7th International Building Physics Conference

IBPC2018

Proceedings

SYRACUSE, NY, USA

September 23 - 26, 2018

Healthy, Intelligent and Resilient Buildings and Urban Environments

ibpc2018.org | #ibpc2018

The effect of the position and temperature difference of local radiant asymmetry on thermal comfort: an experimental investigation

Stijn Van Craenendonck[1,*], Leen Lauriks[1], Cedric Vuye[1], Jarl Kampen[2,3]

[1] EMIB research group, University of Antwerp, Antwerp, Belgium

[2] Department of Epidemiology and Social Medicine, University of Antwerp, Antwerp, Belgium

[3] Biometris, Wageningen University, Wageningen, The Netherlands

*Corresponding email: Stijn.vancraenendonck@uantwerpen.be

ABSTRACT

In cold and moderate climates, poorly designed construction joints can lead to local low surface temperatures, which entails local radiant asymmetry. An experiment was set up to test the hypothesis that overall and local thermal sensation is influenced by temperature difference, and position and distance of local radiant asymmetry. In the experiment, 18 subjects participated where they were introduced in a room at 21°C and 45% relative humidity. The subjects were exposed to local radiant asymmetry created by a cooling plate. This plate was positioned at three different heights, and controlled for temperatures at 3, 6 or 10°C below room air temperature. The data was analyzed using general linear modelling.

The results show that thermal sensation is not influenced by local radiant asymmetry directly, but that the deviation from base comfort level is linked to height and temperature of the cold plate, as well as distance of the plate to the subject. This last effect proved to be the strongest. Contrary to what was expected however, participants felt warmer when exposed to local radiant cooling, compared to when not exposed to it. Further research is needed to determine the cause of this effect.

KEYWORDS

Thermal comfort, thermal sensation, radiant asymmetry, experiment.

INTRODUCTION

While renovating existing buildings, planar parts of the building shell are often insulated without proper care for the joints connecting these parts. In cold and moderate climates, poorly designed construction joints can lead to local wall areas with a low surface temperature. These local colder areas lead, next to a higher risk for surface condensation, to radiant temperature asymmetry and can influence thermal comfort of the residents.

McNall and Biddison started the research into radiant asymmetry by placing subjects in a test chamber of which they cooled and heated one wall or the ceiling. They concluded that no significant discomfort could be attributed to radiant temperature asymmetry due to a wall with view factor 0.2 at 11°C colder than the environment. (McNall & Biddison, 1970) Olesen et al. discovered that subjects could sense small degrees of radiant temperature asymmetry, but much larger asymmetry was needed to cause discomfort. (Olesen et al., 1972) Research by Fanger et al. (Fanger et al., 1985) found that cool walls have the largest influence on thermal comfort compared to floors and ceilings. This influence however was relatively limited: if the surface temperature of the cool wall was less than 10 °C under average air temperature, the percentage of people dissatisfied with the environments was less than 5%.

In all these experiments, the asymmetric environment was realized by cooling entire walls. For construction joints, lower surface temperature is only a local effect which can influence only a specific body region. Research has proven that different body regions have different thermal sensitivities. Cooling of the trunk areas of the body (chest, back) strongly affects overall thermal sensation, while the effect is much less noticeable in the bodies' extremities. (Arens et al., 2006) Nakamura et al showed that different parts of the body not only have different thermal sensation, but also have different influences on overall thermal comfort. (Nakamura et al., 2013)

In this paper, a thermal comfort experiment in a semi-controlled environment is reported to test our hypothesis: overall and local thermal sensation are influenced by temperature difference, position and distance of local radiant cooling.

METHODS

Subjects

18 subjects (16 men, 2 women) participated in the experiment. Mean subject age (± Standard deviation) was 28.2 (± 13.5) years. Average length and weight were 181 (± 8) cm and 77.4 (± 11.1) kg respectively. Clothing was prescribed for all subjects: short-sleeve T-shirt, non-ripped long pants, underwear, socks and closed shoes. Together with the office chair, the total clothing value was 0.52 according to ISO 9920. (Bureau voor Normalisatie, 2009) During conditioning and testing, subjects had to sit at a desk and perform office work on a computer. This corresponds with 1.2 met according to ISO 8996. (Bureau voor Normalisatie, 2004)

Conditions

Experiments took place in a 6.4 m x 4.7 m x 4.1 m room with concrete walls at the University of Antwerp, Belgium (test setup in Fig. 1). The building management system controlled air temperature and relative humidity in the room. Average (± standard deviation) air temperature and relative humidity were 21.7 (± 0.4) °C and 44.9 (± 4.3) %. Radiant temperature was ensured to be equal to air temperature. Air velocity was less than 0.1 m/s at all points.

Plate temperature was based on thermal simulations of typical Belgian construction joints. Setpoints for plate temperature were 0, 3, 6 and 10°C below ambient room temperature.

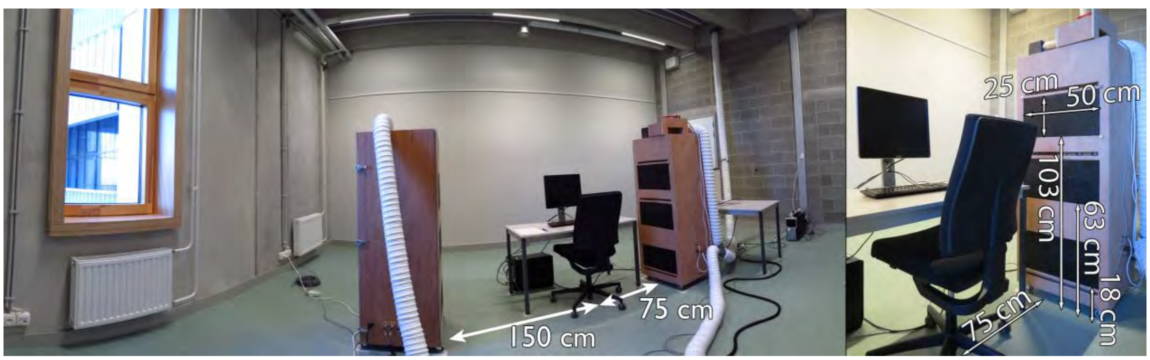

Fig. 1: Test setup

Experimental procedure

The experimental procedure is displayed in Fig. 2. Before subjects entered the test chamber, they filled out a preliminary survey in an anteroom. The temperature and humidity in the anteroom was the same as the test room. After this preconditioning, subjects took place in the test room and started their office work. The first 30 minutes in the test room, no test conditions were applied to let subjects acclimatize to the environment. Afterwards, each subject experienced 3 test phase with 1 randomly selected test condition each. A test condition consisted of a set plate temperature, plate position and distance to subject.

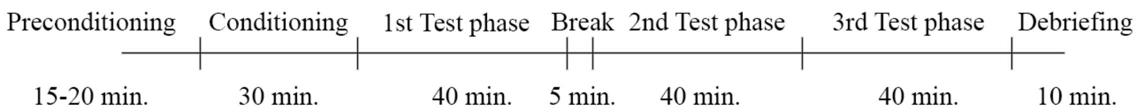

Fig. 2: Experimental procedure

Questionnaire

Subjects were asked to fill out a preliminary survey during preconditioning. In this survey, subjects were asked about age, length, weight, caffeine and alcohol consumption, sleep duration and quality and whether subjects were often warm or often cold.

Subjects had to fill out a questionnaire every 15 minutes, and at 10 and 25 minutes in the conditioning phase. A 5-level scale was used to rate overall and local thermal sensation (TSV) and change preference. A 7-level scale was employed to rate overall thermal comfort (TCV). Overall and local draft perception was noted as yes-no choice, just as acceptability. Local TSV and draft perception had to be rated for 9 different body regions (head, neck, chest, upper arm, lower arm, hand, upper leg, lower leg, foot). These scales were selected because of their widespread use in similar experiments. (Van Craenendonck et al., 2018)

Analysis Methods

Linear regression (McDonald, 2015, pp. 190–208) and chi-square tests (McDonald, 2015, pp. 59–67) were used to determine the influence of demographic data of the sample, such as age and sleep quality, and on general and local thermal sensation votes (TSV) (IBM, 2015). Post-hoc analysis of the standard residuals as proposed by Sharpe (Du Bois & Du Bois, 1989) was employed when the Chi-square test yielded significant results.

The relation between temperature of the cooling plates and local TSV-scores of the subjects was examined using general linear modelling. Temperature of the plate, height of the plate and distance between plate and subject were used as fixed effects.

Analysis was performed in SPSS version 24 (IBM, 2015). A full factorial model was used as a starting point, excluding variables that were not significant for further analysis. Main effects were always included in the model if they were included in a significant second-order effect. Adjusted R^2 (Frost, 2013) was used to assess goodness of fit of the models, and partial η^2 ($p\eta^2$) (Levine & Hullett, 2002) was used to compare effect sizes.

RESULTS

All analysis was performed on the scores each subject gave in the last 5 minutes of each test phase, i.e. at 25 minutes in the conditioning phase, and at 35 minutes in each test phase. Previous research has shown that full adaptation to the thermal environment has occurred at this point. (Van Craenendonck et al., 2018).

First analysis showed that alcohol consumption in the 24 hours prior to the experiment had a significant effect on all thermal sensation scores. It should be noted however that there was only one person who did consume alcohol in the 24 hours prior to the experiment. This person was excluded from further analysis. Age also had a significant effect on TSV-values in the legs (upper legs, lower legs and feet), with people over 60 years old feeling significantly colder. People who self-indicate that they often feel cold, signaled that their head, neck and chest felt significantly warmer than people who don’t indicate often feeling cold. All further analysis was performed with the respective influencing groups once included and once excluded to determine their effect on the conclusions of this paper.

When looking at the TSV-scores nominatively, whole-body ($p = 0.011$), neck ($p = 0.050$), chest ($p = 0.022$), upper arm ($p = 0.003$) and upper leg TSV ($p = 0.029$) are all significantly influenced by distance between cold plate and subject. Subjects exposed to the cold plate at

1,5 m mark thermal sensation for these regions lower than subjects exposed to the plate at 0,75 m. Whole-body ($p = 0.004$) and hand TSV ($p = 0.041$) are influenced by the height of the cooling plate, with subjects exposed to the plate at chest height being significantly colder than subject exposed to the plate at feet height in both cases. Excluding people who self-indicate that they often feel cold from the analysis does not influence these results, and neither does excluding people over 60.

Because different subjects may have different base comfort levels in the ambient conditions of the test room, a new analysis was performed on the change in TSV-values under test conditions compared with the TSV-scores after conditioning. The strongest main effect in each of the models and adjusted R^2-values are displayed in Table 1.

Table 1: Summary of the models for change in thermal sensation

	aR^2	Strongest predictor ($p\eta^2$)		aR^2	Strongest predictor ($p\eta^2$)
Whole-body TSV	0.37	Height (0.26)	Lower arm TSV	0.20	Distance (0.20)
Head TSV	0.19	Height (0.17)	Hand TSV	0.08	Distance (0.10)
Neck TSV	0.35	Distance (0.28)	Upper leg TSV	0.47	Distance (0.23)
Chest TSV	0.32	Distance (0.28)	Lower leg TSV	0.40	Height (0.18)
Upper arm TSV	0.23	Temperature (0.20)	Foot TSV	0.23	Height (0.14)

Temperature of the cooling plate is a significant effect in whole-body thermal sensation ($p = 0.025$), as well as neck ($p < 0.001$), chest ($p = 0.004$), upper arm ($p = 0.004$) and lower arm TSV ($p = 0.017$). In all cases, the change in TSV-values indicated that subjects felt warmer as the temperature of the cold plate was lower. In almost all cases, subjects felt warmer than they did after conditioning. Excluding people who often feel cold from the analysis made the effect of temperature on neck TSV insignificant.

Distance between cooling plate and subject had a significant effect on all TSV-values. As can be seen in Fig. 3, the difference in all cases was greater than zero for participants exposed to the plate at 0.75 m, indicating that they felt warmer than after conditioning. Furthermore, in all cases, subjects exposed to the plate at 0.75 m felt warmer than those exposed to the plate at 1.5 m. Participants subjected to a cooling plate at 0,75 m in all cases felt warmer than after conditioning.

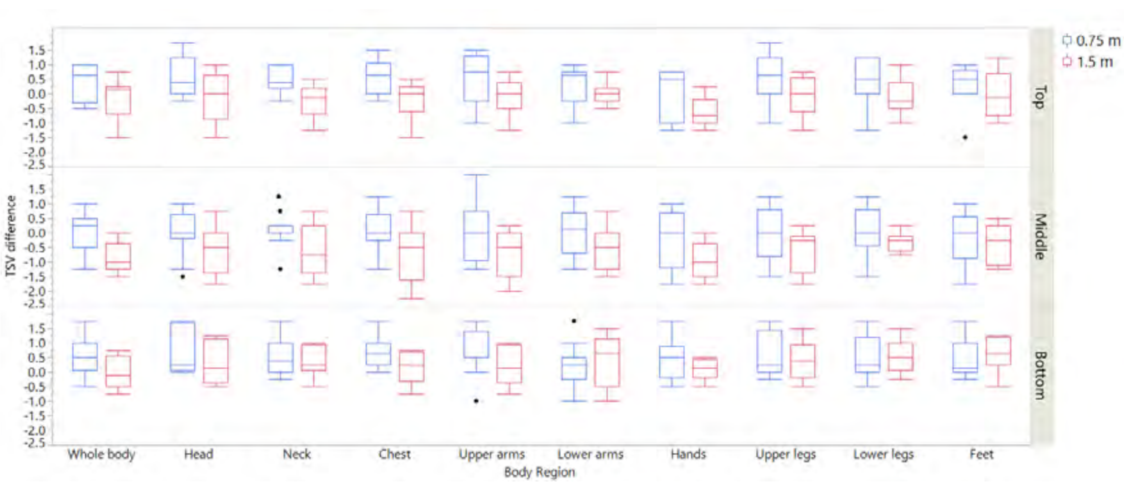

Fig. 3: Difference of TSV value during testing and after conditioning, split by distance between cold plate and subject and by plate height. (Positive indicates warmer during testing)

Plate height had an effect on whole-body TSV ($p < 0.001$), as well as thermal sensation in the head ($p = 0.013$) and leg region (upper legs ($p = 0.006$), lower legs ($p = 0.006$) and feet ($p = 0.021$)). The effect was the same in all cases: difference in TSV between during test and after conditioning was significantly higher for the people exposed to the plate at feet level than those exposed to the plate at chest level, as seen in Fig. 3. People exposed to the plate at chest level always felt colder than after conditioning, while people exposed to the plate at feet level always felt warmer. Removing people over 60 from the analysis made the effect of height of the cold plate on thermal sensation in the feet insignificant.

DISCUSSION

From the results of the whole-body and local TSV-score analysis, it is clear that neither temperature of the cooling plate, nor position (height and distance to subject) have a strong effect on thermal sensation. Even when a statistically significant effect is found, adjusted R^2-values show that only a very small amount of variance in the thermal sensation can be explained by parameters related to local radiant asymmetry.

When looking at the change in thermal sensation during testing vs after conditioning, the parameters related to local radiant asymmetry have a stronger effect. Nevertheless the predictive powers of the models for hand TSV remained very low, as shown by R^2-value in Table 1. The significant effect of plate temperature on neck TSV and height of the cold plate on foot TSV occur to be linked to an uneven distribution of people with different demographics across the test conditions, rather than to local radiant asymmetry.

Distance between cooling plate and subject is often the most important effect in the models for predicting change in thermal sensation. Examining the details, almost all TSV-values are higher during testing than after conditioning, meaning that, on average, subjects feel warmer when subjected to local radiant cooling. These results are counter intuitive: e.g. subjects tend to feel warmer in the leg region when the cold plate at feet level is active. It is also remarkable that all participants subjected to a cooling plate at 0,75 m felt warmer, while the results for participants subjected to a cooling plate at 1,5 m were mixed, with some feeling warmer and some feeling colder than after conditioning. No significant rise in ambient temperature or relative humidity, nor radiant temperature from other parts in the test setup were discovered. Further research will be necessary to determine the cause for this effect.

The results as such confirm previous research by McNall & Biddison and Fanger, in that small radiant temperature asymmetry causes almost no change in thermal sensation in people. Most significant effects are found for bodies' extremities, which suggest that those are more strongly affected by local radiant cooling. However, no logical link existed between the height of the cooling plate and the location of the affected body region. Because results are this unexpected, further validation of the experimental setup will be performed by thermographic imaging with view factor correction to quantify radiant temperature asymmetry at the subjects' position. The results of this validation will provide additional information to explain the results of this experiment. The questionnaire will be validated by running short experiment series in more extreme conditions to test whether it is an adequate instrument to assess the thermal environment.

It should be noted that these results are based on an experiment with 18 subjects. The number of participants is lower than the average of 25 found in literature. (Van Craenendonck et al., 2018) Within these 18 participants, only 2 were female. Schellen et al found evidence for a significant difference in thermal response between men and women. (Schellen et al. 2012) No influence of gender was found in these results, but this may be due to the small amount of females. Further experiments will be conducted to correct for the skewed gender distribution.

CONCLUSIONS

From the experiments, it can be concluded that the temperature difference and position of local radiant asymmetry does not strongly affect thermal sensation directly, but does have an impact on the base comfort level. The effects however are not as expected, with subjects who are exposed to local radiant cooling indicating that they feel warmer. This effect is noticeable for whole-body thermal sensation, as well as local thermal sensation, except in the head.

REFERENCES

Arens, E., Zhang, H., & Huizenga, C. (2006). Partial- and whole-body thermal sensation and comfort - Part II: Non-uniform environmental conditions. *Journal of Thermal*, *31*(1–2), 60–66.

Bureau voor Normalisatie. (2004). *NBN EN ISO 8996: Bepaling van het energiemetabolisme*.

Bureau voor Normalisatie. (2009). *NBN EN ISO 9920: Bepaling van de thermische isolatie en verdampingsweerstand van kleding*.

Du Bois, D., & Du Bois, E. F. (1989). A formula to estimate the approximate surface area if height and weight be known. 1916. *Nutrition (Burbank, Los Angeles County, Calif.)*, *5*(5). https://doi.org/10.1001/archinte.1916.00080130010002

Fanger, P. O., Ipsen, B. M., Langkilde, G., Olesen, B. W., Christensen, N. K., & Tanabe, S. (1985). Comfort Limits for Asymmetric Thermal Radiation, *8*, 225–236.

Frost, J. (2013). Multiple Regression Analysis: Use Adjusted R-Squared and Predicted R-Squared to Include the Correct Number of Variables.

IBM. (2015). SPSS Statistics. Retrieved from https://www-01.ibm.com/software/be/analytics/spss/

Levine, T. R., & Hullett, C. R. (2002). Eta Squared, Partial Eta Squared, and Misreporting of Effect Size in Communication Research. *Human Communication Research*, *28*(4), 612–625. https://doi.org/10.1093/hcr/28.4.612

McDonald, J. H. (2015). *Handbook of Biological Statistics* (3rd ed.). Baltimore, Maryland. Retrieved from http://www.biostathandbook.com/kruskalwallis.html

McNall, P. E. J., & Biddison, R. E. (1970). Thermal and comfort sensations of sedentary persons exposed to asymmetric radiant fields.

Nakamura, M., Yoda, T., Crawshaw, L. I., Kasuga, M., Uchida, Y., Tokizawa, K., … Kanosue, K. (2013). Relative importance of different surface regions for thermal comfort in humans. *European Journal of Applied Physiology*, *113*(1), 63–76. https://doi.org/10.1007/s00421-012-2406-9

Olesen, S., Fanger, P. O., Jensen, P. B., & Nielsen, O. J. (1972). Comfort limits for man exposed to asymmetric thermal radiation. In *Thermal comfort and moderate heat stress* (pp. 133–148). London.

Schellen, L., Loomans, M. G. L. C., de Wit, M. H., Olesen, B. W., & Lichtenbelt, W. D. V. M. (2012). The influence of local effects on thermal sensation under non-uniform environmental conditions - Gender differences in thermophysiology, thermal comfort and productivity during convective and radiant cooling. *Physiology and Behavior*, *107*(2), 252–261. https://doi.org/10.1016/j.physbeh.2012.07.008

Van Craenendonck, S., Lauriks, L., Vuye, C., & Kampen, J. (2018). A review of human thermal comfort experiments in controlled and semi-controlled environments. *Renewable and Sustainable Energy Reviews*, *82*(December 2016), 3365–3378. https://doi.org/10.1016/j.rser.2017.10.053