilation.

1 INTRODUCTION
Personal cooling using air movement has been studied, mainly in the context of personal ventilation (Dalewski et al. 2014). Cooling using moving air is an effective, fast and direct way to provide cooling in a slightly warm environment (Arens et al. 2013). Pallubinsky et al. (2015) show that the air cooling was perceived to be the most comfortable among the five systems tested, followed by the combination of the air cooling and cooling of the desk. Personal cooling reduces the need for whole room cooling by making the user comfortable at their desk only. By replacing whole building cooling by local cooling, the energy demand for cooling can be reduced (Verhaart et al. 2015; Zhang et al. 2010).

The effectiveness of air movement for cooling has been shown in previous experiments and by literature (Zeiler et al. 2015; Arens & Zhang 2008; Arens et al. 2013; Cattarin et al. 2013). The overall energy use and effectiveness of this type of cooling is dependent on the temperature of the air supplied to the user. In this study, the effect of the supply air temperature on comfort level and the preferred airspeed will be shown. This will help to find the optimal range of operation for design and application of PCS.
2 METHODS
Climate chamber tests were performed at a slightly warm environment (27.5°C air temperature). The PCS provided air directly into the breathing zone as is shown in Figure 1B. The airspeed was controlled by the test subjects themselves using a simple slider, shown in Figure 1. Twelve test subjects were recruited among the student population, seven females and five males. Each subject took part in four separate tests. The characteristics of the subjects is summarized in Table 1.

Figure 1: Slider (A) used by the test subjects to control the airspeed of the PCS that supplies cool air through the ducts (B).

The subjects had personal cooling available in three of the four tests. The tests were performed in two sets, first the reference test (T0) and a training session with supply air from the PCS available at 25°C (T1). This way, the reference case forms a benchmark. Furthermore, the test subjects learn to use the system at the training session and the learning effect of the system operation is eliminated in the real tests. Following these two sessions were two tests with cooling available at 23°C (T2) and 26°C (T3). These tests were done in random order to compensate for the unlikely learning effect between T2 and T3.

Table 1: Physical characteristics of the test subjects of the experiments. The data is given in the format average ± standard deviation.

<table>
<thead>
<tr>
<th></th>
<th>Number</th>
<th>Age</th>
<th>Height</th>
<th>Weight</th>
<th>BMI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Female subjects</td>
<td>7</td>
<td>25.8 ±4.2 yr.</td>
<td>1.69 ±0.10 m</td>
<td>68.7 ±13.1 kg</td>
<td>23.9 ±2.9 kg/m²</td>
</tr>
<tr>
<td>Male subjects</td>
<td>5</td>
<td>24.8 ±1.7 yr.</td>
<td>1.81 ±0.14 m</td>
<td>87.4 ±20.3 kg</td>
<td>26.8 ±5.4 kg/m²</td>
</tr>
</tbody>
</table>

The tests were performed in the climate chamber located at Eindhoven University of Technology, previously described by Schellen et al. (2012). In this experiment, two test subjects were placed in the chamber at the same time as shown in Figure 2. Both desks were equipped with a PCS. The supply unit was positioned away from the subject and the air was blown into the breathing zone directly, cooling mainly the head. This position was used in previous tests (Zeiler et al. 2015) and is also used by Dalewski (2014). One subject wearing contact lenses complained about dry eyes as a result of the airflow.
The position of the slider resulted in the same airspeed in each test. The relation between the position of the slider and the airspeed in the breathing zone was linear. The temperature in the breathing zone depended on the supply air temperature and the length of the ducting and the distance between the supply duct and the subject. The air mixed more at low airspeeds, which caused the air temperature in the breathing zone to be slightly higher at lower airspeeds.

Figure 3 shows the test schedule. Each test lasted for 90 minutes with 30 minutes accustomization outside the climate chamber at a neutral temperature before entering. During the stay in the climate chamber, the test subjects were allowed to work on their own computer. The thermal sensation and thermal comfort of the subjects was assessed using a computer-based questionnaire installed on the subject’s own computer. Every 15 minutes, a new questionnaire popped up for the subject to fill out. The questionnaire asked for thermal sensation on the ASHRAE 7-point sensation scale as well as comfort for seven body parts (whole body, head, neck, arms, hands, legs and feet) and questions relating to symptoms of sick building syndrome (SBS). After leaving the climate chamber, the subjects were asked to fill out a form with open questions related to the overall conditions experienced and the functionality of the local cooling system.

In addition to the questionnaire, skin temperatures were collected at 14 sides in accordance with NEN-EN-ISO 9886 (2004), which can be used to calculate the mean skin temperature.

The test subjects received an advice for preferred clothing and were asked to wear similar clothing during all tests. Most subjects complied with this, however, some subjects wore different outfits. This was caused by the outside conditions that were colder on some days during the testing period. The clothing values and the environmental temperature in the room during the experiments is shown in Table 2. On average, the effect of this is minor.
Table 2: The general information of the tests: the air temperature in the room and the average clo-values. The format is mean ±standard deviation.

<table>
<thead>
<tr>
<th>Test Variants</th>
<th>Room air temperature [°C]</th>
<th>Clo-Value</th>
<th>Male subjects</th>
</tr>
</thead>
<tbody>
<tr>
<td>T0 (reference test)</td>
<td>27.6 ±0.2</td>
<td>0.61 ±0.15</td>
<td>0.49 ±0.04</td>
</tr>
<tr>
<td>T2 (23°C supply)</td>
<td>27.3 ±0.3</td>
<td>0.64 ±0.10</td>
<td>0.51 ±0.04</td>
</tr>
<tr>
<td>T3 (26°C supply)</td>
<td>27.4 ±0.4</td>
<td>0.70 ±0.15</td>
<td>0.50 ±0.04</td>
</tr>
</tbody>
</table>

The test subjects started their test right after entering the climate chamber. In the beginning of the tests, the subjects were in a thermally neutral state and in most cases the cooling was started right away to compensate for the warm environment. After a habituation period, the number of interactions with the system reduced. Figure 4 shows that the subjects used the system extensively. The system responds directly, so corrections to overshoot could usually be made within seconds. During the whole test, the subjects kept interacting with the PCS and make small adjustments. After 30 minutes, most subjects seemed to have found their preferred settings and a steady airspeed setting is reached. The data on thermal sensation and comfort is analysed for the remaining one hour of testing.

Figure 4: The average airspeed as selected by the test subjects. After 30 minutes, the number of airspeed adjustments decreased. The performance of the system is assessed for the last hour of the test.

3 RESULTS
The preference for the low (23°C, T2) and the high (26°C, T3) supply temperature is assessed by using the questionnaires (thermal sensation, thermal comfort and the SBS symptoms) and the use pattern of the subjects during the last hour of the tests. The reference case (T0) is compared to the two temperature settings and the two temperatures were compared to each other. All data sets were checked for normality using the Kolmogorov-Smirnov test. A normal distribution could not be assumed. Therefore, all data was assumed to be non-parametric. The comfort and the thermal sensation was analysed using the Wilcoxon signed-rank test, which is used for non-parametric and dependent data with a 95% confidence interval. Four body parts were relevant for the performance of the system, since they were affected by the airflow directly. These were, the whole body, the head, the neck and the arms. In Figure 5, the thermal sensation votes are shown for these body parts separately and for the tests T0, T2 and T3. The significant differences are shown using the asterisk.
Figure 5: The thermal sensation of the four most relevant body parts: whole body, the head, the neck and the arms in all three tests. The differences between the reference case (T0) and the other cases is significant in all cases.

Compared with the test T0, the thermal sensation was significantly lower for the whole body and three specific body parts displayed. Between T2 and T3, the only body part where there is a significant difference, are the arms. Most test subjects’ arms were not covered by clothing during all tests. This lead to a large number of people voting slightly cool (below neutral) for the arms during T2.

The comfort votes show a similar trend to the thermal sensation votes, however, less obvious. In Figure 6, the comfort votes are shown for the same body parts as in Figure 5. There is only a significant difference between tests T0 and T2 for the hands (the arms are displayed in Figure 6), the neck and the whole body. For the head, there was no significant improvement of comfort. The effect was similar in the other body parts, with the exception of the arms. The comfort of the arms was not significantly different for any of the tests.

The votes on the SBS symptoms show some differences between the tests. The air was reported to be less stuffy in both T2 and T3 compared to T0. The subjects reported less headache and a clearer head in T2 compared to T0 and T3.

In Figure 7, the differences in the T2 and T3 are shown. There is a significant difference in the average setting chosen by the test subjects during the last hour of the tests. The chosen setting was lower in T2, which is what can be expected. There is no difference in the number of interactions between the T2 and T3 tests. The number of interactions during T2 and T3 is
significantly less than it in the training session (T1), which shows that the tests randomly eliminated the learning effect in T2 and T3.

Figure 6: The comfort votes for the same body parts as above. The difference between the three tests is less clear in this case. There is a significant improvement of the comfort for the whole body, the neck and the hands was shown in T2 compared with T0.

Figure 7: In these two figures, the differences in the use of the system is shown. There is no significant difference in the number of interactions between the two tests, however, the average setting for T2 over the last hour of testing is significantly lower than for T3.
Table 3: The significant differences in the questionnaires between the tests. The P-values shown are below 0.05, the values in bold are showing the values below 0.01

<table>
<thead>
<tr>
<th>P-value</th>
<th>Wilcoxon Signed-Rank test</th>
<th>Between T0 and T2</th>
<th>Between T0 and T3</th>
<th>Between T2 and T3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Whole body thermal sensation</td>
<td>$6.54 \times 10^{-6}$</td>
<td>$3.67 \times 10^{-6}$</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Whole body comfort</td>
<td>$3.92 \times 10^{-3}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Thermal sensation of the head</td>
<td>$5.28 \times 10^{-5}$</td>
<td>$2.42 \times 10^{-7}$</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Comfort of the head</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Thermal sensation of the neck</td>
<td>$1.03 \times 10^{-4}$</td>
<td>$2.65 \times 10^{-5}$</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Comfort of the neck</td>
<td>$1.63 \times 10^{-2}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Thermal sensation of the hands</td>
<td>$3.81 \times 10^{-4}$</td>
<td>$9.38 \times 10^{-7}$</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Comfort of the hands</td>
<td>$9.89 \times 10^{-3}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Thermal sensation of the arms</td>
<td>$4.51 \times 10^{-4}$</td>
<td>$4.18 \times 10^{-3}$</td>
<td>$4.67 \times 10^{-2}$</td>
</tr>
<tr>
<td>10</td>
<td>Comfort of the arms</td>
<td>$6.81 \times 10^{-4}$</td>
<td>$4.95 \times 10^{-2}$</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Thermal sensation of the feet</td>
<td>$2.68 \times 10^{-5}$</td>
<td>$1.84 \times 10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Comfort of the feet</td>
<td>$3.62 \times 10^{-2}$</td>
<td>$4.37 \times 10^{-3}$</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Thermal sensation of the legs</td>
<td>$2.02 \times 10^{-3}$</td>
<td>$3.25 \times 10^{-2}$</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Comfort of the legs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Perceive the air as stuffy or fresh</td>
<td>$1.31 \times 10^{-3}$</td>
<td>$1.78 \times 10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Have a headache or not</td>
<td>$1.17 \times 10^{-3}$</td>
<td></td>
<td>$2.35 \times 10^{-2}$</td>
</tr>
<tr>
<td>17</td>
<td>Find it difficult to think or have a clear head</td>
<td>$3.16 \times 10^{-3}$</td>
<td></td>
<td>$1.28 \times 10^{-2}$</td>
</tr>
<tr>
<td>18</td>
<td>Feel tired or rested</td>
<td>$2.28 \times 10^{-3}$</td>
<td>$3.12 \times 10^{-3}$</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>Find it difficult or easy to concentrate</td>
<td>$4.04 \times 10^{-3}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>Feel sleepy or alert</td>
<td>$1.51 \times 10^{-4}$</td>
<td>$4.14 \times 10^{-3}$</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>Indicate the ability to work in percentage</td>
<td>$1.61 \times 10^{-4}$</td>
<td>$3.59 \times 10^{-2}$</td>
<td>$1.43 \times 10^{-2}$</td>
</tr>
</tbody>
</table>

4 DISCUSSION
This study gives a clear indication that temperature of the supply air for personal cooling is an important aspect. The increased comfort for the lower supply temperature is in line with the findings of Dalewski et al. (2014) who found that a higher airspeed at a higher temperature increased the perceived air quality and a lower airspeed at a lower temperature increased mainly thermal comfort. The preference for the lower supply temperature (23°C) indicates a challenge for designing an optimal energy saving PCS. If supply air is provided at this temperature, the supply air needs to be cooled in a large part of the summer.

An option is not to use active air cooling at all and cool only using moving air, as is done in studies by Pasut (2014) and Zhai (2013) among others. This choice more efficient in terms of energy saving, however, in hot climates, additional whole room cooling will still be needed. Higher airspeeds can also compensate, however, the acceptance for higher airspeeds is culturally determined (Cattarin et al. 2013).

There is a large spread in the use pattern between subjects for both the interactions and the airspeed settings. The preference for airspeed seems to be personal. Therefore, user interaction is important. This is in accordance with the findings of Cattarin et al. (2013). Further investigation of the user pattern and specific personal characteristics can give an indication to an underlying pattern and other factors that might have influenced the choices of the user. This can be addressed in future experiments.

The experiment was performed with a small number of test subjects in a limited number of test cases. However, the outcomes give a good indication for the direction of design of future personal cooling systems and experiments.
5 CONCLUSIONS
In this test, a supply air temperature of 23°C was preferred. This case showed a significant improvement in comfort over the reference case for most body parts. Having the PCS available was preferred by most people, shown by the improvement in perceived air quality in both cases. In the reference case, the average thermal sensation was close to 1 (slightly warm). In the cases with cooling, the thermal sensation was closer to neutral, which improved significantly from the reference case with the average thermal sensation as slightly warm.

The use pattern between the two cooling cases was similar and there was no significant difference between the cases in number of interactions. The average airspeed setting selected over the last hour of the test with the lower supply temperature was lower than for the high supply temperature.

ACKNOWLEDGEMENT
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