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Energy-efficient comfort with a heated/cooled chair: results from human subject tests

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Abstract

A novel heated/cooled chair was evaluated for its effect on thermal sensation and comfort. The chair is exceptionally efficient, allowing standalone battery operation over long periods. Its capabilities at providing comfort needed to be established.

Twenty-three college students participated in 69 2.25-hour tests. Four heated/cooled chairs were placed in an environmental chamber resembling an office environment. The chamber temperatures were 16°C, 18°C and 29°C. During the tests the subjects had full control of the chair power through a knob located on the chair. The heated/cooled-chair results could be compared to those of conventional mesh and cushion chairs tested in the same three environmental conditions in a previous study, as well as to a thermoelectrically heated and cooled chair.

Subjective responses for thermal sensation and comfort were obtained at 15-minute intervals. The results show that the heated/cooled chair strongly influences the subjects' thermal sensation and improves thermal comfort and perceived air quality. No significant differences were found between men and women. The chair provided comfortable conditions for 92% of the subjects in a range of temperatures from 18°C to 29°C.

1 Introduction

Buildings currently account for 40% of primary energy consumption in many countries, and are a significant source of carbon dioxide emissions [1]. Roughly half of this is for heating and cooling. The floor area of commercial and institutional buildings is expected to grow by almost 195% by year 2050 [2], so reducing building energy consumption is a priority.

Despite the significant energy used to serve the demand for thermal comfort, poor thermal comfort is one of the most common complaints from building users. Although buildings are designed to have at least 80% of occupants satisfied with their thermal environment [3], a survey of 215 buildings shows that only 11% of them met this criterion [4].

Personal comfort systems (PCS) are a promising technology for both improving occupants' thermal comfort and simultaneously reducing buildings' heating and cooling energy. They provide comfort by targeting a relatively small amount of energy directly onto occupants. Several authors have reported that the use of PCS decreases occupants' dissatisfaction.

PCS saves energy by enabling the ambient air temperature to be less controlled. In U.S. commercial buildings, a typical temperature range between setpoints for heating and cooling systems (setpoint deadband) is between 21.5°C and 24.5°C. Each 1°C broadening of this deadband reduces annual HVAC energy use by approximately 10% [5,6]. This is a very significant amount. At the same time, several laboratory studies [7-12] have established that PCS can produce comfort across ambient temperature ranges in the vicinity of 18-30 °C. This implies that a building can be controlled with an extended thermostat deadband while still maintaining occupants' thermal comfort. A recent field study has demonstrated this for the winter season, using a foot-warming PCS at 19°C [13].

By widening the comfortable ambient deadband, personal comfort systems allow energy to be rather easily saved in new and existing buildings, improve buildings' resilience to future climate change, and serve to deepen demand response during peak temperatures. PCS can be deployed to assist existing air conditioning (AC) systems or, in climates characterized by moderate temperatures, to enable low-energy conditioning strategies or the avoidance of AC altogether.

A heated/cooled chair is a type of PCS that has been found to provide improved comfort. Watanabe at al. [14] studied the influence of a ventilated chair incorporating two fans in the back and seat to provide isothermal forced airflow for cooling. The authors concluded, based on survey's results, that the chair provided an acceptable ambient temperature at 30°C. Kogawa et al. [15] tested ventilated chairs in an office. The chair had two air nozzles installed on both armrests. Results showed that the ventilated chair could keep occupants comfortable at 27ºC, cooling the occupant up to one unit on the seven-point thermal sensation scale. Brooks and Parsons [16] tested in cool environments a car seat heated with encapsulated carbon fabric. They reported improved overall thermal comfort at ambient temperatures below 20°C. Zhang et al. [17] tested a car seat whose surfaces were both heated and cooled by water tubes, extending the drivers' range of acceptable ambient temperatures 9.3 °C downwards and 6.4 °C upwards.

Pasut et al. [10] tested a chair with thermo-electric devices providing heating and cooling in the surface of the seat. The chair improved subjects' thermal comfort and thermal sensation in a range of temperatures from 16°C to 29°C. Some subjects reported an unpleasant sensation at 29°C coming from contact with the cold surfaces of the chair's back and seat.

The Center for the Built Environment (CBE) at UC Berkeley has developed a new type of heated and cooled PCS chair with highly optimized energy efficiency. The goal of this study is to quantify its comfort performance and determine the range of ambient temperatures within which its users are comfortable.

2 Description of test chair

The CBE heated/cooled office chair (here referred to as 'PCS chair') uses a maximum of 16 watts for heating and 3.6 watts for cooling. With such low energy consumption the chair can operate for multi-day periods on a battery that is recharged at night when the chair is not in use. The chair is made from a conventional mesh chair into which three fans are integrated into the seat and back, and two electrical heating elements are sewn into the mesh (Figure 1). The fans are positioned within plenums, lined with a reflective foil material, that enclose the seat and back. Cooling is by isothermal air movement parallel to the user on the plenum side of the mesh. The chair's fans were selected for their low energy use, noise level (at max velocity 19.8 dbA), and lack of vibration. In cold conditions the heating elements conduct heat to quite localized areas of the occupant's back and seat, and the reflective plenum lining returns to the body radiant heat lost from the heating elements and the body surface itself. The chair can have fabric covers stretched over the chair's mesh seat and back surfaces to provide variety in visual appearance and tactile texture. The chair has a switch with settings for heating, cooling, or off, and the power level is controlled by a knob.

Measurements with a segmented thermal manikin show that in maximum cooling mode, the PCS chair's active elements increase whole-body sensible heat loss by 12-30W over that of a typical mesh chair. The difference in body heat extraction depends on the nature of the PCS chair's fabric cover. The chair's coefficient of performance (COP; body heat extracted/electrical power in) is therefore 3 to 8 in cooling mode. In heating mode, the reduction of whole-body heat loss relative to that of a typical mesh chair is around 14W at maximum input power (16W).

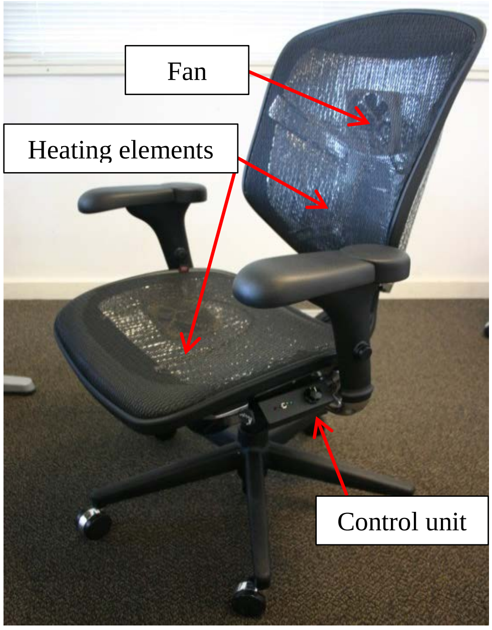


Figure 1a: Mesh PCS chair

Figure 1b: Covered PCS chair

3 Methods

3.1 Subjects and test conditions

Human subjects using the PCS chair had their comfort evaluated under three different room air temperatures: 16°C, 18°C and 29°C. The relative humidity of the chamber was kept at 50% ±1%. The air velocity was less than 0.1 m/s. Twenty-three subjects (12 females and 11 males) participated in each of the three test conditions, for a total of 69 tests. The subjects were selected with a normal (healthy weight) body mass index (BMI). The BMI of the sample ranged from 19.4 to 24.8, and the age from 19 to 32. Sample size and subjects characteristics are comparable to those in previous studies. In order to reduce cultural differences, only subjects who lived in US at least for the last three years were selected.

Four workstations were installed in the Controlled Environmental Chamber at UC Berkeley (Figure 2). The chamber has a dimension 5.5 m × 5.5 m × 2.5 m, windows on both sides, resembling a realistic office environment. The triple-glazedwindows are well shaded by fixed external shades. The temperature of the inner glass pane is controllable and was kept isothermal with the interior. Subjects were instructed to dress in light summer clothing (T-shirt, long pants, and a pair of light shoes, 0.5 clo), and for the cold conditions they were provided a thick long-sleeve shirt to increase their clo value to 0.8. During the tests the subjects were allowed to adjust the heating or cooling levels of the PCS chair using the controls on each chair. They were asked to perform computer-related activities, including their own assignments, during the tests.

Figure 2 Chamber set up

3.2 Test schedule

The experiments were carried out at CBE between October 2013 and December 2013.

Two types of tests were conducted:

- Long test of 135 minutes: This test was used only at the 29°C and 16°C chamber temperatures. The test was divided in four thirty-minute periods separated by five-minute breaks. Upon their entrance into the chamber subjects were asked to sit on the test chair, and adjust its power according to their preferences. The first 30-minute period was used to let subjects stabilize. Two of the four chairs were equipped with the fabric cover over the mesh. During the second 5-minute break (between the second and third 30-minute period) the chair positions were switched, so subjects who were using covered chairs in the second period used uncovered chairs during the third period, and vice-versa. During the breaks the subjects would stand, and in the middle of the break period, they took 12 vertical steps on a 22-cm high step-stool. This was to simulate the metabolic increase that occupants experience when moving about away from their desks in actual office environments. The final thirty-minute period was used to test additional climate-adaptive measures. For the warm tests at 29°C subjects were provided a 1.2-watt USB-powered desk fan, and for the cool test at 16°C the subjects were allowed to wear an extra layer for the torso (a sweatshirt) if they wished, in order to reach a total insulation of 1.0 clo.

Figure 3 shows a schematic representation of the long test schedule.

- Short test of 100 minutes: Used only at 18°C, this test is identical to the previous option, except that it omitted the final 35 minute section in which the subjects used fans or wore extra clothing.

The survey questions automatically appeared on subjects' computer screen based on pre-set schedules (Figure 3).

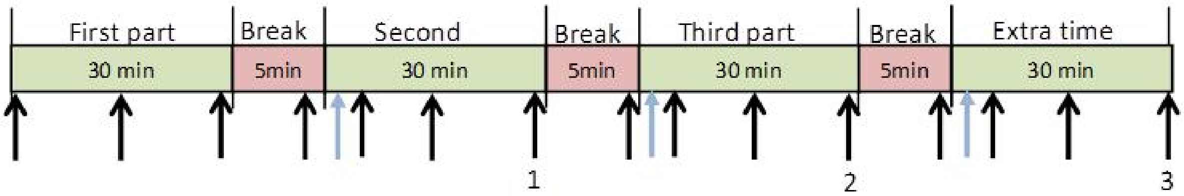


Figure 3 Test schedule. Black arrows indicate times when the surveys were administrated. 1,2,3 represent the surveys used in the statistical analysis. Blue arrows are described in text below.

3.3 Survey questions

The survey questionnaires included whole-body thermal acceptability, perceived air quality, thermal sensation, preferred thermal sensation, thermal comfort, air movement acceptability, and preferred air movement. To better understand the impacts of chair on individual body parts, thermal sensation, preferred thermal sensation, and thermal comfort questions were asked independently for the local body parts: back, gluteal region, head, chest, and feet.

A survey question example is shown in Figure 4.

The light blue arrows in Figure 3 represent a series of four short surveys, one every minute, that focused only on the whole body thermal comfort and thermal sensation, and on the regions mostly affected by the chair: the back and pelvis. The short surveys were administered right after each break, starting as closely as possible after sitting down. Their purpose was to determine the lengths of time required by the chair to influence thermal comfort and thermal sensation after an occupant has been away from the workstation.

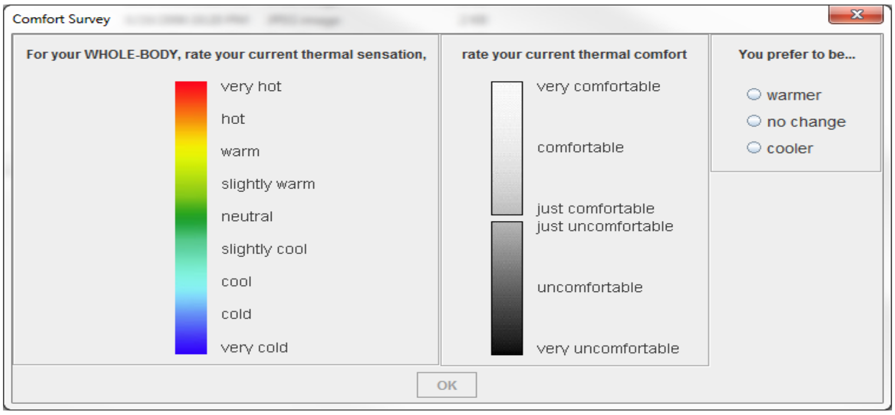


Figure 4 Survey example questions

Similar to Melikov and Kacmarczyk [18], we used two questions to investigate perceived air quality: “Please rate your acceptance of current air quality” and “The air is.”, with a scale for this last ranging from ‘fresh’ to ‘stuffy’. Each acceptability scale is a continuous scale [19], ranging from “clearly acceptable” (+1) to “clearly unacceptable” (−1), and split in the middle with two labels “just acceptable” and “just unacceptable”.

4 Results

4.1 Whole body thermal sensation and comfort

The authors had previously tested a thermoelectrically heated and cooled chair against two conventional office chairs, in the identical environmental conditions as this study. The two conventional chairs, one meshed and one cushioned, produced almost identical thermal comfort responses in the occupants [10]. As the current study followed the same test procedures and conditions as the earlier study, the earlier study's results for the conventional chairs are used in this paper as reference conditions for the tests of this new chair.

Statistical analysis was performed with a non-parametric method called permutation test, using the software R [20] . In the graphs the red symbol "*" represents a statistically significant difference ($p<0.05$). Each configuration was compared against the others. The big "*" shown below the reference condition boxes indicates that all the differences between the reference configuration and the PCS chair configurations are statistically significant.

The results for the whole body thermal sensations and whole body thermal comfort, for the three environmental conditions, are presented in Figure 5 and Figure 6.

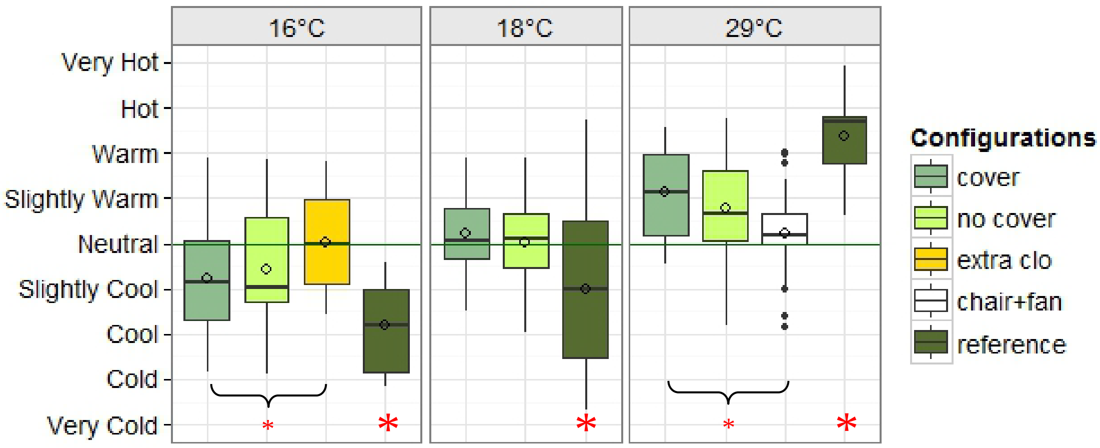


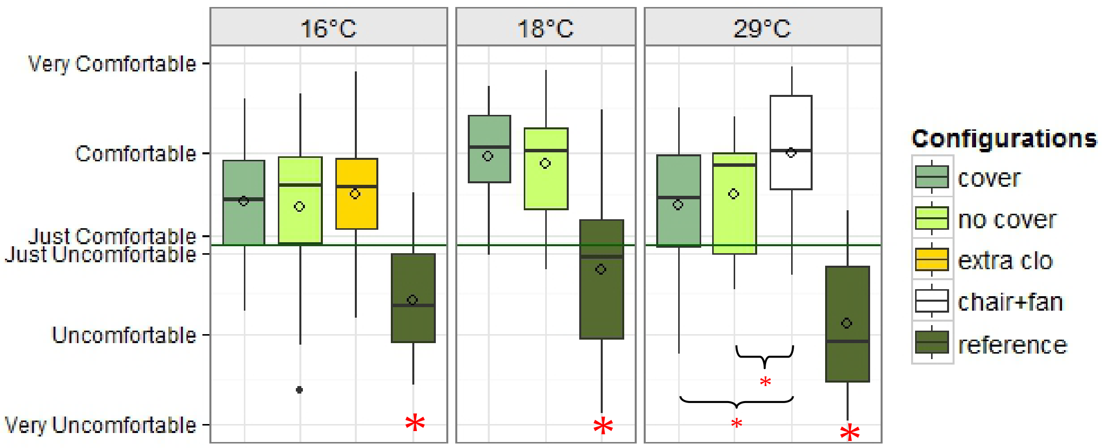
Figure 5: Whole body thermal sensation. 'cover' refers to the fabric cover over the chair's mesh surfaces. 'extra clo' refers to the additional clothing layer. 'chair + fan' refers to the use of the desk fan.

Figure 5 shows that, compared to the reference conventional chair, the PCS chair affected whole-body thermal sensation by 1 to 2 thermal sensation scale-units under each of the three environmental conditions. This strong effect occurred even though the chair's heating and cooling is applied only to local portions of the body.

At 29°C the use of the small desk fan enhanced the effect of the PCS chair, moving the thermal sensation toward neutrality. At 16°C the combination of the PCS chair and the extra clothing layer (extra clo) also moved the sensation towards neutral.

There is no statistically significant difference between the chair with and without a cover, at any of the three temperatures. The cover's thin cloth layer between the body and the chair's seat and back does not significantly degrade thermal sensation for either heating or cooling. The differences seen are each in the expected direction, in that the cover does slightly reduce the chair's heat transfer for both heating and cooling.

Adding the sweatshirt produced a statistically significant difference between the configurations "cover" and "extra clo", and a p value close to significance (0.07) between "no cover" and "extra clo". The effect of the cloth chair covering is again present but small.



Comfortable rate (%) 74 74 78 18 91 91 31 74 70 91 19

Figure 6 Whole body thermal comfort.

In Figure 6 the whole-body thermal comfort votes are presented for the three different environmental conditions. Below the name of each configuration, the figure shows the percent of votes on the comfortable side of the scale. The PCS chair improved the whole-body thermal comfort effectively under all the test conditions.

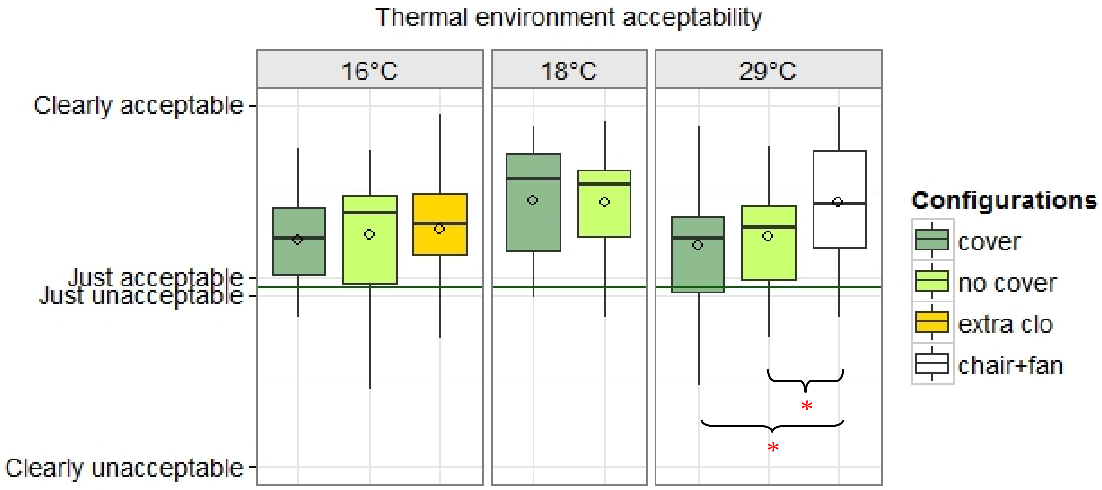
At 16°C the PCS chair increased the percentage of subjects who voted in the comfortable range from 18% for the reference case to 74%. Although there was a difference in overall thermal sensation between the configurations “cover” and “extra clo” (Figure 5), this difference did not affect the whole-body thermal comfort.

At 18°C the PCS chair also improved thermal comfort (Figure 6), raising the percentage of comfortable vote from 31% to 91%.

The thermal comfort results at 29°C are analogous to the thermal sensation results seen in Figure 5. The chair itself had a strong effect on thermal comfort, and the combination of PCS chair and USB-powered desk fan resulted in a very high percent of subjects’ positive thermal comfort votes, reaching 91%.

4.2 Thermal environment acceptability

During the tests the subjects were asked to rate the acceptability of the thermal environment. The results are presented in Figure 7. For this specific question we could not use the results from the previous study as reference, since the acceptability question had not been included in its questionnaire. The majority of the answers are located on the positive side of the chart, showing that the chair creates an acceptable environment for each of the conditions. Also for this question the configuration “chair+fan” performed particularly well.



Acceptability rate (%) 74 74 78 87 91 70 74 91

Figure 7 Thermal environment acceptability

4.3 Local thermal sensation and comfort in the back and pelvis area

Specific questions were asked for the body parts most influenced by the PCS chair's heating and cooling—the back and pelvis. Figure 8, Figure 9, Figure 10, and Figure 11 respectively report the results for back thermal sensation, back thermal comfort, pelvis area thermal sensation, and pelvis area thermal comfort.

The presence of the cloth cover on top of the chair's surfaces had no statistically significant effects on thermal sensation and thermal comfort for subjects' back and pelvis area.

For the test conditions at 29°C, the configuration "chair+fan" is statistically different in terms of back and pelvis thermal comfort compared with the configuration "cover" (Figure 9 and Figure 11). The overall improved thermal comfort with the fan (Figure 6) appears to have impacted perceived comfort for these local body parts, even though they are not directly cooled by the fan.

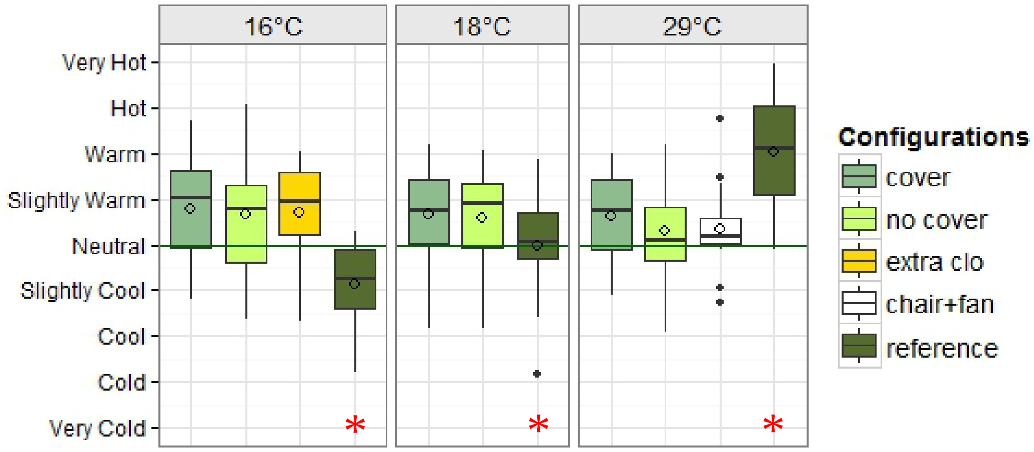


Figure 8 Back thermal sensation

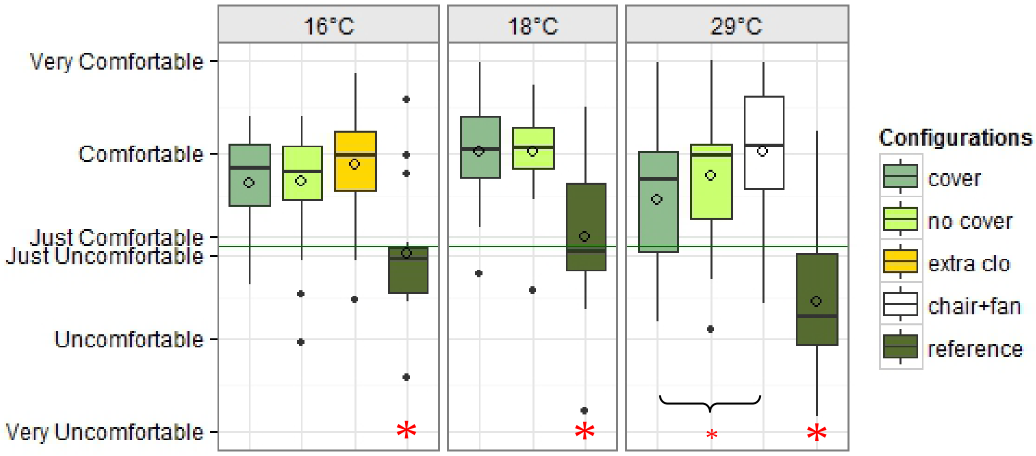


Figure 9 Back thermal comfort

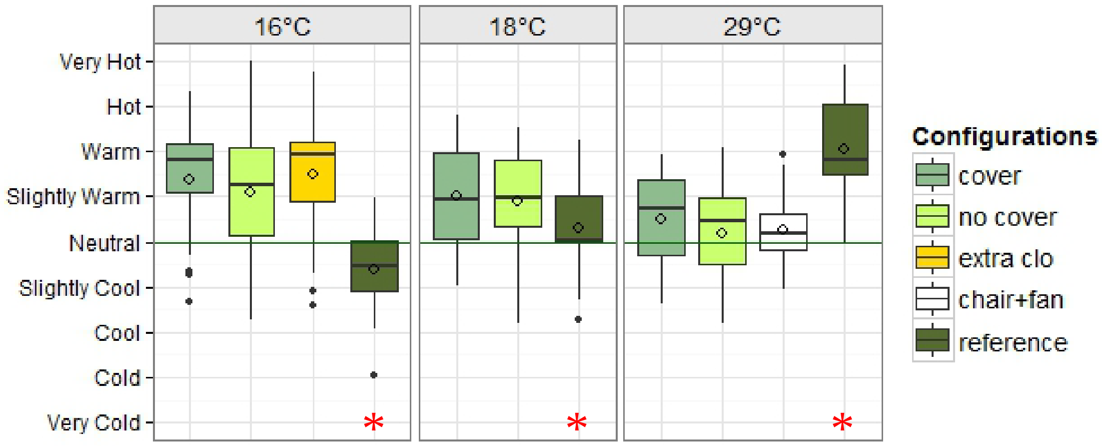


Figure 10 Pelvis area thermal sensation

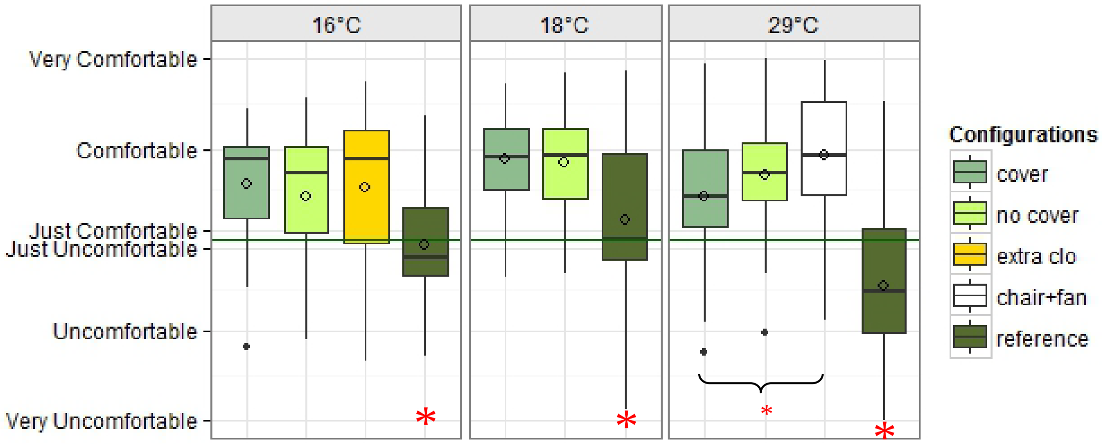
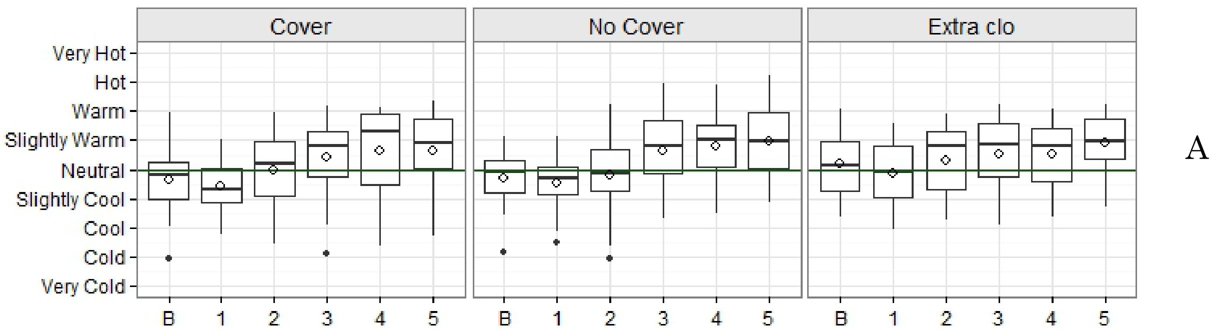


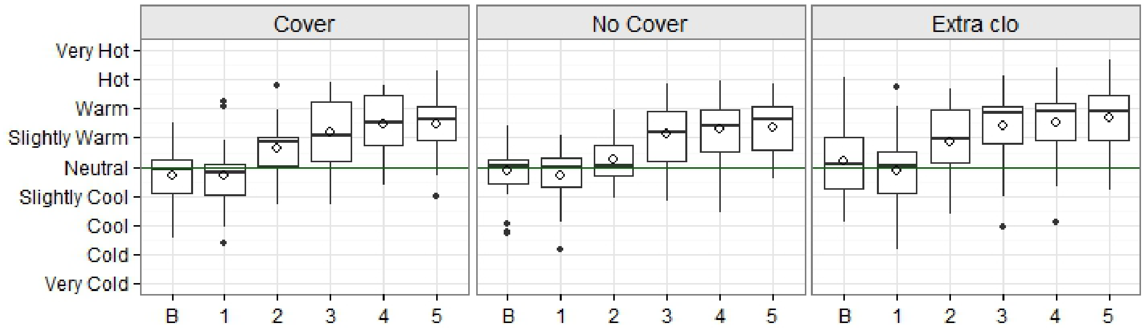
Figure 11 Pelvis area thermal comfort

4.4 Transitory experience

Immediately after the subjects returned to the PCS chair following the breaks, a short survey was administrated each minute for five minutes. It was administrated to assess how quickly the PCS chair re-establishes comfortable conditions after a break. Together with questions about whole-body thermal sensation and comfort, the short survey focused on the body parts mostly affected by the chair: the back and pelvis area.

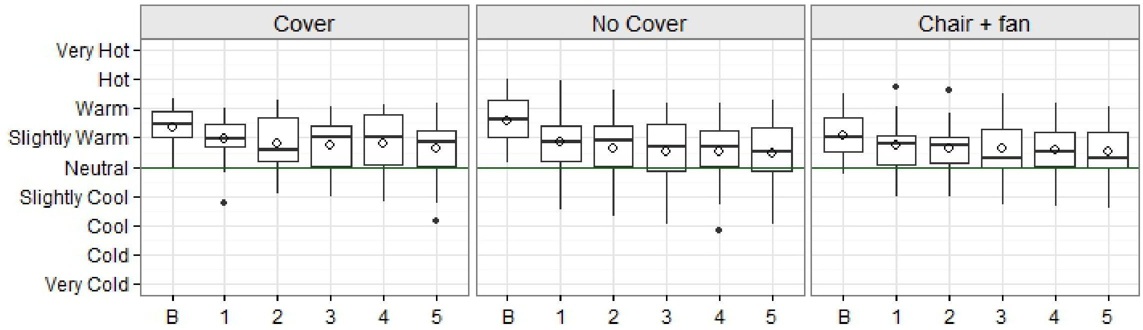
Figure 12 and Figure 13 report the back and pelvis thermal sensations for test configurations at 16°C and 29°C respectively. The letter "B" in the abscissa represents the result from a survey administrated at the very end of the break time, before the subjects were asked to sit down on the PCS chair. The five numbers after the letter "B" represent, in sequence, the five short surveys administrated after the subjects sat down. The time between each survey, and between "B" and "1", is one minute.



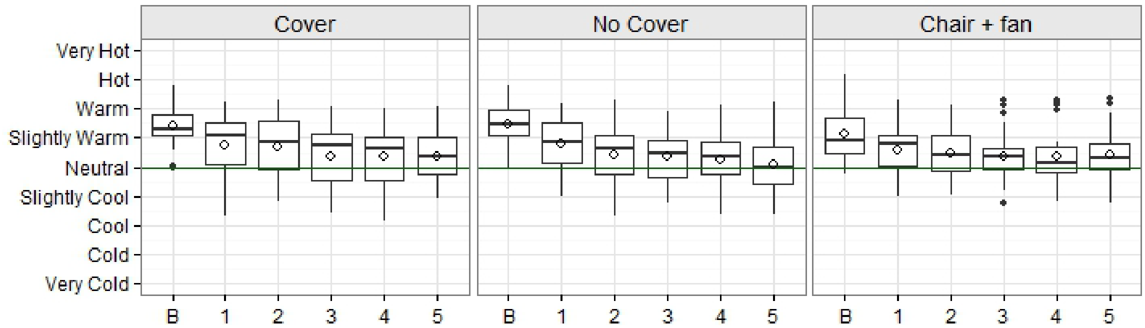


B

Figure 12 Transient at 16°C. A) Back thermal sensation B) Pelvis area thermal sensation



A



B

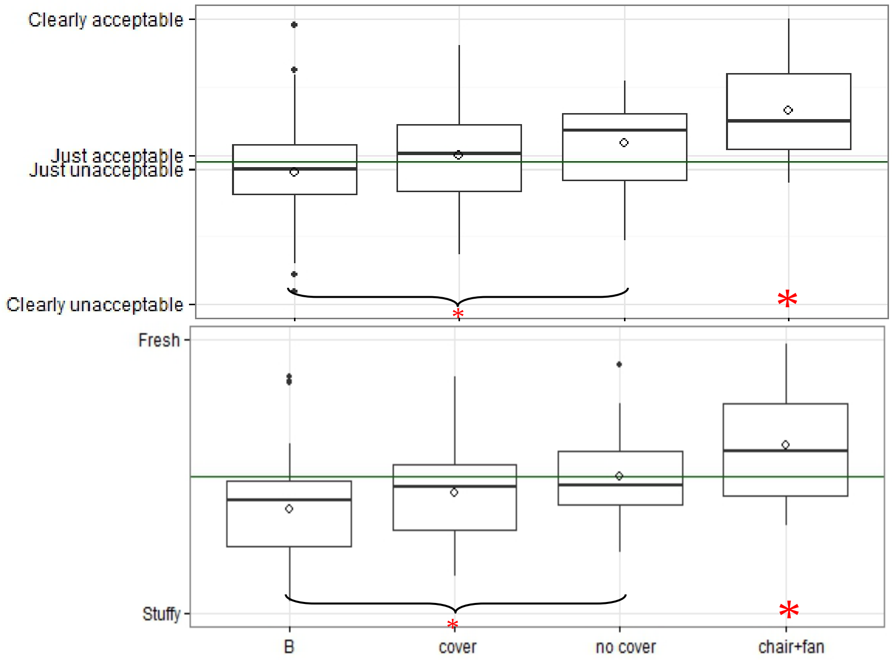
Figure 13 Transient at 29°C. A) Back thermal sensation B) Pelvis area thermal sensation

With the chair in heating mode (Figure 12), the subjects' thermal sensation decreased slightly during the first minute after the break, changing its trend during the second minute, when a clear improvement occurred. With the third minute the thermal sensation became stable. The chair has an occupancy sensor, which turns off heating and cooling when un-occupied. Upon the sitting, the heating tape started to be heated and it appeared that it needed about one minute before the subjects felt its warmth. The reduction in metabolic level associated with sitting down causes the initial cooling, which is then counteracted by the chair's heating.

The PCS chair's ability to modify thermal sensations is stronger in cooling mode (Figure 13). The subjects' thermal sensation was improved within the first minute after the break. Upon sitting and activating the fans, the convective cooling effect was perceived almost instantaneously by the subjects. The cooling effect is aided by the reduction in metabolic rate associated with sitting down.

4.5 Perceived air quality

Because perceived air quality decreases in warm environments, it is analyzed here for the 29°C test condition. The chamber's outside air supply rate ranged between 85 and 104 L/s, so with four subjects plus one experimenter in the chamber, the fresh air ventilation was 17 to 21 L/s per person. The outdoor air quality was excellent and with the high outside air rate the actual indoor air quality was very good. In Figure 14 the results for "air quality acceptability" and "perceived air freshness" are reported. The votes for each chair configuration are compared with the votes from the break ("B"), when subjects were away from the chair and the desk fan. The comparison may indicate how the PCS chair affected subjects' air quality perception. (These questions were not asked in the previous study of the conventional reference chair [10], so the perceived air quality could not be compared to a reference condition).



A

B

Figure 14 A) Air quality acceptability at 29°C.   B) Air freshness

Based on Figure 14 A and B, the configuration "chair+fan" reported the best perceived air quality. This result is in line with other previous studies [18,21-23], showing that in a warm environment some air movement direct on occupant's face not only improves comfort and thermal sensation, but also perceived air quality.

There is a statistically significant difference between the configurations "no cover" and "B", while there is no difference between "B" and "cover". This difference may be related to some air escaping the uncovered PCS chair plenums, and thereby entering the subjects' thermal plumes and breathing area.

5 Discussion

5.1 Whole-body thermal comfort and thermal sensation

The PCS chair has a strong effect on subjects' overall thermal sensation (Figure 5) and thermal comfort (Figure 6). Zhang [24] defined the "most influential group" of body parts affecting thermal comfort as the back, chest, and pelvis. She showed that sensation from these body parts has a dominant impact on overall sensation. The PCS chair affects two of these three influential body parts. This may explain the strong influence that it had on subjects' whole-body thermal sensation.

The small differences in thermal comfort and thermal sensation results for the PCS chair with and without cover show that the chair's predominant cooling effect comes from air moving inside the plenum, parallel to the human body, rather than air escaping from the plenum through the mesh fabric. The thin and smooth fabric layer used to cover the chair's surfaces added little thermal resistance between the human body and the chair plenum.

At 29°C, the best results were obtained for the combination of PCS chair and the USB-powered desk fan (see Figure 6). The difference in thermal comfort between the configurations with PCS chair only and "chair+fan" may be related with subjects' need for more air movement at the face/head level. Zhang [24] showed that cooling the head was critical to comfort in warm/hot conditions. The desk fan, by cooling the subject's faces, reduced or eliminated thermal discomfort related with this body part and the whole body. This is seen in Figures 15A and 15B where the results for the questions "rate your face thermal sensation" and "rate your acceptance of the amount of air movement" are reported respectively. The numbers below the charts represent the percent of subjects who asked for more, no change, or less air movement. For the two configurations without desk fan, the subjects' face thermal sensation votes have a mean and median value between "slightly warm" and "warm", while for the configuration with the desk fan the values are closer to neutral. The amount of air movement in the chamber was rated poorly for the two configurations with the PCS chair alone, 96% of them preferring more air movement (Figure 15B). The 1.2-watt desk fan raised the percent of subjects who wanted "no change" in air movement from 4% to 66%.

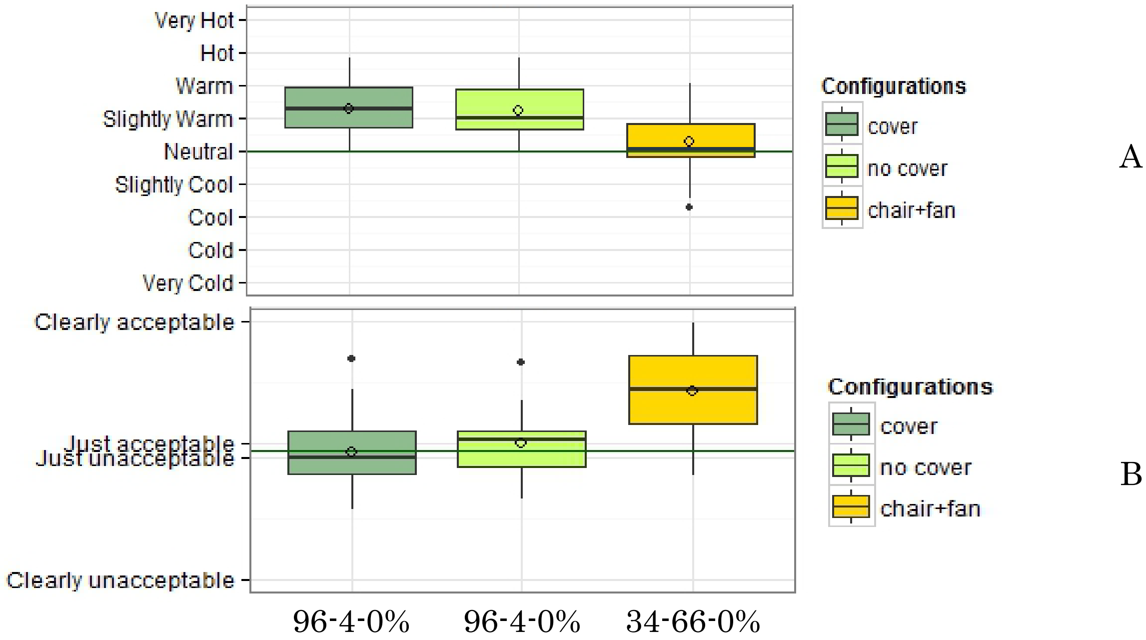


Figure 15A) Face thermal sensation at 29°C, 15B) Air movement acceptability at 29°C. Lower axis: percent of subjects who wanted "more-no change-less" air movement.

5.2 Gender Effect

In all the test conditions, subjects had control of their chair heating and cooling levels, so this study allows a comparison of the chair's temperature-correction capability for men versus women. Evaluating each test condition individually, the thermal sensation and comfort responses of females and males showed no significant differences at any of the temperatures. However, the dataset was small for comparing subgroups with small differences. By combining the two conditions 'cover' and 'no cover', the dataset is doubled. Doing this adds some variation into the test chair's h/c capability, which is always slightly less with the cover. It would represent situations where there was an equal mix of covered and uncovered chairs in an office. Figure 16A and B show that there is a small significant difference in men and women's comfort at 16C, even though there is no significant difference in thermal sensation at any temperature.

These charts show that the experiment has tested the limits of the chair's corrective power (when the chair is the only personal conditioning option available). More than 30% of women are voting 'uncomfortable' at 16C, and more than 20% of both men and women are uncomfortable at 29C. Around 20% of women are below 'cool' (scale -2) at 16C, and more than 20% of men are beyond 'warm' (scale +2) at 29C.

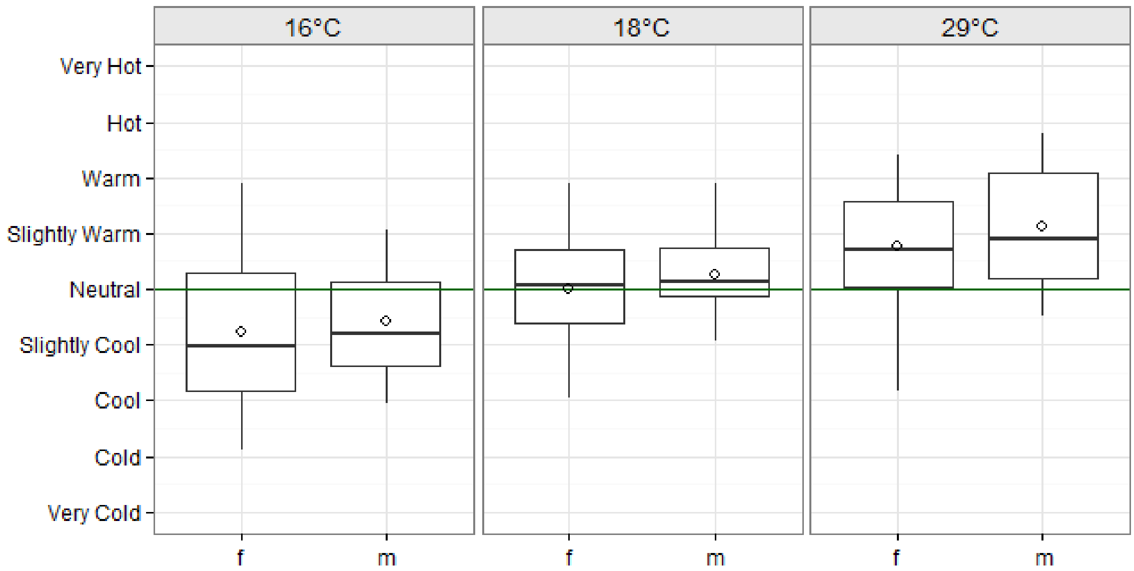


Figure 16A Comparison of thermal sensation responses between females and males Configurations "cover" and "no cover" analysed together

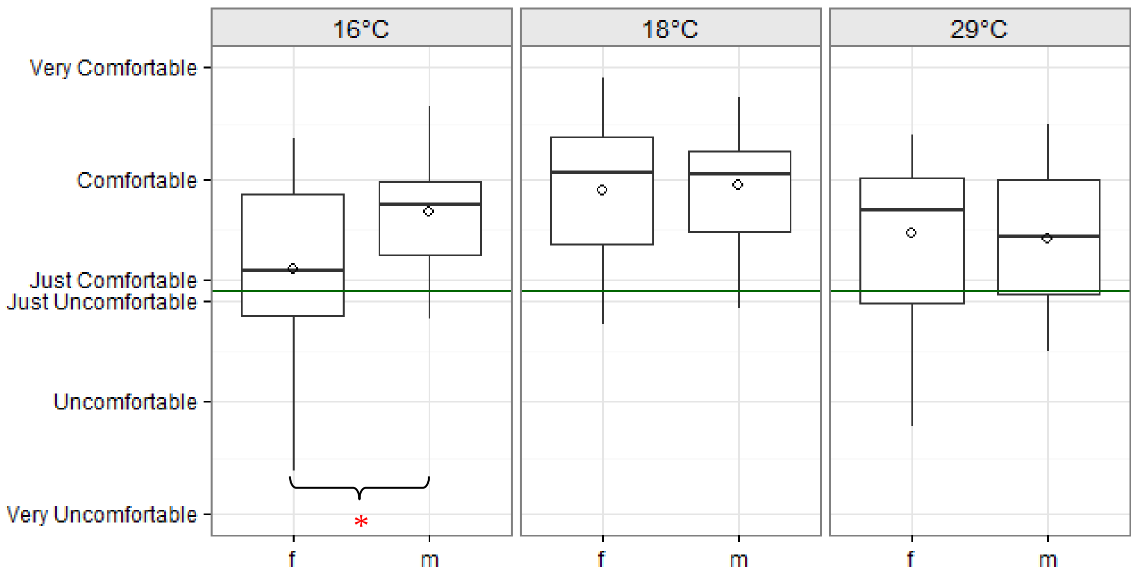


Figure 16 B Comparison of thermal comfort responses between females and males. Configurations "cover" and "no cover" analysed together

Parsons [25] found that women vote cooler than men in cold conditions (15°C, 18°C) and the same as men in neutral and warmer conditions. This study shows these trends throughout.

5.3 Comparison with a different type of heated/cooled chair

The reference chair data described above came from a previous study done by the authors. This study's purpose was to characterize the effectiveness of an office chair with same shape and support structure as the present one but heated and cooled with thermoelectric (TE) devices under a tightly woven fabric surface. The subjects in that study were given an exit survey at the end of each test to better understand their responses to the TE chair, and there was some dissatisfaction in cooling mode. Although the chair had been able to adequately cool the users, some of them did not like the feeling of sitting on a cold surface in a warm environment. Since the PCS chair uses only convection at room temperature to cool its surfaces (and thereby the subjects' clothing and skin surfaces), it is instructive to compare the 29°C results for the TE chair with those of this study (see Figure 17, Figure 18, and Figure 19). The analysis considers only the differences between the TE chair (labeled 'Pasut et al (2013)') and the different configurations of PCS chair.

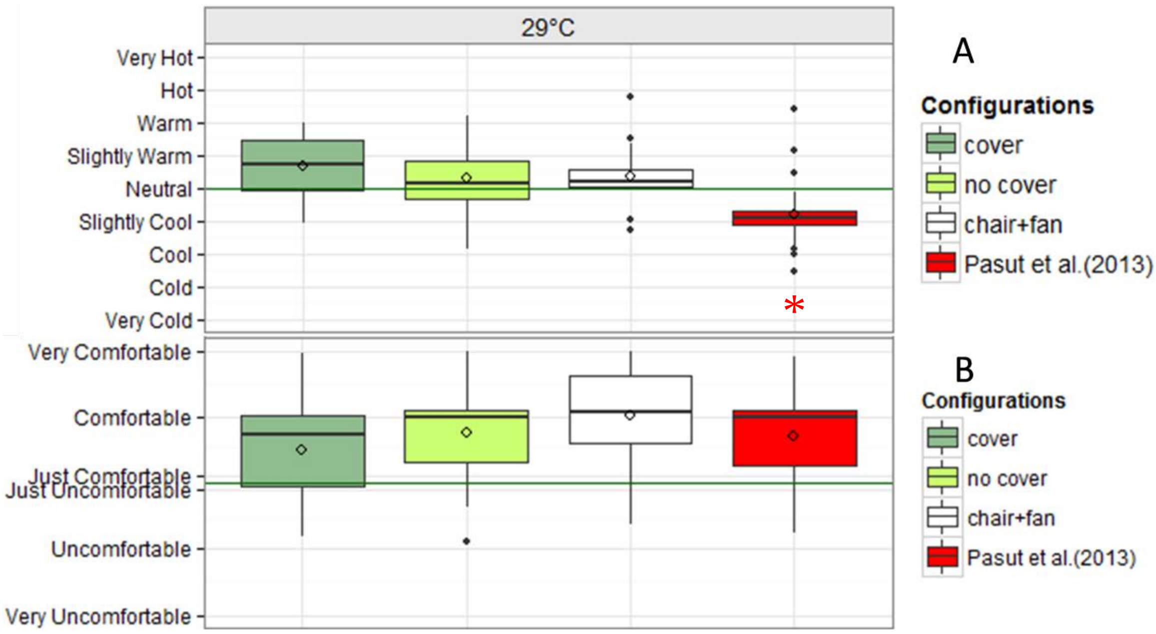


Figure 17A) Back thermal sensation, 17B) Back thermal comfort

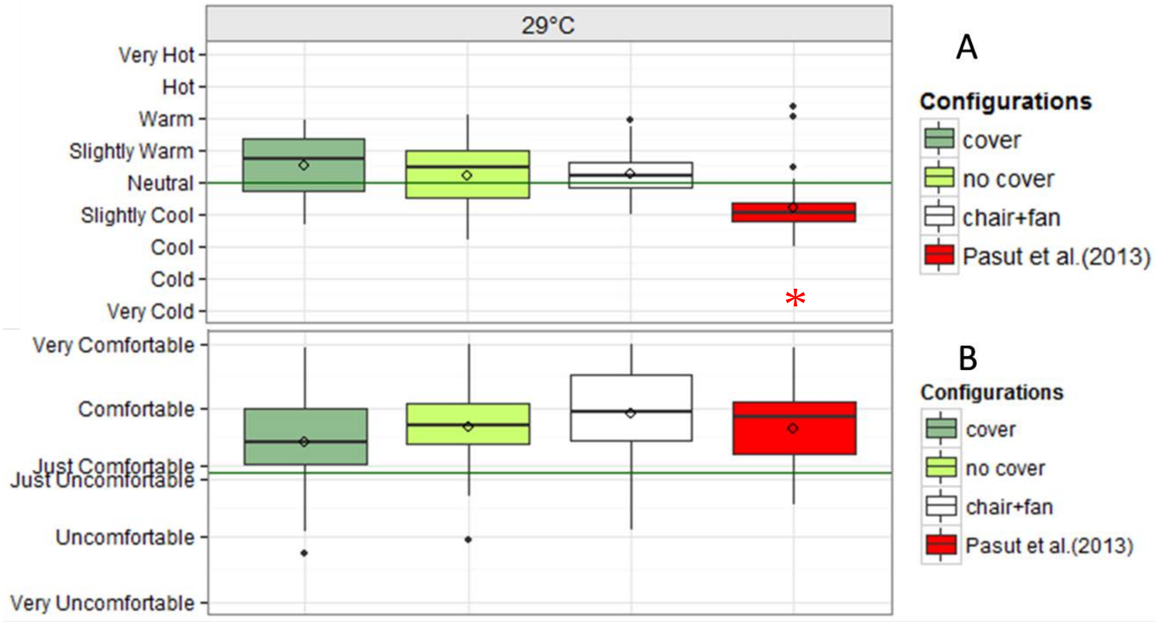


Figure 18A) Pelvis area thermal sensation, 18B) Pelvis area thermal comfort

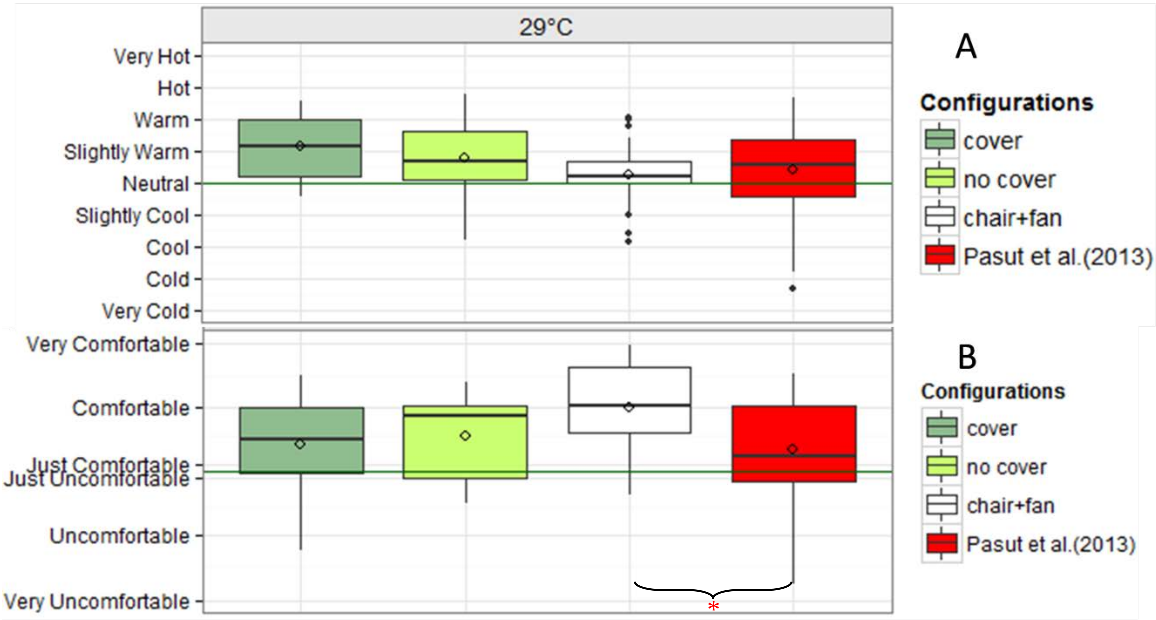


Figure 19A) Whole body thermal sensation, 19B) Whole body thermal comfort

It can be seen that the back and pelvis thermal sensations (Figure 17A and 18A) are significantly cooler for the TE chair than for the three configurations of the PCS chair. On the other hand, local thermal comfort (Figure 17B and 18B) is not significantly different. There is little difference in whole-body sensation or comfort that cannot be attributed to the desk fan

(Figure 19A and B). From the exit survey comments, it may be that some subjects object to the cool tactile sensation of the TE surface, but this is not reflected in the comfort results.

5.4 Experimental realism

The natural evolution of this work is toward systematic field tests. Such field tests provide larger and more realistic samples of office occupants and their environments. For example, the age distribution in an actual office will be greater than in these laboratory tests, and other factors such as body mass and activity level are likely to be more realistic. Similarly, the experience of working all day in different types of buildings can be captured.

The authors are now performing three field studies of the PCS chair, one each in: an uncooled naturally ventilated building, a mechanically cooled building without operable windows, and a radiantly cooled building without operable windows. In the HVAC buildings the temperature setpoints are varied as part of the experiment. HVAC energy and thermal environment are monitored, and the subjects surveyed repeatedly through warm and cool seasons. These tests will help establish the practical feasibility and limits of operating actual office buildings with a combination of PCS devices and relaxed central HVAC control.

6 Conclusions

The PCS chair plus the small desk fan is seen to provide comfortable conditions for more than 90% of the subjects in a range of temperatures from 18°C to 29°C, and around 75% at 16°C. The potential energy consequences in real buildings are large: an 11°C setpoint deadband — under which 90% of PCS chair users are seen to be comfortable — yields an energy saving of more than 50% in many climates [5,6]. The energy saving is not significantly offset by the chair energy consumption, which is tiny compared to central HVAC. The chair system's maximum power is 4.8 watts for cooling (3.6W for the chair plus 1.2W for the desk fan) and 16 watts for heating, and power is drawn only when occupied. The same amount of heating and cooling from central HVAC requires 500-1,000W per occupant, and for central HVAC the power is on all the time.

The PCS chair is capable of providing comfortable conditions quickly upon sitting down: within two minutes in heating mode, and instantaneously in cooling mode. It also provides each individual occupant the ability to adapt according to their personal thermal characteristics.

By convectively cooling the chair contact surfaces with room-temperature air, the chair avoids overcooling the back and pelvis area in warm environments. The fan has a dramatic effect on air movement preference in the warm condition, as well as on perceived air quality. There were no significant differences between the responses of women and men, perhaps because of adaptive opportunities provided to each occupant by the chair, clothing, and fan.

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