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Energy and Buildings 113 (2016) 15–22

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

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ARTICLE INFO

Article history:
Received 21 September 2015
Received in revised form
30 November 2015
Accepted 10 December 2015
Available online 12 December 2015

Keywords:
Local cooling
Individual climatization
Overheating
Thermal comfort
Thermal sensation
Occupant satisfaction

ABSTRACT

Public and commercial buildings tend to overheat. Recent studies indicate individual comfort systems based on local climatization can improve occupant satisfaction and simultaneously decrease the energy load of buildings. This study evaluated the effect of local cooling in both women and men on indicators of occupant satisfaction: thermal sensation, thermal comfort and skin temperatures.

All measurements were conducted in a climate chamber (Priva, the Netherlands) with an ambient temperature of $32.3 \pm 0.3\,^{\circ}C$ (mean $\pm$ SD). In total, 16 healthy young men and women were exposed to different local cooling conditions for 45 min: face cooling, back cooling, underarm cooling, foot sole cooling and 30 min of combined face-underarm cooling. The cooling conditions were separated by 30 min of 'no cooling'. Thermal sensation and thermal comfort were evaluated with VAS-scales. Skin temperatures (26 sites) were measured using wireless temperature sensors. 'Face cooling' and combined 'face-underarm cooling' significantly improved thermal sensation and comfort compared with 'no cooling' for both women and men. Women had significantly higher skin temperatures compared with men.

Local cooling of the face alone and face and underarms combined are effective ways to improve thermal sensation and thermal comfort in a warm thermal environment.

1. Introduction

One third of the primary energy supply is used for the ventilation and air-conditioning of commercial and public buildings; mainly to achieve occupant satisfaction [1]. Nevertheless, thermal comfort is often not achieved. In addition, the overheating of buildings became a hot topic in the Western world in the recent years [2,3]. The risk of overheating is a consequence of a combination of very high insulating construction materials and the heat load of occupants and equipment. Moreover, global warming worsens the scenarios. As a result of the overheating problem, the energy demand of buildings rises to ensure thermal comfort for the occupants. To prevent energy costs from increasing and simultaneously keeping occupants satisfied, efficient and creative low-energy cooling techniques are needed. It has been suggested that individualized comfort systems might be promising alternatives to overall air conditioning, especially for those buildings/building areas that host largely sedentary occupants (e.g. offices and open plan offices) [4–8].

Today, many buildings have a tightly controlled indoor climate as determined by the ASHRAE Standard 55 and ISO Standard 7730, based on Fanger's predicted mean vote model (PMV) [9–12]. Creating a thermal environment conforming to these standards means that very little ambient temperature variation is tolerated. Since a large number of building occupants report thermal discomfort, even though the recommendations of the standards are met, the question is whether these (PMV-) standards are actually suitable.

The large level of perceived discomfort (especially in summer [13]) might be due to significant inter-individual differences in the thermal sensation and thermal comfort of building occupants: physiological parameters such as sex, age, body composition, metabolic rate, insulation, acclimation, behavioral parameters such as physical activity and clothing behavior, and individual preferences for ambient temperature might have a considerable effect on an individual's perception of the thermal environment [14,15]. A study among young Europeans indicated that the preferred ambient temperature may vary by as much as $10\,^{\circ}C$ [38].

Recent investigations confirmed that individually attuned comfort systems have the potential to save a significant amount of energy (up to 50% compared with overall air-conditioning), and

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http://dx.doi.org/10.1016/j.enbuild.2015.12.016
0378-7788/

improve individual occupant satisfaction [7]. Applying individually attuned local cooling may allow an increase in overall indoor temperature without negatively affecting the occupant's thermal comfort. Moreover, individualized local cooling provides the possibility for building occupants to create their own preferred thermal environments tailored to their individual needs at a given moment.

To optimize the design of individual local cooling systems, it is necessary to evaluate the impact of different local cooling conditions and different target regions of the human body (actuators) on thermal comfort. Furthermore, regarding the anticipated automated control of individual local cooling systems ('human in the loop' comfort systems), it is important to study possible indicators, i.e. physiological parameters (e.g. local skin temperature) that correlate to thermal comfort. Considering the overheating problem we introduced above, we especially focused on the optimization of occupant comfort in a warm environment. It is crucial to evaluate the individual response of women and men with respect to local cooling in mild heat, since there is barely any data available. Moreover, there is lack on information about the response and effectiveness of different cooling conditions on physiological parameters and thermal comfort of women and men.

We hypothesize that individualized local cooling can effectively improve occupant thermal sensation and comfort in a warm environment. Accordingly, this study aims to:

1. Evaluate the effect of five different local cooling conditions (actuators) on whole-body thermal sensation, thermal comfort and skin temperatures of young, healthy volunteers in a warm thermal environment
2. Identify sex differences in whole-body thermal sensation, thermal comfort and skin temperatures with respect to local cooling in a warm thermal environment
3. Identify potential physiological indicators of whole-body thermal comfort in a warm thermal environment.

2. Methods

2.1. Facilities

The experiment was established in a climate chamber that is located at the laboratory of the 'Priva' company (De Lier, the Netherlands). The chamber dimensions are depicted in Fig. 1. During the experiments, the average ambient air temperature was 32.3 ± 0.29 °C (mean ± SD, as shown in Section 2.5). Air temperature was kept stable by a combination of radiant heating and air conditioning. Floor, ceiling and three walls (Fig. 1) of the climate chamber were built of water-perfused aluminum panels. Water temperature of ceiling and floor panels was set at 29 °C; wall panel water temperature was set at 32 °C and ingoing airflow was set at 35 °C. Relative humidity was not controlled in the present setting. On average, relative humidity was 29.3 ± 3.42%.

2.2. Participants

Sixteen young, healthy volunteers, 8 men and 8 women, participated in the study. Before informed consent was obtained, the participants were provided with detailed information concerning the experimental procedures. Importantly, no information was provided about the conditions and ambient temperature they were exposed to. All participants were normotensive and non-obese. Four women were on oral contraceptives; all other participants did not take any medication that might alter their cardiovascular, hormonal or thermoregulatory responses to temperature changes. Participant characteristics are provided in Table 1.

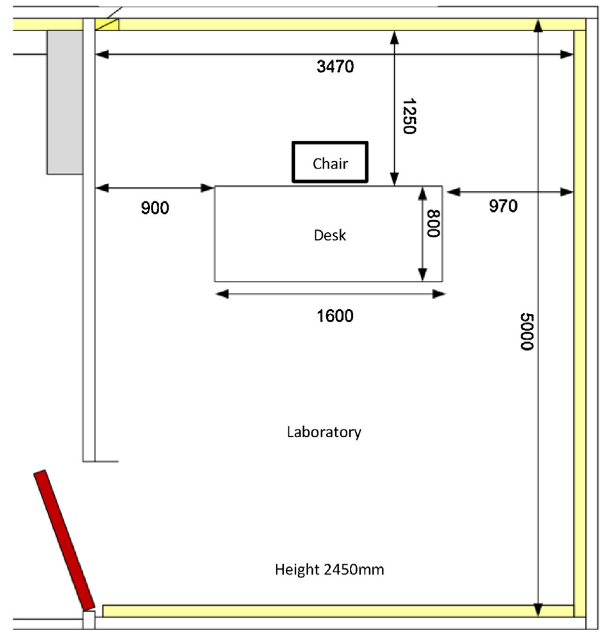

Fig. 1. Laboratory dimensions and desk position. The yellow surfaces indicate water-perfused aluminum wall panels; the ceiling and floor consisted of water-perfused aluminum panels as well. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Participant characteristics.

	Mean ± SD	Minimum	Maximum
Age [years]	23.5 ± 3.5	20	32
Height [m]	1.79 ± 0.11**	1.57	2.00
Weight [kg]	69.1 ± 9.8*	56.5	92.9
BMI [kg/m^2]	21.5 ± 2.1	18.4	25.8

* $P < 0.05$.
** $P < 0.001$ difference between women and men.

2.3. Experimental procedures

Participants visited the laboratory between May and July 2014. Average outside daytime temperature (8:00 AM–8:00 PM) was 16.3 °C [16]. Participants arrived at the laboratory at 8.30AM in the morning. In total 26 wireless skin temperature sensors (iButtons, Maxim Integrated Products, CA, USA) were attached to the their skin with semi-adhesive tape (Fixomull® stretch, BSN medical GmbH, Hamburg, Germany). Participants wore their own underwear and additional standard clothing, which consisted of a loose-fit cotton T-shirt, jogging pants and cotton socks (clo ≈ 0.54) [17]. After preparations were finished, participants entered the climate chamber and sat down on a chair (clo ≈ 0.1, Fig. 2) [17–19].

The experiments lasted for 6 h, and in the meantime, participants were allowed to perform regular deskwork (approximately 1.2 METs). Desk and chair were individually adjustable in height to ensure comfortable sitting posture. During the experiment, participants were exposed to five different local cooling conditions that were provided randomly: (1) 'face cooling', (2) 'underarm cooling', (3) 'back cooling', (4) 'foot sole cooling' and (5) combined 'face-underarm cooling'. The different conditions were separated by a 30-min period of 'no cooling', except for the conditions 'underarm cooling' and 'face-underarm cooling'. These were executed consecutively for practical reasons (Fig. 3 provides an example of the time schedule).

Fig. 2. Experimental setup. The white arrows indicate the outlet of the fan. The outlet position was adjustable in height and angle to individually direct the airflow onto the participant's face.

2.4. Cooling elements and materials

'Face cooling' was conducted using a conventional fan, directed at the participant's forehead region from a distance of approximately 60 cm, depending on the sitting posture of the participant. Set-up and air speed of the fan have been tested and verified in a pilot experiment prior to commencement of the present study. The custom-made fan was positioned approximately 15–20 cm above the participant's head and it supplied regular ambient, non-cooled air. The airflow had a downward tendency to make it more comfortable for the participants' eyes (Fig. 2). The airflow was set at the same steady state for all participants, equaling around 1.28 m/s as measured by a Pitot tube (TA460-P, Airflow instruments, UK) at the outlet of the hose. During 'face cooling', participants were asked to maintain a straight sitting posture to keep their head in the airflow of the fan.

For 'underarm cooling' and 'foot sole cooling', a cooling panel with a 1 mm aluminum top, a 5 mm chip tray underside and a water-cooling system in between was used. The water-cooling system consisted of thin hosepipes (4 mm) provided with a permanent water flow. Water temperature was controlled according to the cooling load. Temperature of the cooling panel during 'underarm cooling' and 'face-underarm cooling' was $22.7 \pm 0.81\,^{\circ}$C while it was $21.8 \pm 0.62\,^{\circ}$C during 'foot sole cooling' as determined by pilot testing. During 'underarm cooling', participants were asked to keep their underarms and wrists on the cooling panel while using the computer and mouse. During 'foot sole cooling', participants were asked to place their feet soles flat onto the cooling panel. During 'back cooling', participants sat on a tailor-made chair with a water-perfused seat back. The same water-cooling system as used for the cooling panel was integrated in the seat back, covered by a thin layer of fabric. Continuous water exchange in the hosepipes was maintained to prevent heat accumulation. Participants were instructed to sit straight and to keep in constant contact to the cooled seat back. For back cooling, the water supply temperature was set to 30 °C (as previously determined by pilot testing) due to the proximity of the cooling device and the large surface area covered.

2.5. Measurements

Participants evaluated the thermal environment at 10-minute intervals. Whole body thermal sensation and thermal comfort were reported on Dutch visual analog scales (VAS), using an automatic recording system on a personal desktop. We used the standard 7-point ASHRAE thermal sensation scale (−3 cold to 3 hot) and another continuous VAS scale to indicate thermal comfort (Fig. 4A). The thermal-comfort-scale was divided into two parts to urge participants to indicate whether they perceived the thermal environment as 'comfortable' or 'uncomfortable'. Thermal preference and perceived importance to change the thermal environment were also indicated on continuous VAS scales (Fig. 4B and C). Another VAS scale was used to evaluate the subjective amount of sweating (0 no sweating, 10 sweating).

Ambient temperature and relative humidity were measured using four wireless combined temperature/humidity sensors (Hygrochron®, DS1923, Maxim Integrated Products, CA, USA). The four sensors were attached to a string hanging next to the subject's chair-back at 10 cm, 30 cm, 60 cm and 110 cm height (from the ground). Ambient temperature measurements were performed according to EN-ISO 7726 [20].

Skin temperatures were measured using wireless iButtons® dataloggers (DS1922L, Maxim Integrated Products, CA, USA). Mean skin temperature was calculated based on 14 body sites recommended by EN-ISO 9886 [21]. Twelve additional locations were added to obtain symmetrical skin temperature data from both sides of the body (Fig. 5). All temperature measurements (ambient and skin temperature) were recorded at 1-min intervals.

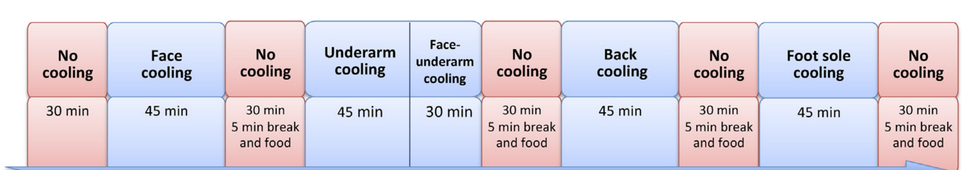

Fig. 3. Example of the time schedule. The conditions' sequence was randomly allocated. During the first 5 min of 'no cooling', participants were allowed to leave the climate chamber for a toilet break. After participants entered the chamber again, they were provided with a standard meal (open sandwich). Tepid water was served ad libitum.

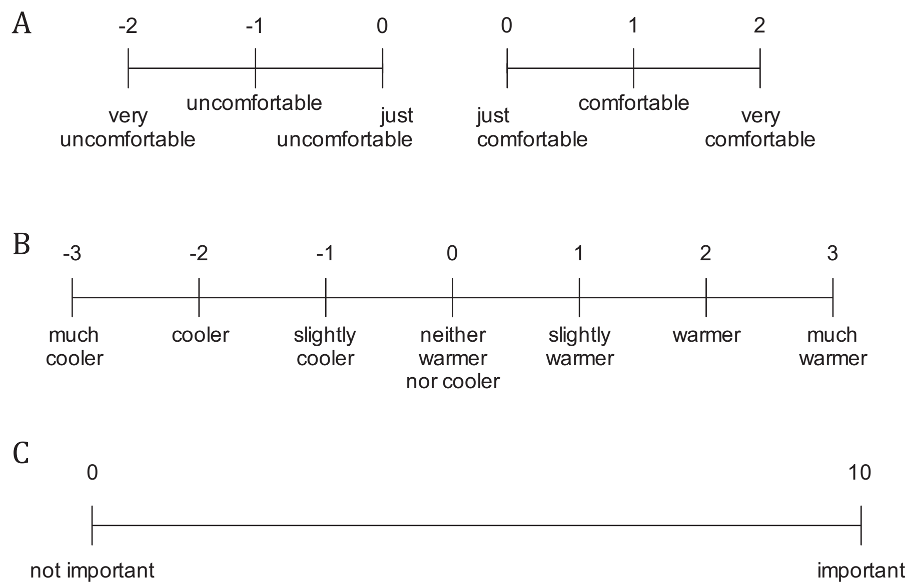

Fig. 4. English versions of the questionnaire scales. (A) Thermal comfort scale ('how do you perceive your thermal environment?'), (B) VAS for thermal preference ('what would you prefer at the moment?') and (C) VAS indicating importance to change ('how important is it for you to change the thermal environment?').

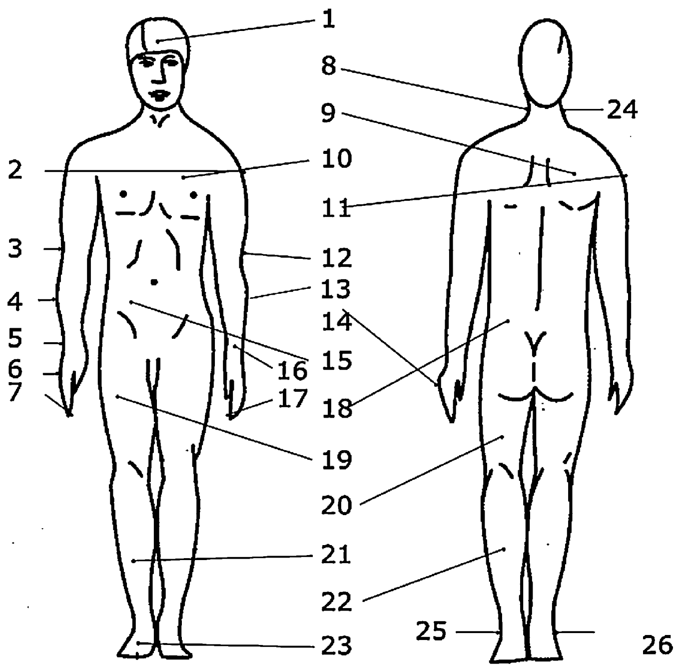

Fig. 5. iButton locations.

2.6. Statistics

All results are presented as mean ± standard deviation (SD). For all conditions, the average of the last five minutes of physiological data and the respective final subjective voting were used for analysis. The commercially available software package PASW Statistics 20.0 (SPSS Inc., Chicago, USA) was used to analyze the data. Analysis of conditional probability was performed using Matlab 2010a for Apple Mac computers.

2.6.1. Actuators

A repeated measures design was used to pairwise compare the five cooling conditions with 'no cooling' per outcome parameter. Statistical significance was assumed if $P < 0.05$. If the assumption of sphericity was violated, a Bonferroni correction was performed to adjust for multiple comparisons.

2.6.2. Sex differences

To detect sex differences, independent sample *t*-tests per condition and per outcome parameter for women and men were performed. Statistical significance was assumed if $P < 0.05$ and a trend was assumed if $0.05 < P < 0.1$.

2.6.3. Indicators

Physiological parameters such as skin temperature were previously identified as possible indicators of thermal sensation and thermal comfort [22]. To detect physiological predictors (indicators) of whole-body thermal sensation and thermal comfort, Spearman correlation coefficients between skin temperatures and thermal sensation as well as thermal comfort were calculated. We calculated Spearman correlation coefficients for the following scenarios: (1) whole-body thermal sensation/comfort and skin temperature data of all cooling conditions combined for each participant, (2) whole-body thermal sensation/comfort and skin temperature data of all participants combined for each cooling condition. The scenarios were tested for all participants together and women and men apart.

2.6.4. Post hoc power analysis

A post hoc power calculation using G*power 3.1 software [23] was performed for the applied repeated measures ANOVA design. Using an achieved partial η^2 of 0.248, the corresponding effect size f of 0.574, an α of 0.05 and the sample size of 16, the achieved power $(1 - \beta)$ equals 0.92.

3. Results

3.1. Actuators

3.1.1. Whole body thermal sensation and thermal comfort

Whole-body thermal sensation and thermal comfort during the cooling conditions 'face cooling', 'underarm cooling', 'back cooling', 'foot sole cooling' and 'face-underarm cooling' were compared with whole-body thermal sensation and thermal comfort during

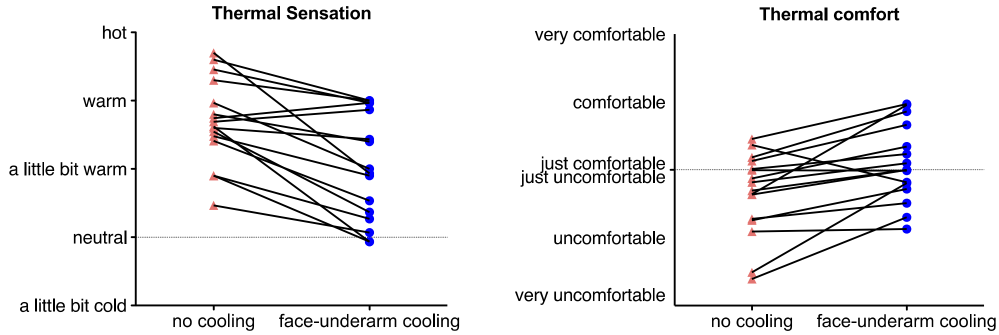

Fig. 6. Final voting's of thermal sensation and thermal comfort ($n = 16$) during 'no cooling' and 'face-underarm cooling'.

Table 2
Thermal sensation and thermal comfort of the final subjective voting per cooling condition ($n = 16$).

Condition	Mean ± SD	
	Thermal sensation	Thermal comfort
'No cooling'	1.70 ± 0.62	−0.36 ± 0.61
'Face cooling'	1.22 ± 0.74*	−0.01 ± 0.78*
'Underarm cooling'	1.54 ± 0.92	−0.23 ± 0.75
'Back cooling'	1.54 ± 1.01	−0.29 ± 0.85
'Foot sole cooling'	1.87 ± 0.68	−0.67 ± 0.67
'Face-underarm cooling'	1.04 ± 0.79**	0.09 ± 0.56*

* $P < 0.05$ in comparison with no cooling.
** $P < 0.001$ in comparison with no cooling.

'no cooling' periods. Within in the analyses, 'no cooling' served as baseline condition and separated the five cooling conditions (Fig. 2).

The cooling conditions 'face cooling' and 'face-underarm cooling' significantly lowered ($P < 0.05$, respectively $P < 0.001$) whole-body thermal sensation compared with 'no cooling' (Table 2 and Fig. 6). As depicted in Fig. 6, 'face-underarm cooling' resulted in decreased votes of whole-body thermal sensation for the majority of the participants; some votes decreased from 'warm' or 'slightly warm' to 'neutral' during 'face-underarm cooling'. Concurrently, also whole-body thermal comfort significantly improved ($P < 0.05$) during 'face cooling' and 'face-underarm cooling' (Table 2 and Fig. 6). None of the other cooling conditions caused significant changes in whole-body thermal sensation and/or thermal comfort. Fig. 6 shows that approximately 50% of the comfort votes during 'face-underarm cooling' raised toward the comfortable side of the scale. Importantly, no significant time effects on whole-body thermal sensation and/or thermal comfort were observed, as tested by repeated measures ANOVA.

Moreover, participants rated their 'want to' and 'importance to' change the thermal environment during all the cooling conditions (Fig. 4). Again, only 'face cooling' and 'face-underarm cooling' significantly decreased their 'want' ($P \leq 0.02$ and $P \leq 0.003$) and 'importance' ($P \leq 0.049$ and $P \leq 0.022$) to change.

3.1.2. Self-reported sweating

Self-reported sweating was significantly lower during 'face cooling' (4.80 ± 2.60) and 'face-underarm cooling' (4.72 ± 3.28) compared with 'no cooling' (6.63 ± 2.15). In contrast, participants tended to report more sweating during 'foot sole cooling' (7.35 ± 2.49), although this trend was not significant ($P < 0.052$). 'Back cooling' and 'underarm cooling' did not significantly alter self-reported sweating compared with 'no cooling'.

3.1.3. Skin temperatures

There was no significant variation in mean skin temperature between the conditions (Table 3). Mean proximal skin temperature was significantly higher during 'underarm cooling', but significantly lower during 'back cooling' compared with 'no cooling'. Mean distal skin temperature was significantly higher during conditions 'face cooling', 'underarm cooling' and 'back cooling', compared with no cooling'.

3.2. Sex differences

The present study did not reveal significant differences in whole-body thermal sensation and thermal comfort between women and men in any of the conditions.

Table 3
Mean, proximal and distal skin temperatures of the final five minutes per condition ($n = 16$).

Conditions	No cooling	Face cooling	Underarm cooling	Back cooling	Foot sole cooling	Face-underarm cooling
Mean skin temperature						
M + F	35.28 ± 0.49	35.45 ± 0.46	35.51 ± 0.42	35.09 ± 0.45	35.34 ± 0.52	35.43 ± 0.38
M	35.04 ± 0.57	35.21 ± 0.43	35.29 ± 0.45	35.02 ± 0.52	35.09 ± 0.49	35.27 ± 0.44
F	35.51 ± 0.24##	35.70 ± 0.35##	35.73 ± 0.27##	35.15 ± 0.38	35.59 ± 0.45#	35.58 ± 0.24
Proximal skin temperature						
M + F	35.55 ± 0.58	35.81 ± 0.50	35.89 ± 0.45*	34.80 ± 0.60*	35.68 ± 0.58	35.82 ± 0.43
M	35.40 ± 0.74	35.64 ± 0.50	35.78 ± 0.53	34.85 ± 0.76	35.54 ± 0.63	35.77 ± 0.52
F	35.70 ± 0.32	35.97 ± 0.48	36.00 ± 0.37	34.74 ± 0.43	35.82 ± 0.53	35.86 ± 0.34
Distal skin temperature						
M + F	34.70 ± 0.54	35.05 ± 0.53**	34.90 ± 0.67*	34.98 ± 0.54*	34.89 ± 0.64	34.86 ± 0.61
M	34.40 ± 0.60	34.80 ± 0.60	34.61 ± 0.78	34.82 ± 0.60	35.56 ± 0.69	34.68 ± 0.75
F	35.00 ± 0.24##	35.29 ± 0.34#	35.19 ± 0.40#	35.14 ± 0.45	35.22 ± 0.41##	35.05 ± 0.39

Data is presented as mean ± SD. M = men, F = women.
* $P \leq 0.05$ in comparison with 'no cooling'.
** $P < 0.001$ in comparison with 'no cooling'.
\# $P < 0.1$ difference between women and men.
\## $P < 0.05$ difference between women and men.

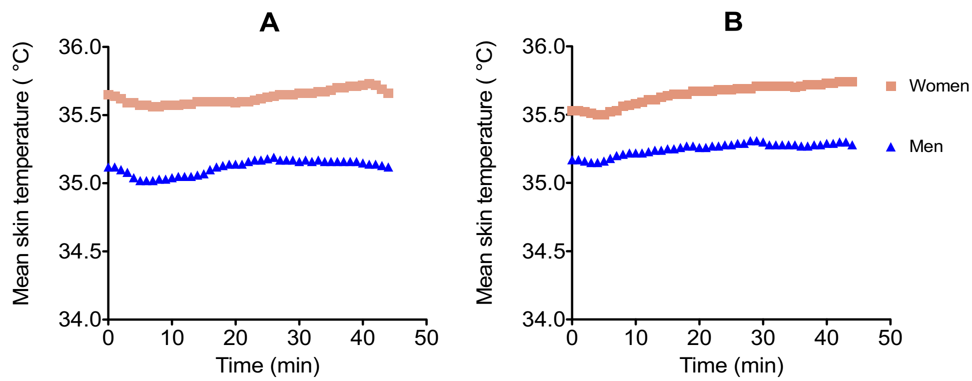

Fig. 7. Mean skin temperature trends of women and men during condition 'face cooling' (A) and 'underarm cooling' (B) (n = 16, 8 men and 8 women).

3.2.1. Skin temperatures

Women had significantly higher mean skin temperature in condition 'no cooling', 'face cooling', 'underarm cooling' and foot sole cooling ($P \leq 0.05$) compared with men (Table 3 and Fig. 7). Furthermore, women had significantly higher distal skin temperatures during 'no cooling', 'face cooling', 'underarm cooling' and 'foot sole cooling' compared with men. Proximal skin temperature was not significantly different between women and men. Skin temperature was not significantly related to whole-body thermal sensation or thermal comfort in neither of the scenarios or groups described in the statistics Section 2.6.3.

4. Discussion

The present study shows that local convective cooling of the face combined with local conductive cooling of the underarms significantly improved thermal sensation and comfort in a warm environment of 32.2 °C in contrast to the other four local cooling conditions that were tested. Although no significant differences in thermal comfort between men and women were detected, women had significantly higher mean skin temperature throughout the majority of the measured conditions. The results of the present study may have important practical implications and demonstrate the advantages of using individual comfort systems.

4.1. Actuators

The combined face-underarm cooling was the only cooling condition that encouraged the participants to rate the thermal environment as being 'just comfortable' (0.09 ± 0.56). None of the other cooling conditions ('underarm cooling', 'back cooling' and 'foot sole cooling') significantly improved thermal sensation or thermal comfort compared with 'no cooling'. 'Foot sole cooling' was de facto the only condition causing participants to perceive the thermal environment as warmer and less comfortable compared with 'no cooling' ($P \leq 0.08$).

Earlier studies indicated cooling of proximal body regions had the highest impact on (overall) thermal sensation and thermal comfort. For example, Zhang et al. [24] reported that for convective local cooling, especially the back, chest and pelvis would be the best target regions to influence overall thermal comfort. Interestingly, the backseat-cooled chair used in the present study did not improve whole-body thermal comfort and sensation, even though it very effectively lowered the proximal body temperatures of the participants (−0.75 °C). However, cooling of the back raised complaints in some of the female participants (headache and/or dizziness), indicating that the conductive cooling technique used in the present study might have been too intense, causing a strong imbalance between proximal and distal body temperatures.

In contrast, a recent study by Pasut et al. [7] showed that chair cooling combined with the application of a desk fan very positively influenced thermal comfort in a warm condition of 29 °C. However, the authors do not report any data on the effect of the cooled chair alone without the combination of the desk fan, which makes it difficult to examine the effect of the chair cooling alone. As a matter of fact, the head, which usually represents the target of a fan, plays a very important role in thermoregulation. Alongside to thermoregulatory advantages caused by increased airflow and fresh air supply around the head region, it also improves perceived air quality, sick building symptoms and general occupant comfort [6,25,40]. Hence, cooling of the head region together with the back might have blurred the effects of back cooling alone in the study of Pasut et al. [7].

In addition to the positive effects on occupant comfort and energy savings, individual local cooling systems might as well have beneficial health effects. It has recently been hypothesized that spending too much time in a constant climate can cause vulnerability to temperature fluctuations [41]. In a warm thermal environment, human physiological thermoregulation (e.g. vasomotion and evaporation) is stimulated more compared with a thermo-neutral ambient condition, to dissipate excessive body heat. Moreover, more calories are burned in warm conditions compared with thermo-neutral conditions [26,37,39]. Since the Western world is facing a global problem of obesity, leaving the TNZ every now and then may contribute to a healthier lifestyle [27].

Given the fact that the combined cooling technique investigated in the present study was most effective, it would be relevant to evaluate the effect of other combinations of conductive and convective local cooling on whole-body thermal comfort in a warm environment. It has been decided to apply an ambient temperature of 32.2 °C to intensify and clarify the effect of local cooling. However, it is relevant to verify the present results in moderate conditions as more regularly encountered in temperate climates. Moreover, future investigations should focus on optimization of cooling methods, for example with respect to the level of airflow and eye dryness.

4.2. Sex differences

Although no substantial sex differences with respect to thermal sensation or thermal comfort were identified, differences in thermal physiology of women and men were evident. In three of the five provided conditions, women had significantly higher mean skin temperatures (approximately +0.5 °C) and distal skin temperatures (approximately +0.6 °C) compared with men. Congruently, Hardy and Du Bois [33] had already established various sex differences in thermoregulation in 1940. They found that women had

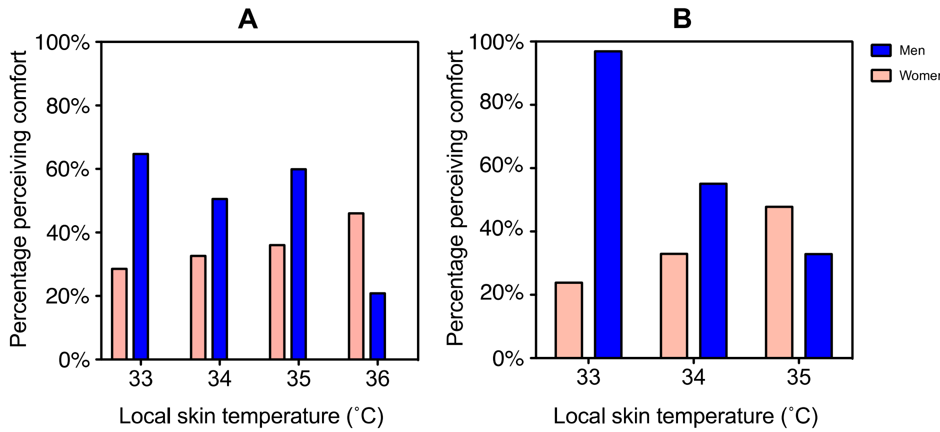

Fig. 8. Results of the conditional probability analysis of the hands (A) and the underarms (B) for women ($n = 8$) and men ($n = 8$). The y-axis represents the percentage of participants that felt comfortable at the given local skin temperature (x-axis).

up to 1.7 °C higher skin temperatures compared with men in warm dry ambient conditions up to 36 °C. Ever since, these findings have been confirmed by various studies [28–30]. Moreover, higher evaporation rate and earlier sweat onset are evident in men, which is likely to contribute to lower skin temperatures in warm ambient conditions [30,31]. Correspondingly, a study by Schellen et al. [14] indicated women had lower mean skin temperatures and were more likely to report discomfort, when situated in a mild cold environment. This may be explained by the sex-related differences in the thermoneutral zone, which seems to be shifted to higher temperatures in women compared with men [26]. The thermoneutral zone is defined as "*the range of* (ambient) *temperatures at which temperature regulation is achieved only by control of sensible (dry) heat loss*, i.e. *without regulatory changes in metabolic heat production or evaporative heat loss. The thermoneutral zone (TNZ) will therefore be different when insulation, posture or basal metabolism vary*" [32]. Generally, women have a lower resting metabolic rate, less muscle mass and more fat mass compared with men, which is why their TNZ is expected to be different. As a matter of fact, Hardy and Du Bois [33] observed that seminude women increased metabolic rate at temperatures below 31 °C, whereas men increased metabolic rate below 28.5 °C. In practice, it is very important to consider that women and men may react differently upon the same thermal environment, and this is likely to influence individual thermal comfort and sensation.

4.3. Possible indicators

To evaluate potential physiological indicators of thermal comfort, the relations between skin temperature and whole-body thermal sensation and thermal comfort were examined. No statistically significant correlations were observed.

Next to a correlation analysis, conditional probability analysis (conform the Bayesian method [36]) was performed to calculate the probability of perceived whole-body thermal comfort at a given local skin temperature. 'Comfortable' was defined as being the entire thermal comfort VAS range from 'just comfortable' to 'very comfortable' (Fig. 3A). Analysis was performed using skin temperature data and the respective whole-body thermal comfort data of the final 5 min of all conditions.

The percentage of participants perceiving thermal comfort did not change significantly with changing local skin temperatures. However, when performing conditional probability analysis for women and men separately, women were more likely to perceive thermal comfort given higher local skin temperatures at the hands and the underarms (Fig. 8A and B). The opposite was true for men: the probability of perceiving thermal comfort decreased given higher skin temperatures at hands and underarms. For example, only 24% of the females were comfortable at 34 °C underarm skin temperature, whereas 97% of the men reported thermal comfort. In contrast, 46% of the women but only 21% of the men felt comfortable at a 36 °C hand skin temperature. The same trend appeared for various other body sites, e.g. neck, shoulder region (scapula, deltoid region), fingers and lower legs. However, the trends described above were not consistent over all body sites. Therefore, it would be necessary to perform additional studies with more participants in order to be able to generalize the results.

Although differences between women and men with respect to thermal comfort and skin temperatures were established much earlier, many models for thermal comfort, such as the PMV model, do not incorporate these differences. Interestingly, Fanger [10] indicated women and men would prefer similar temperatures, so the same boundary conditions would be needed to create thermal comfort. However, as indicated by a biophysical study by our group, thermo-neutrality and thermal comfort are not necessarily equal, and are significantly influenced by physiological differences in metabolism and tissue insulation [34]. Furthermore, Karjalainen [35] underpinned the need to incorporate differences between women and men to configure indoor environments, which is in line with the results of this study.

5. Conclusion

Overall, the present study concludes that face cooling by means of increased airflow in combination with conductive underarm cooling is an effective way to improve thermal sensation and thermal comfort in a warm environment. Furthermore, we confirm earlier studies that show that in warm conditions women had higher mean and distal skin temperatures compared with men. However, no direct relationship between skin temperatures and whole-body sensation or comfort was identified.

Individualized local cooling seems to be an effective method to comply with the varying needs and preferences of women and men individuals with respect to overall thermal comfort in warm thermal environments. In practice, the application of individualized cooling may allow for increasing occupant satisfaction and simultaneously saving energy due to a reduction of ventilation and air-conditioning of the entire office space.

Acknowledgements

This study was performed within the User Centered Energy Reduction (UCER) project, which is a project of the TKI EnerGO (TKIGB01006). The experiments described in this paper were conducted in close cooperation with the partners of Kropman, NXP, Vabi, TNO, Eindhoven University of Technology and Delft University of Technology.

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