Thermal sensation and thermal comfort in changing environments

Velt, K. B.; Daanen, H. A M

published in
Journal of Building Engineering
2017

DOI (link to publisher)
10.1016/j.jobe.2017.02.004

document version
Publisher's PDF, also known as Version of record

document license
Article 25fa Dutch Copyright Act

citation for published version (APA)
Velt, K. B., & Daanen, H. A. M. (2017). Thermal sensation and thermal comfort in changing environments. *Journal of Building Engineering*, *10*, 42-46. https://doi.org/10.1016/j.jobe.2017.02.004

Journal of Building Engineering 10 (2017) 42–46

Contents lists available at ScienceDirect

Journal of Building Engineering

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

Thermal sensation and thermal comfort in changing environments

K.B. Velt[a], H.A.M. Daanen[a,b,*]

[a] Department of Human Movement Sciences, Faculty of Behaviour and Movement Sciences, Vrije Universiteit Amsterdam, MOVE Research Institute Amsterdam, Van der Boechorststraat 7, 1081BT Amsterdam, The Netherlands
[b] TNO, Kampweg 5, 3769ZG, Soesterberg, The Netherlands

ARTICLE INFO

Keywords:
Thermal sensation
Thermal comfort
Thermal transients
Thermal perception

ABSTRACT

It is the purpose of this study to investigate thermal sensation (TS) and thermal comfort (TC) in changing environments. Therefore, 10 subjects stayed in a 30 °C, 50% relative humidity for 30 min in summer clothes and then moved to a 20 °C room where they remained seated for 30 min (Hot to Reference - HR). Similarly, 11 subjects moved from a 10 °C, 50% relative humidity to a 20 °C environment (Cold to Reference – CR) dressed in winter garments. TS (9 point scale from −4 (very cold) to +4 (very hot)) decreased from 1.5 ± 0.4 (mean ± SD) to −0.8 ± 0.8 for HR and increased from −1.7 ± 1.4 to 0.8 ± 0.9 for CR. TC (5 point scale from 0 (comfortable) to +4 (extremely uncomfortable)) dropped from 1.5 ± 0.5 to 1.2 ± 0.4 for HR and from 1.9 ± 0.7 to 1.3 ± 0.4 for CR. The difference in TS between HR and CR at the end of period in 20 °C illustrates the considerable dependence of thermal sensation on exposure history. It is therefore recommended to increase room temperature when it is hot outside and decrease room temperature when it is cold outside in order to maintain a neutral thermal sensation.

1. Introduction

Humans are homeotherms and controlling body core temperature is easier in stable thermal environments. It is therefore not surprising that most scientific studies address thermal sensation and thermal comfort under stable environmental conditions such as during office work. However, it has been recognized that thermal transients have an important effect on thermal sensation [1]. There seems to be a recent interest revival regarding thermal comfort in changing thermal environments [2–5]. Additionally, the recent revisions to ASHRAE-55 regarding the thermal environment for human occupancy encouraged the discussion on the influence of outdoor temperatures on indoor comfort [6]. This paper intends to add to the pool of information. More specifically we intend to investigate transients from a mildly warm environment to a reference temperature of 20 °C and from a mildly cold environment to the reference temperature with a focus on thermal sensation.

Thermal sensation is a standard parameter in most thermal experiments. It is uniformly defined in ISO 7730 [7] and ASHRAE standard 55 [8] with a scale ranging from −3 (cold) to +3 (hot). The scale is sometimes extended to −4 (very cold) to +4 (very hot) to cover a wider range [9,10]. Mostly, thermal sensation and its derivation PPD (percentage of dissatisfied people) are used to assess satisfaction with the climate. Thermal comfort is defined by ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) as the condition of mind that expresses satisfaction with the thermal environment. In our study we used a 5-point scale (0 comfortable, +4 extremely uncomfortable) [9]. Thermal comfort can be partially influenced by different contextual and cultural factors but it is primarily an effect of the heat exchange between the body and the environment [11].

When the environment suddenly changes in temperature, it takes time to adapt and to change to a new thermal equilibrium [12]. Dahlan & Gital [2] found that the changes in thermal sensation scores after a temperature change are dependent on the temperature difference between the two environments. Participants' thermal comfort changed to more comfortable after a drop of ambient temperature from 35 °C to 24 °C and became more uncomfortable after an increase of ambient temperature from 24 °C to 35 °C (ΔT=11 °C). Gagge et al. [9] described the phenomenon overshoot. When a person moves between two environments with different ambient temperatures, thermal sensation scores in the second environment are affected by the previous environment. More recently, Du et al. [3] performed a study including three experiments on this topic and observed a small overshoot in thermal sensation when participants moved from a cool room (resp. 12 °C, 15 °C and 17 °C) to a 22 °C room. What they also found was that thermal experience has a large influence on people's thermal sensation. When the participants moved from the neutral room back to the cold room (2nd transient) the thermal sensation scores dropped immediately after the transient, and then slightly increased (approximately 0.5

---

[*] Corresponding author at: Faculty of Behaviour and Movement Sciences, Vrije Universiteit Amsterdam, Van der Boechorststraat 7, 1081BT Amsterdam, The Netherlands.
E-mail address: h.a.m.daanen@vu.nl (H.A.M. Daanen).

http://dx.doi.org/10.1016/j.jobe.2017.02.004
Received 29 September 2016; Received in revised form 30 January 2017; Accepted 9 February 2017

units). Liu et al. [4] reported a study of also three experiments where they investigated the transient from hot to a reference temperature close to thermal neutrality. They found that TS scores decreased sharply when a person moves from a hot room (resp. 32 °C, 30 °C and 28 °C) to a room of 25 °C and a large negative overshoot occurred. After the transient from the 25 °C room to the hot room, TS scores increased and a positive overshoot occurred. However, TS values were lower than the TS scores when the participant stayed in the hot room the first time. These two studies could be used to describe how persons respond to changes in ambient temperature. However, the neutral room has a different temperature in both studies, resp. 22 °C [3] and 25 °C [4]. This means that the two studies cannot be compared to each other in order to find the difference in the response between a hot-neutral change and a cold-neutral change. Xiong et al. [5] performed a study to investigate the effect of a change in ambient temperature on, among others, thermal sensation. They performed three experiments including a change of ambient temperature from resp. 32-26-22°C to 37°C and back to resp. 32-26-22°C. They concluded that all transients had a significant effect on thermal sensation. When the difference in ambient temperature increased, the effect on thermal sensation became more pronounced. When the temperature development was 22–37 °C-22 °C, the change in thermal sensation was 3 units while when the temperature development was 32–37 °C-32 °C, the change in thermal sensation was only 1 unit.

The described studies were mostly performed in Asia. A comparison of thermal comfort between Asia and Europe has not yet been made, but one could imagine that the requirements of a thermal comfortable environment are different due to the climate and acclimatization status. Consequently, the results of these field studies cannot be directly applied in the Netherlands. Further, in the previous described studies the different experiments were performed on the same day. Thus the participants' body in the second and third test could already be heated or cooled due to the previous tests and thereby affect the results. Therefore, the aim of this study was to investigate thermal sensation and thermal comfort in changing environments. We hypothesize that thermal sensation in a reference room temperature of 20 °C differs significantly after a period of cold and heat exposure, independent of thermal status of the body.

2. Materials and methods

2.1. Subjects

11 Healthy Dutch subjects (7 males and 4 females) participated in this study. Females were aged 26 ± 5 (Mean ± Standard Deviation) years, had a height of 167 ± 8 cm and body mass of 60 ± 4 kg. Males were aged 24 ± 5 years, had a height of 181 ± 7 cm and body mass of 78 ± 4 kg. The subjects did not perform heavy exercise prior to the experiment and did not consume coffee two hours prior to the experiment. The subjects were fully informed of the goals, protocol and possible risks before giving a written consent to participate in the experiment. The study was approved by the Ethics Committee of the VU University (Amsterdam, The Netherlands).

2.2. Experimental design

The experiments were scheduled in two morning sessions lasting two hours, with three days in between. The experiments were carried out in the climatic chamber at TNO Soesterberg (the Netherlands) in the last week of August 2015. The average maximum temperature in August in the Netherlands is 22 °C, and this was also the maximum hourly temperature during the days of the experiment (https://data.knmi.nl/datasets).

The first session involved the transition from a simulated summer environment (30 °C, 50% relative humidity) to a reference environment (20 °C, 50% relative humidity) abbreviated as HR. The second session involved the transition from a simulated winter environment (10 °C, 50% relative humidity) to the reference environment (20 °C, 50% relative humidity) abbreviated as CR. The choice of temperature and relative humidity for the summer and winter environment was based on weather reports of the Royal Netherlands Meteorological Institute (KNMI). The subjects were dressed in standardized summer- and winter clothing. For the summer scenario this was underwear, shorts, a T-shirt, socks and low shoes (about 0.2 Clo [13]). In the winter scenario this was underwear, jeans, a long sleeve shirt (with or without buttons), a winter jacket, socks and shoes (about 1.12 Clo [13]).

The subjects was seated in the climatic chamber set to the summer/winter environment and sat there for 30 min. Thereafter (at t=30 min), they proceeded to the chamber set to the reference environment of 20 °C and sat there for 30 min. In both climatic chambers the participants did not change their clothing.

2.3. Measurements and methods

The measurements were executed in two adjacent climatic chambers (only 3 m apart) with temperature control better than 0.2 °C, humidity control ranging from 10%RH to 90%RH (only above 4 °C) with an accuracy of 2% (above +25 °C) or 5% (below +25 °C) and air displacement of less than 0.2 m/s (Weiss Enet, Tiel, The Netherlands). The core temperature (Tre) was assessed using a rectal thermometer (Yellow Springs Instruments 400 series, Yellow Springs, OH, USA) read using a resistance meter (Velleman DVM 851, Gavere, Belgium). The rectal thermometer was inserted 10 cm beyond the anal sphincter and the cable was fixed to the lower back with tape. The measurements were repeated every five minutes. Skin temperature was measured every minute with an accuracy of 0.0625 °C using iButtons (DS19221, Maxim Integrated Products Inc., Sunnyvale, CA, USA) [14] placed on C5 in the neck, the right scapula under the spina scapula, the dorsal side of the left hand and on the muscle belly of m. tibialis anterior of the right leg. A weighted average of the temperatures of the four locations resulted in the mean skin temperature (Tsk) [15].

Mean body temperature (Tb) was calculated according to Burton [16].

Thermal sensation was assessed every 5 min using a 9-point scale (from −4=very cold to +4=very hot) and thermal comfort was assessed every 5 min using a 5-point scale (from 0=comfortable to +4=extremely uncomfortable) [10]. Body mass (including clothing) was measured on a weighing scale (Sartorius F300S, Göttingen, Germany) before the experiment. The height was measured using a stadiometer (SECA 222, Apeldoorn, the Netherlands) before the experiment.

2.4. Data analysis

For the analysis of rectal temperature (Tre), mean body temperature (Tb), thermal sensation (TS) and thermal comfort (TC) discrete values at each fifth minute of the experiment were selected. Skin temperature (Tsk) was determined every minute. One female subject was removed from the dataset for the HR condition due to missing data.

Statistical analyses were performed using Statistica 13.1 (Dell Inc.). To examine if and to what extent transients influence thermal comfort and thermal sensation, a Wilcoxon rank sum test was performed for TS and TC before- and after transient as dependent variables for each condition. To define the effect of transients on mean skin, mean body and rectal temperature, independent sample T-tests were performed. P values lower than 0.05 were accepted as significant.

3. Results

Table 1 summarizes the average Tre, Tb and Tsk as well as TS and TC before and after the transient for males, females and both genders grouped.

Table 1
Average mean skin temperature (Tsk), rectal temperature (Tre), mean body temperature (Tb), Thermal sensation (TS) and Thermal Comfort (TC) with standard deviation between subjects for males, females and all investigated subjects before and after the transient. Bold values indicate significant ($p < 0.05$) differences between before and after transient. No significant differences between females and males were observed.

		HR				**CR**			
		Before		**After**		**Before**		**After**	
Variable	**Gender**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Tsk (°C)	both	**33.9**	**0.5**	**32.4**	**0.5**	**31.5**	**0.6**	**32.4**	**0.6**
Tre (°C)	both	37.3	0.3	37.3	0.2	37.2	0.3	37.1	0.3
Tb (°C)	both	**36.6**	**0.2**	**35.7**	**0.4**	35.2	0.5	35.6	0.6
TS	both	**1.5**	**0.4**	**−0.8**	**0.8**	**−1.7**	**1.4**	**0.8**	**0.9**
TC	both	1.5	0.5	1.2	0.4	**1.9**	**0.7**	**1.3**	**0.4**
Tsk (°C)	female	**34.0**	**0.4**	**32.4**	**0.3**	31.2	0.8	32.1	0.6
Tre (°C)	female	37.3	0.3	37.4	0.3	37.0	0.4	36.9	0.3
Tb (°C)	female	**36.7**	**0.2**	**35.8**	**0.4**	34.9	0.7	35.2	0.7
TS	female	1.7	0.1	−1.6	0.9	**−2.5**	**0.6**	**0.1**	**1.1**
TC	female	1.5	0.5	1.7	0.6	**2.4**	**0.6**	**1.4**	**0.4**
Tsk (°C)	male	**33.9**	**0.6**	**32.4**	**0.5**	**31.7**	**0.4**	**32.7**	**0.4**
Tre (°C)	male	37.3	0.3	37.2	0.2	37.3	0.2	37.2	0.2
Tb (°C)	male	**36.6**	**0.2**	**35.7**	**0.4**	**35.4**	**0.4**	**35.9**	**0.3**
TS	male	**1.3**	**0.5**	**−0.5**	**0.5**	**−1.3**	**1.6**	**1.2**	**0.5**
TC	male	**1.5**	**0.5**	**1.0**	**0.0**	1.7	0.6	1.2	0.3

3.1. Thermal strain

In the HR condition, Tsk of the male participants averaged 33.9 ± 0.6 °C before the transient. Tsk dropped significantly to 32.4 ± 0.5 °C (mean ± SD). Tsk of the female participants before the transient was 34.0 ± 0.4 °C and decreased significantly to 32.4 ± 0.3 °C.

In the CR condition Tsk of the male participants in the cold environment averaged 31.7 ± 0.4 °C and increased significantly to 32.7 ± 0.4 °C after the transient. Tsk of the female participants before the transient was 31.2 ± 0.8 °C and remained close to stable (value after transient was 32.1 ± 0.6 °C).

The rectal temperatures remained unchanged for males and females after the transient (Table 1).

There were no differences between males and females for Tsk, Tre and Tb, therefore the average values for males and females are shown in Table 1 as well.

There was no difference in Tre, Tb and Tsk between the HR and CR condition in the reference temperature room.

Fig. 1 shows the mean skin and rectal temperature for the transitions.

3.2. Thermal sensation and thermal comfort

In the HR condition, TS was influenced by the temperature transient in both males and females. The TS votes of the males decreased significantly from 1.3 ± 0.5 to −0.5 ± 0.5 units. In the female group TS votes decreased from 1.7 ± 0.1 to −1.6 ± 0.9 units. Despite this large difference in females, significancy was not reached probably related to the large scatter in the TS score after the transient and the small number of females in the HR cohort. In the CR condition TS was significantly affected in both males and females. The TS votes of the male participants changed from −1.3 ± 1.6 to 1.2 ± 0.5 units and in the female participants TS votes increased from −2.5 ± 0.6 to 0.1 ± 1.1 units.

In the HR condition, TC was significantly influenced by the temperature transient in male participants, but not in females. The TC votes of the males increased from 1.5 ± 0.5 to 1 units (all male participants had equal TC votes after the transient) while in the female group TC votes increased from 1.5 ± 0.5 to 1.7 ± 0.6 units. In the CR condition, TC was significantly affected in females but not in males. The TC votes of the male participants changed from 1.7 ± 0.6 to 1.2 ± 0.3 units and in the female participants TC votes decreased from 2.40 ± 0.6 to 1.4 ± 0.4 units.. Fig. 2 shows thermal sensation and thermal comfort for the transitions.

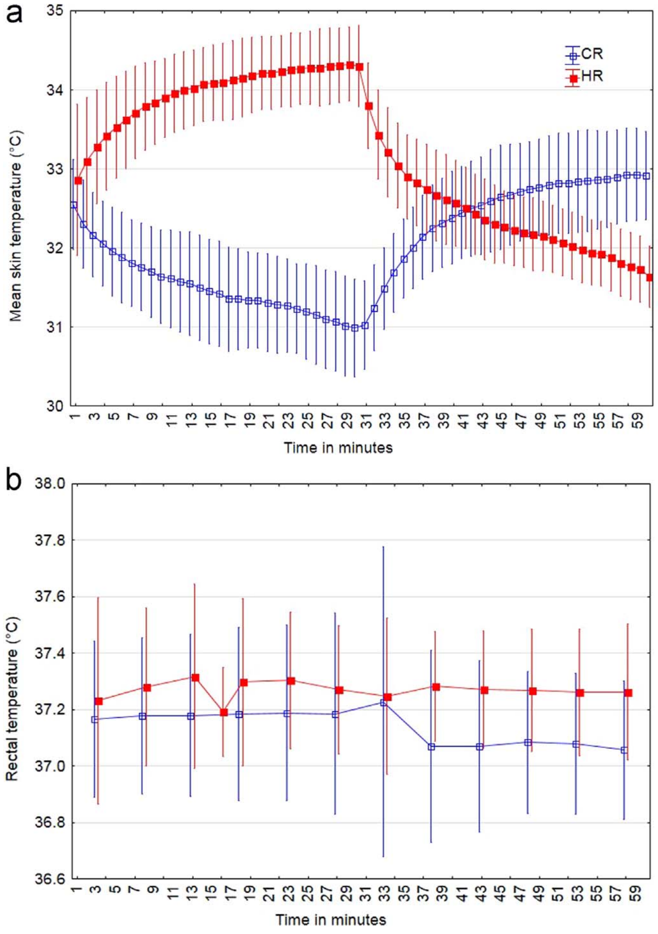

Fig. 1. Mean skin temperature (a) and core temperature (b) in °C for the transition of hot to reference temperature (HR) and cold to reference temperature (CR). Vertical bars represent standard deviation.

TS was significantly lower for the HR condition (−0.8 units) after the transient than for CR (+0.8 units). The values for TC did not differ after the transient.

4. Discussion

The experiment investigated the effect of temperature changes on TS and TC in a HR (hot-reference) condition and a CR (cold-reference) condition. The participants' TS vote decreased 2.3 units when entering the reference environment after exposure to a warm thermal environment. Entering the reference environment after a period in the cold lead to an increase in TS vote of 2.5 units. TS during the reference temperature after cold exposure was 0.8 units and −0.8 units after heat exposure. Thus, TS strongly depends on exposure history, in line with the hypothesis. Although we observed TS of −0.8 after pre-exposure to heat and TS of +0.8 after pre-exposure to cold, we cannot conclude that TS may have been close to zero without pre-exposure. In summer clothes prolonged exposure to 20 °C would lead to a negative heat balance.

TC votes decreased 0.3 units, slightly towards zero (comfortable)in HR and TC votes decreased 0.6 units, slightly towards zero (comfortable) for CR. TC votes during the reference temperature showed no dependence of exposure history. Participants experienced the ambient temperature of 10 °C as more uncomfortable than the temperature of 30 °C (1.9 versus 1.5 respectively). The clothing insulation in the cold was insufficient to maintain thermal equilibrium and in turn thermal

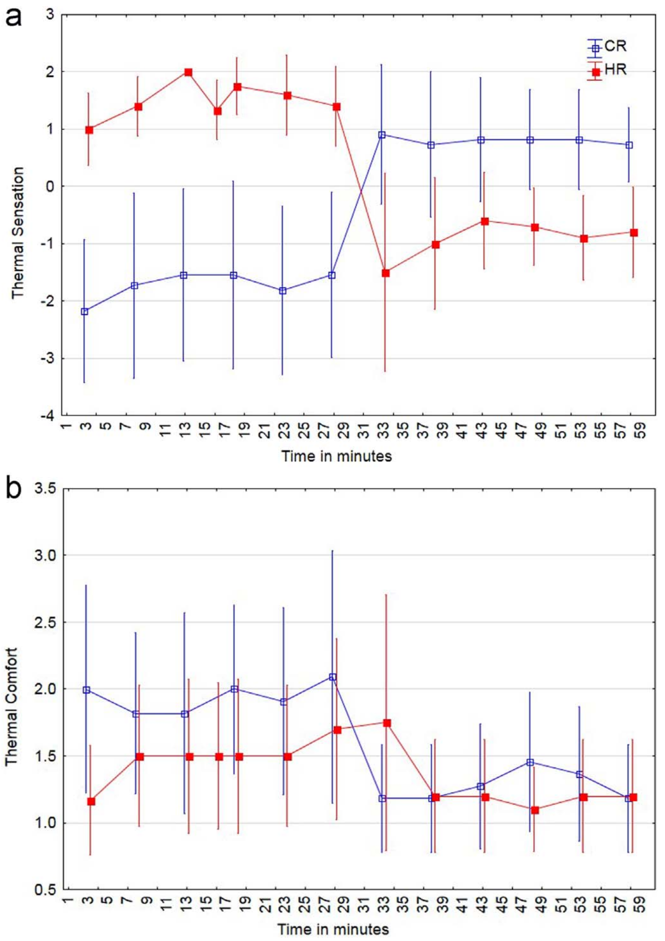

Fig. 2. Thermal sensation (a) and thermal comfort (b) in arbitrary units for the transition of hot to reference temperature (HR) and of cold to reference temperature (CR). Vertical bars represent standard deviation.

comfort. This is substantiated by the decreased mean skin temperature in the cold (Fig. 1). The mean skin temperatures in the reference temperature were similar after cold exposure and after heat exposure. This is likely due to the fact that different garments were worn for CR and HR.

Mean skin temperature decreased 1.5 °C for HR and increased 0.9 °C for CR averaged over males and females with females having slightly lower skin temperatures in the cold. The number of female subjects in our study is too small to make a fair gender comparison; the observation that female skin temperatures are lower than male skin temperatures is consistent with the literature (e.g. [17]).

Although it is documented that thermal (dis)comfort depends on many factors [18], there are observations that thermal discomfort is associated with a deviation of mean body temperature (Tb) from 36.5 °C [9]. Tb in the 30 °C chamber was 36.6 ± 0.2 °C which only deviates 0.1 °C from ideal. This could explain the fact that people feel 'a little uncomfortable' in this environment. Tb In the 10 °C chamber was 35.2 ± 0.5 °C, a deviation of 1.3 °C from ideal. This implies people feel more uncomfortable because their mean body temperature is lower than ideal and is reflected in TS and TC. In both scenarios the mean body temperature changed to 35.6–35.7 °C after the transient to the reference temperature room. Mean body temperature depends on core temperature, which is quantified using rectal temperature in our study. It is well established that rectal temperature is a slow responder to thermal changes when compared to esophageal temperature (e.g., [19]). However, esophageal probes are less accepted since participants may experience vomit reflexes and Fig. 1b shows that changes over time are small in Tre.

Therefore, our hypothesis can be confirmed that TS differs between pre-exposure to cold and to heat, even though thermal status of the body (mean body temperature) is not different. It has to be mentioned that the clothing package that we supplied was different for the CR than the HR condition. However, we believe that this corresponds to real live, where people adapt their clothing to the thermal situation. The insulation of the garments that the participants were wearing resulted in a similar mean body temperature of 25.6 – 25.7 °C during the stay in the 20 °C room, indicating that we were successful in maintaining a comfortable body temperature.

According to De Dear and Ring [20] humans are more sensitive to temperature declines than they are to temperature increases. This is related to the fact that the amount of thermoreceptors sensitive for cold is higher than for heat [21]. Further, the thermoreceptors sensitive for cold lie immediately below the epidermis and the receptors for heat lie in the upper layers of the dermis [22]. In our study, the ambient temperature changes were from 30 °C to 20 °C and 10–20 °C respectively, both changes of 10 °C. The change in thermal sensation for the temperature drop was 2.3 units, and 2.5 units for the temperature increase. The observations of De Dear are therefore not in line with our results regarding TS. In our study, TC votes changed 0.3 units for the temperature drop and 0.6 units for the temperature increase. It should be mentioned that there was more discomfort prior to the transient in the cold so that changes are relatively large.

Regarding thermal sensation votes, Kato et al. [23] stated that thermal sensation is mainly related to the skin temperature. This is supported by Teunissen et al. [24]. Running a correlation analysis on the data of the current study shows there is also a significant correlation between the skin temperature and thermal sensation (CR: r=0.414, HR: r=0.674), while core temperature has no significant effect. These results are thus in line with previous studies [23,24].

As presented in Fig. 1 there is a decrease in Tre due to the transient from cold to the reference temperature, but not in the transient from hot to reference. When the human body is placed in a cold environment, the body induces vasoconstriction to reduce heat loss in the extremities. There is still an amount of blood flow to the extremities required to maintain a sufficient flow of oxygen to the cells. When this cold blood returns to the body core it has to be heated again before it reaches the heart. This process is called afterdrop and causes the small though significant decrease of the core temperature [13].

5. Conclusion

A temperature transient of 10 °C significantly influences thermal sensation and thermal comfort votes. When the transient was from hot to 20 °C, mean TS vote changed to 'a little cold' and mean TC vote changed to more comfortable. When the transient was from cold to 20 °C, mean TS vote changed to 'a little warm' and mean TC vote changed to more comfortable. The deviation of TS vote from zero at the end of period in the 20 °C room illustrates the considerable dependence of thermal sensation on exposure history, even though mean body temperature did not differ. It is therefore recommended to set the thermostat slightly higher when it is hot outside and slightly lower when it is cold outside in order to maintain a neutral thermal sensation.

Acknowledgements

The authors acknowledge VDL, Heavac and TNO for financial support of the study. We also thank the participants for contributing in the study.

References

[1] H. Zhang, C. Huizenga, E. Arens, D. Wang, Thermal sensation and comfort in transient non-uniform thermal environments, Eur. J. Appl Physiol. 92 (6) (2004) 728–733.

[2] N.D. Dahlan, Y.Y. Gital, Thermal sensations and comfort investigations in transient conditions in tropical office, Appl Ergon. 54 (2016) 169–176.

[3] X. Du, B. Li, H. Liu, D. Yang, W. Yu, J. Liao, et al., The response of human thermal sensation and its prediction to temperature step-change (cool-neutral-cool), PLoS One 9 (8) (2014) e104320.

[4] H. Liu, J. Liao, D. Yang, X. Du, P. Hu, Y. Yang, et al., The response of human thermal perception and skin temperature to step-change transient thermal environments, Build. Environ. 73 (2014) 232–238.

[5] J. Xiong, Z. Lian, X. Zhou, Investigation of subjectively assessed health symptoms and human thermal perceptions in transient thermal environments, Procedia Eng. 121 (2015) 212–216.

[6] C. Chun, A. Kwok, T. Mitamura, N. Miwa, A. Tamura, Thermal diary: connecting temperature history to indoor comfort, Build. Environ. 43 (2008) 877–885.

[7] ISO_7730, Ergonomics of the Thermal Environment — Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria. International Standards Organisation, Geneva, 2005.

[8] ASHRAE_standard_55. Thermal Environmental Conditions for Human Occupancy. ASHRAE (⟨www.ashrae.org⟩). 2013.

[9] A.P. Gagge, J.A.J. Stolwijk, J.D. Hardy, Comfort and thermal sensations and associated physiological responses at various ambient temperatures, Environ. Res. 1 (1967) 1–20.

[10] ISO_10551. Ergonomics of the Thermal Environment – Assessment of the Influence of the Thermal Environment Using Subjective Judgement Scales. International Organization for Standardization, Geneva. 1995.

[11] B.W. Olesen, K.C. Parsons, Introduction to thermal comfort standards and to the proposed new version of EN ISO 7730, Energy Build. 34 (2002) 537–548.

[12] S. Kuno, A New Concept of Air-Conditioning Systems Based on the Theory of Thermal Comfort in Transitional Conditions. Proceedings ISETS07;7:1171–1174, 2007.

[13] K.C. Parsons, Human Thermal Environments: The Effects of Hot, Moderate, and Cold Environments of Human Health, Comfort and Performance, CRC press, 2014.

[14] W.D. van Marken Lichtenbelt, H.A. Daanen, L. Wouters, R. Fronczek, R.J. Raymann, N.M. Severens, et al., Evaluation of wireless determination of skin temperature using iButtons, Physiol. Behav. 88 (4–5) (2006) 489–497.

[15] ISO_9886. Ergonomics – Evaluation of thermal strain by physiological measurements,. International Organization for Standardization, Geneva. 2004.

[16] A. Burton, Human calorimetry: the average temperature of the tissues of the body, J. Nutr. 9 (1935) 261–280.

[17] L. Lan, Z. Lian, W. Liu, Y. Liu, Investigation of gender difference in thermal comfort for Chinese people, Eur. J. Appl Physiol. 102 (4) (2008) 471–480.

[18] M. Cabanac, B. Massonnet, R. BePaiche, Preferred skin temperature as a function of internal and mean skin temperature, J. Appl. Physiol. 33 (1972) 699–703.

[19] L.P. Teunissen, A. de Haan, J.J. de Koning, H.A. Daanen, Telemetry pill versus rectal and esophageal temperature during extreme rates of exercise-induced core temperature change, Physiol. Meas. 33 (6) (2012) 915–924.

[20] R. De Dear, J. Ring, Human experience of sudden environmental temperature transients, Indoor Air 3 (1993) 181–192.

[21] A.C. Guyton, Textbook of Medical Physiology, Saunders, Philadelphia, USA, 2002.

[22] H. Bazett, B. McGlone, Experiments on the mechanism of stimulation of end-organs for cold, Am. J. Physiol. 93 (1930) 632.

[23] M. Kato, J. Sugenoya, T. Matsumoto, T. Nishiyama, N. Nishimura, Y. Inukai, et al., The effects of facial fanning on thermal comfort sensation during hyperthermia, Pflug. Arch. 443 (2) (2001) 175–179.

[24] L.P. Teunissen, L.C. Wang, S.N. Chou, C.H. Huang, G.T. Jou, H.A. Daanen, Evaluation of two cooling systems under a firefighter coverall, Appl. Ergon. 45 (6) (2014) 1433–1438.