Effects of daytime cool vs warm exposure on evening thermal perception and thermoregulation

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Abstract. Thermal conditions experienced during daytime can be different from those experienced after working hours outdoors or at home. Since most dwellings in Central and Western Europe in the temperate climate zone are naturally ventilated (NV), while public spaces and offices are often air-conditioned (AC), a substantial gap between daytime and evening thermal exposure can occur. This thermal gap likely reduces acclimation to the more 'natural' climate outdoors and in NV spaces, and therefore may affect thermoregulation and thermal perception. Structural information on how thermal conditions experienced during daytime (e.g. in offices) influence thermal perception and physiology in the evening (at people's private homes). Therefore, the present study seeks to assess the impact of staying in cool vs. warm environments during daytime working hours on thermal perception and thermophysiology in the evening at home.

In this hybrid laboratory and field study, 31 participants (41±17 years, BMI: 24±3 kg/m^2) were exposed to a simulated workday in either 21 °C (cool) or 28 °C (warm) at two separate occasions. Thermal sensation, thermal preference and mean skin temperature were measured at eight timepoints throughout the day (lab) and evening (home) until the following morning.

Preliminary results suggest that daytime thermal conditions affect people's thermal perception and thermophysiology after working hours at home. The effect is most pronounced just after arriving at home and decreases over time. Importantly, our results raise the question whether conditioning of work places solely based on on-site productivity and comfort, but without considering the impact on comfort and well-being during leisure and recovery time at home, is the way to go in the future.

Keywords: Thermal perception, air conditioning, natural ventilation, thermoregulation.
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1. Introduction

People working in public and commercial spaces are often exposed to thermal conditions that are more or less independent from naturally-occurring outdoor temperatures, as many of them are air-conditioned (AC). In Germany, only about 2% of residential buildings, but about 50% of non-residential, e.g. office buildings, are equipped with AC [1]. For both types of buildings, numbers are expected to rise sharply within the upcoming years, according to the International Energy Agency [2]. Particularly in the Asian and North American region, the use of AC is already much more widespread, in both residential and non-residential buildings, than in Europe [2].

Thermal conditions in AC spaces are usually strictly controlled and uniform, based on indoor environmental standards such as ASHRAE 55 [3]. In contrast, in naturally ventilated (NV) dwellings, thermal conditions vary within the time of a day and night, as well as through different seasons of the year.

Consequently, people who spend the majority of their daytime in AC spaces may perceive more 'natural' thermal environments as less comfortable, which may also include their homes. In contrast, people working in NV spaces (or even outdoors) are likely to benefit from natural acclimatisation effects and may thus be better adapted to the fluctuating conditions of a specific time and season. A person's individual thermal physiology and thermal perception may be influenced by factors including, but not limited to, age, BMI, physical fitness, thermal preference, and thermal acclimatisation.

The widespread availability of AC in public and commercial buildings as well as offices is likely also affecting people's choices and behaviours at home: if natural acclimatisation in spring and summer during daytime is prevented by the use of AC, it may be hypothesised that people would be more inclined to the usage of AC at home. Considering the progress of climate change, which brings along an increase in global average temperature, but also increasingly frequent and more intense summer heat waves, it is likely that many people will want to acquire an AC unit for their homes, to reproduce the controlled conditions they are used to from their work environments. Unfortunately, this will cause an increased energy demand, which counteracts the need to reduce our environmental impact, and can further worsen the issue of overheated cities and the heat island effect [2, 4].

To avoid getting drawn deeper into this vicious circle, it is important to assess whether being exposed to particular thermal conditions during daytime working hours will influence human thermal physiology and perception in the later course of the day. This knowledge brings us a step ahead in the design and implementation of sustainable, comfortable, and healthy indoor environmental conditions, in order to make both people and buildings more resilient. Hitherto, structural information on the interaction of daily thermal history on thermal physiology and perception, is lacking. Therefore, the present study seeks to evaluate the effect of cool vs warm conditions in a simulated office environment, on thermoregulation and thermal perception in the evening at home. We hypothesise that staying in a cool environment during the day will result in higher (thus warmer) thermal perception of natural summer conditions after working hours at participants' homes. The measurements described in this article are part of a larger study. For the purpose of this conference paper, the analysis of a limited set of measurements obtained will be presented.

2. Methods

2.1 Study design

To assess the effects of a cool vs warm environment during the workday on thermoregulation and thermal perception in the evening at home, a hybrid study with a controlled laboratory part and an observational field part was set up: a simulated workday at the laboratory and subsequent field observations at the participants' private homes. To account for differences in the order of exposures, a cross-over design was selected, where all participants underwent one cool (C, 21 °C) vs one warm (W, 28 °C) laboratory condition, followed by the observational part at the participants' homes. Wherever possible with respect to scheduling, two participants were coupled with each other for both sessions, and sat together in the simulated office environment throughout the day. Others were at the laboratory by themselves for both sessions.

2.2 Participant characteristics

A sample of 32 healthy male and female participants (one dropout for personal reasons, thus n=31 for analysis; age: 41±17 years, BMI: 24±3 kg/m²) was recruited for the study based on an a-priori sample size calculation (G*power [5]) with α=.05, β=.8, η2=.5 (medium effect size). This calculation resulted in a total population of 27, which we increased by 20% to include drop-out. Participants were screened for their general health status to assess eligibility for the study. Amongst other things, exclusion criteria included the intake of medication as well as acute and active diseases that are known to affect thermoregulation.

2.3 Study procedures and measurements

Participants arrived at the laboratory in the morning at 08:00 a.m.. Upon arrival, their COVID-19 vaccination status was checked, and an antigen test was performed if necessary. After ensuring the participants were either fully vaccinated or tested negative, they were equipped with sensors to mean skin temperature at 4 ISO-defined sites [6] using wireless temperature sensors (iButtons®, Maxim Integrated, USA) over one-minute intervals. Whole-body thermal sensation was assessed using the ASHRAE 7-point scale (−3=cold, −2=cool, −1=slightly cool, 0=neutral, 1=slightly warm, 2=warm, 3=hot) and thermal preference using a 7-point scale (−3=much cooler, −2=cooler, −1=slightly cooler, 0=no change, 1=slightly warmer, 2=warmer, 3=much warmer) at eight time points throughout the day: 1. 9:00h, 2. 11:00h, 3. 13:00h, 4. 14:00h, 5. 16:00h (1-5 at the laboratory), 6. 18:00h, 7. 22:00h, and 8. 7:00h the following morning (6–8 at participants' homes). During the two experimental days, participants were asked to wear the same clothes both days (long-sleeved light top or short-sleeved light top, long trousers, underwear, socks, and low shoes). Thermal conditions in the laboratory room were assessed using a commercially available air temperature sensor (Testo 480, Probe 0632 1543, Titisee-Neustadt, GER). Moreover, participants were equipped with a tailormade portable environmental monitoring station to be used at their homes, to control for environmental conditions during the observational part of the study. Participants were instructed to keep it in close (but not too close) proximity of their whereabouts. They were instructed to carry the device with them whenever they changed a room for more than 10 minutes. The device did not have a display in order to avoid any influence of environmental measurements on subjective perception and survey results. Participants were instructed to go home after the laboratory part of the study without delay, with minimal physical activity (preferably by car or public transport) and to prevent extreme thermal exposure (such as direct sun radiation or strong draft).

2.4 Statistics

Mean skin temperature, thermal sensation and thermal preference were compared over the eight designated time points between condition C and W using Wilcoxon Signed Rank tests for non-parametrical data in the software R. A difference with $p<.05$ was considered as statistically significant, and a trend towards significant difference was assumed at $p<.10$. Data is presented as mean±standard deviation.

3. Results

Ambient temperature in the laboratory during condition C was 22.4±1.7 ˚C and 27.7±1.6 ˚C during condition W. Temperatures observed at people's homes at the day of condition C ranged 23.4±1.9 ˚C [min 19 and max 29.7 ˚C] and 23.5±1.65 ˚C [min 18.9 and max 31.5 ˚C] at the day of condition W ($p>.05$). Throughout the day and evening until the following morning of condition C, mean skin temperatures of 29.8± 5.1˚C [range 17–39.3 ˚C], thermal sensation of −1 (median) [min −3 and max 3] and thermal preference of 1 (median) [min −3 and max 3] were observed. Throughout the day and evening until the following morning of condition W, mean skin temperatures of 29.8±6 ˚C [range 13.3–37 ˚C], thermal sensation of 1 (median) [min −2 and max 3] and thermal preference of −1 (median) [min −3 and max 1] were measured.

3.1 Mean skin temperature

Mean skin temperature was statistically significantly lower during condition C compared with condition W for timepoints 1–5 (V=0 for timepoints 1–5, all $p<.000$, effect sizes range=0.88–0.90 for timepoints 1–5, Fig. 1). At timepoint 6, a trend was observed towards higher mean skin temperatures in condition C compared with condition W (V=110.5, $p=.094$, effect size=0.32). There was no significant difference in mean skin temperature at timepoints 7 and 8 between C and W.

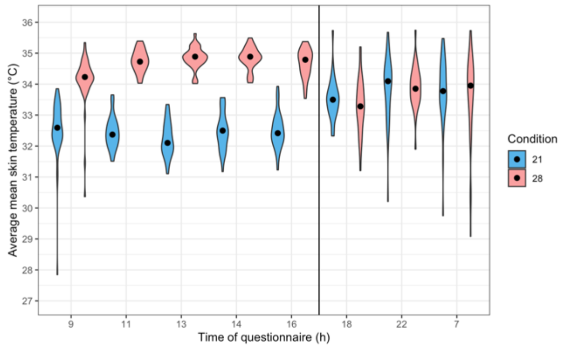

Fig. 1 – Mean skin temperature at the questionnaire times for the cool (21 ˚C) and warm (28 ˚C) condition.

3.2 Thermal sensation

Thermal sensation was significantly lower during condition C compared with condition W for timepoints 1–5 (V=0 for timepoints 1–5, all $p<.000$, effect size=0.88 for timepoints 1–5, Fig. 2). At timepoint 6, the first observed at participants' homes, thermal sensation was significantly higher at condition C compared with condition W (1.4±0.9 vs 0.7±0.6, V=129, $p<.000$, effect size=0.64). At timepoint 7, the difference was no longer statistically significant. At timepoint 8, a trend towards significantly higher thermal sensation in the morning after condition C compared with condition W was observed (V=124.5, $p=.079$, effect size=0.39).

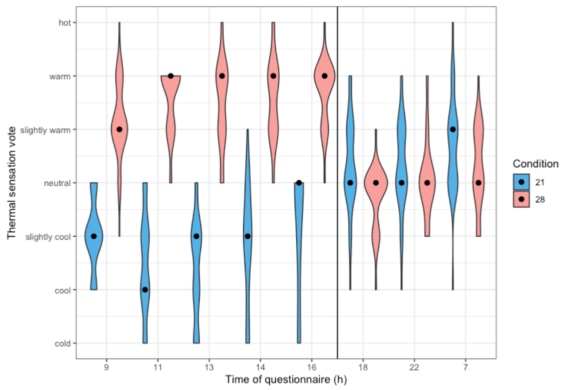

Fig. 2 – Thermal sensation votes at the questionnaire times for the cool (21 ˚C) and warm (28 ˚C) condition.

3.3 Thermal preference

Thermal preference was significantly higher during condition C compared with condition W for timepoints 1–5 (V_1=300, V_2=496, V_3=496, V_4=496, V_5=351; all $p<.000$, range effect size=0.87–0.88 for timepoints 1–5; Fig. 3). At timepoints 6–8, thermal preference was not different between condition C (0.8±0.7) and W (0.9±0.7).

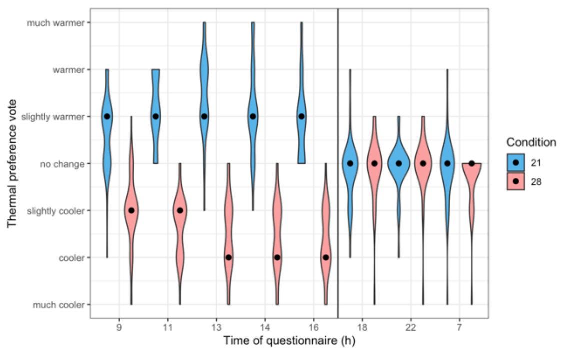

Fig. 3 – Thermal preference votes at the questionnaire times for the cool (21 ˚C) and warm (28 ˚C) condition.

4. Discussion and conclusion

The present paper aimed at establishing the effect of daytime (workplace) thermal exposure on thermal perception in the evening (at home). Preliminary analysis shows a significant effect of circadian thermal history on whole-body thermal sensation, where exposure to a cool (21 ˚C) environment during the day produced higher (meaning warmer) thermal sensation at the participant's private home, one hour after leaving the laboratory environment. In contrast, when participants were exposed to a warm (28 ˚C) environment during the day, thermal sensation was lower at the participants' private home, one hour after leaving the laboratory environment. The effect diminished until five hours after leaving the lab, even though a trend towards a difference in thermal sensation was observed in the morning after exposure to a cool vs warm environment. Even though no significant differences in measured physical thermal conditions were detected, thermal sensation was significantly different after participants arrived at home. As thermal perception (thermal comfort and sensation) is closely related to thermoregulatory behaviour (such as changing clothes, opening and closing windows, or operating a thermostat or an AC unit) [7, 8], it may be anticipated that higher thermal sensation at home, particularly in summer, would lead to a desire for (artificial) cooling. In accordance with our hypothesis, it may thus be expected that people who also work in air-conditioned offices are more inclined towards the use of AC at their homes, to counteract the higher thermal perception.

Alongside with the significant increase in thermal sensation one hour after leaving the lab on the day of the cool condition, a trend towards higher mean skin temperatures was observed. It is well-established that thermal sensation is related to skin temperature [9]. Both absolute mean skin temperature, but also the rate of change of skin temperature, play roles in this relationship. As expected, mean skin temperature was lower in the cool laboratory condition and higher in the warm laboratory condition, which also produced the corresponding thermal sensation (lower in cool and higher in warm condition). After the first part of the experiment, which took place in the controlled laboratory environment, participants left for their private homes. Interestingly, at this point, a trend towards higher mean skin temperatures after the cool condition vs lower mean skin temperatures after the warm condition was observed, which is also reflected in thermal sensation. It might be speculated that this reversal could be due to thermoregulatory behaviour (e.g. seeking relatively warmer or cooler environments, in spite of the instructions provided by the researchers), or even a change in physical activity (i.e. more physical activity to generate warmth after the cool condition). Since thermoregulatory behaviour is a very natural automatic act (think of rolling up sleeves for better cooling or a hunched posture with crossed arms in front of the chest for heat retention), participants might not even have noticed this, let alone had the intention to actively warm up or cool down and thus resist the instructions. Analysis of these potential confounders will be part of the ongoing analysis. Moreover, as the latter part of the experiment was of observational character and in real-life circumstances, the environment was not controllable. This led to differences in thermal exposure from participant to participant and from day to day, which may have also played a role in this context.

When interpreting the above results, it should be considered that opposed to thermal sensation, thermal preference was not different in the second, observational part of the study, in the hours after the cool vs the warm laboratory condition. Interestingly, participants even indicated to prefer warmer temperatures during the cool condition, which may enhance the comfort feeling related to the higher thermal sensation after returning home, based on thoughts related to thermal alliesthesia [10]. Thermal alliesthesia describes the pleasure perceived when moving from an uncomfortably cold or hot environment to the respectively opposite condition, e.g. standing in front of a lit fireplace after returning home from a winter walk, or jumping into cold water on a hot summer day. The state of alliesthesia is, however, usually not very long-lasting, but rather attenuates as soon as the body has returned to a state of thermal equilibrium. With respect to our results, the cool vs warm laboratory conditions could explain the higher thermal sensation after the cool condition, and the lower thermal sensation after the warm condition (with no change in thermal preference, due to higher respectively lower sensation and skin temperatures in cool vs warm), as well as the diminishment of this effect over time. Deeper analysis of this relationship is warranted.

The results presented in this paper are part of a larger study and the analysis has not been finalised, which is why the presented findings may not be the final conclusion of the investigation. The original idea of the study was to assess the effect of daytime air-condition exposure on thermal perception in naturally-ventilated spaces in warm summer evenings. Unfortunately, the summer of 2021, when the measurements took place (end of June till beginning of October) was much cooler than expected based on the record-breaking summers of the preceding years. Even though our collected dataset does not necessarily reflect what we originally wanted to investigate, the data still points towards the same original hypothesis: being exposed to (overcooled) air-conditioned spaces for the major part of the day (in this case ~8 hours) influences the thermal sensation of warmer (outdoor or naturally ventilated) spaces in the evening.

In conclusion, we have observed higher thermal sensations at home after being exposed to cool daytime environments, and the other way around. Further analysis is needed to unravel the underlying relationships between skin temperature and thermal perception and influences of confounding variables as well as to relate our findings to the available knowledge on short-term acclimation and seasonal adaptation.

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6. References

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Data access statement

The datasets generated and/or analysed during the current study are not yet available, as they are still being processed. However, the authors will make every reasonable effort to publish the datasets as soon as possible in the near future.