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Improved understanding of thermal comfort could yield energy savings in heritage buildings

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Abstract. It is necessary to improve the understanding of thermal comfort to reduce energy consumption for heating and cooling in heritage buildings, which are often energy inefficient and where interventions are limited. Personal thermal comfort models based on measurements of environmental conditions and the individual's physiological and subjective responses represent a potential solution to ensure the optimization of existing systems. Past research shows that lighting could impact thermophysiology and subjective perception of thermal conditions, but it is not clear whether the impact is sufficient to make light adaptation an appropriate solution to reduce energy consumption in heritage buildings, where people live and work. The research conducted under realistic semi-controlled conditions in an office environment of an existing building addresses this research gap. The paper presents the first partial simplified analyses and preliminary results of a wider ongoing study, mainly showing a correlation between skin temperature and air temperature and a partially promising effect of light on subjective thermal perception. Our research on the effect of light on thermal comfort does not provide definitive conclusions but rather highlights the need for further investigation in actual heritage buildings.

Keywords: minimal intervention renovation, heritage buildings, thermal comfort, light

1. Introduction

The building and construction sector plays a significant role in global energy consumption, accounting for 36% of the total energy consumption [1]. While new buildings consume less energy, about 35% of the EU's buildings are over 50 years old, and almost 75% of buildings are energy inefficient [2]. These buildings offer great potential for reducing environmental impacts, but renovating existing buildings can be challenging. It entails high initial costs, disruption for building occupants, and compatibility issues. When it comes to energy renovations of heritage buildings, which in the context of European history are of great value, conservation constraints pose an additional challenge. There are three primary approaches to improving the energy efficiency of buildings: (1) Improving the thermal transmittance, or U-values, of building materials and components can help reduce heat transfer and improve overall energy efficiency. (2) Addressing and mitigating thermal bridges, which are areas of higher heat transfer, can also contribute to enhanced energy performance. And (3) Improving the management and control of ventilation systems that can help minimize energy losses associated with air exchange, further boosting the energy efficiency of buildings. To preserve the appearance, all those

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strategies can be difficult to implement in buildings protected as cultural heritage. Therefore, alternative solutions need to be considered to ensure occupants' comfort, minimize energy use, and preserve heritage value. Since 38% of building consumption comes from systems [3], providing thermal comfort to building occupants, an improved understanding of thermal comfort and appropriate adaptation of existing building systems could contribute to reducing energy consumption.

Thermal comfort is defined as a condition of mind, expressing satisfaction with the thermal environment. Fanger's model, considering air temperature, radiant temperature, air speed, air humidity, metabolic rate, and clothing, is often used to determine it. The model and standards such as ASHRAE 55 and ISO 7730 define acceptable ranges of thermal comfort-related parameters, focusing on the comfort of the group, but do not address individual differences. Personal thermal comfort models address the issue.

Recent research focuses on the use of environmental and non-intrusive wearable sensors to measure and predict an individual's comfort based on past survey responses [4]. Discomfort recognition potentially enables smart building systems to respond appropriately, activating only when necessary. Such a system ensures that energy is not used when it is not needed. Implementation of occupant-centric control strategy was reported to save air-conditioning energy by 22% and improve comfort by 29% [5].

Research on the development of predictive thermal comfort models has mainly focused on the measurement of thermal comfort-related factors and physiological responses, while the results from multi-domain studies suggest the existence of multi-domain effects. Previous research has been done on the impact of light on thermal comfort, but the results are not conclusive [6].

The relationship between light and thermal comfort may be caused by a subjective association between spectral power distribution and illuminance of light with cool or warm room temperatures, a correlation between visual and thermal comfort, or non-image forming effects of light that impact circadian rhythms [6,7]. The effects of light on humans are described by the five α-opic spectral sensitivity curves system, which considers the responses of photoreceptors in human eyes [8]. Photosensitive retinal ganglion cells cause melanopic responses to lighting conditions (melanopic lux), influencing the regulation of circadian rhythm, which is linked to body temperature fluctuations. As body temperature is linked to thermal comfort, describing light conditions with melanotic lux is appropriate.

While past research has shown that lighting can impact thermophysiology and subjective perception of thermal conditions, it is unclear whether the effect is sufficient to make light adaptation an appropriate solution to reduce energy consumption in buildings, including heritage buildings, where people live and work. The development of thermal comfort models that consider all the most important factors influencing thermal comfort and take other domains, such as lighting, into account can contribute to a more efficient use of heating and cooling energy. Adaptation of existing building systems would be a particularly useful solution for heritage buildings where building interventions are limited.

The goal of our broader research is to develop personal thermal comfort models, recognizing thermal discomfort based on all the relevant factors. Office environment mimicking a real-file scenario was used in our study. Personal thermal comfort models could provide comfort improvements and energy savings in heritage buildings through small interventions with smart systems. This paper presents a simplified analysis and preliminary results based on responses of the first 5 participants, included in the study. Since air temperature and skin temperature influence thermal comfort the most, according to previous research [4], those two factors were observed.

2. Materials and Methods

2.1. *Experimental Setting*

The experiment took place in an office environment as shown in Figure 1. Existing central heating and air conditioning were used to regulate the indoor air temperature. The light was controlled by spectrally adjustable luminaires. Posters with illustrations and potted plants were added to the space to provide a less laboratory-like feeling. The study's approach of using an office environment, similar to one that could exist in heritage buildings, can provide valuable insights applicable to such buildings. The research conducted under realistic semi-controlled conditions aims to address the research gap identified in past studies.

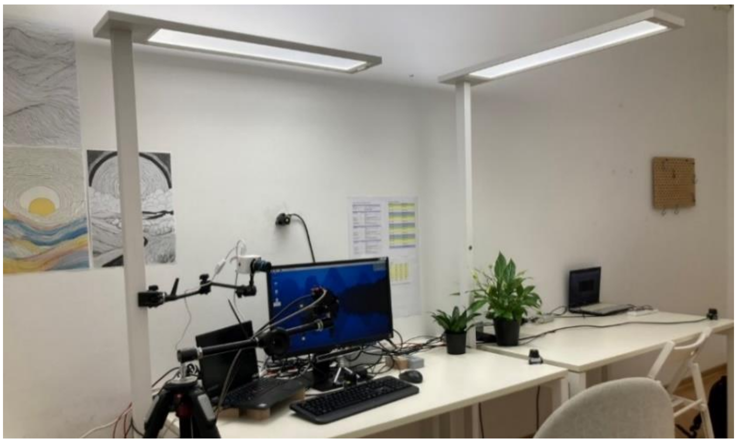

Figure 1. Experimental setting in the office

2.2. *Procedure*

The experiments were conducted during January and March 2024. Participants engaged in a five-day experiment following a structured protocol as presented in Figure 2. The experiment spanned from 8:30 AM to 3:20 PM each day. Participants were instructed to abstain from eating two hours before the experiment. Participants wore short sleeves and long trousers with closed shoes throughout the experiment. The main goal of the experiment was not revealed to the participants to avoid biased survey answers.

During the experiment, participants followed a structured schedule consisting of 10 minutes of acclimatization, followed by four blocks of repeated activities each day. Each block consisted of a break, 80 minutes of work and 5 minutes of relaxation.

During the work period, participants engaged in computer-based office-like activities of their choice. This ensured that participants did not focus exclusively on their environment, but that their activities were similar to those in real-life conditions. Unified snacks were provided during breaks to ensure metabolic stability and unify the effect of the meal on thermal comfort.

On the first introductory day, participants were exposed to neutral conditions: goal room temperature was between 24 and 25°C and illumination was constant with medium intensity. Participants were exposed to warmer conditions on the second and fourth days (26 to 27°C). On one day the light was warm-white and on the other day, it was cool-white. The illumination level varied throughout the day and was repeated twice, ensuring that the time of the day, impacting physiology, was considered in subsequent analysis. The same lighting pattern was applied on the third and fifth day when the participants were exposed to colder conditions (22 to 23°C). The illuminance values of lights measured at the eye level in the horizontal direction are presented in Table 1. The correlated color temperature (values) indicator is not stated, since lights with different spectral power distributions can have the same CCT, but different effects on humans [9]. Therefore, melanopic lux values, describing the effect of lights on human photosensitive retinal ganglion cells are stated instead.

Table 1. Photopic and melanopic illuminances (lux) measured at the eye level in horizontal direction

	Neutral-white moderate light	Warm-white bright light	Warm-white dim light	Cool-white bright light	Cool-white dim light
Photopic lux	380	730	33	728	31
Melanopic lux	327	320	21	743	34

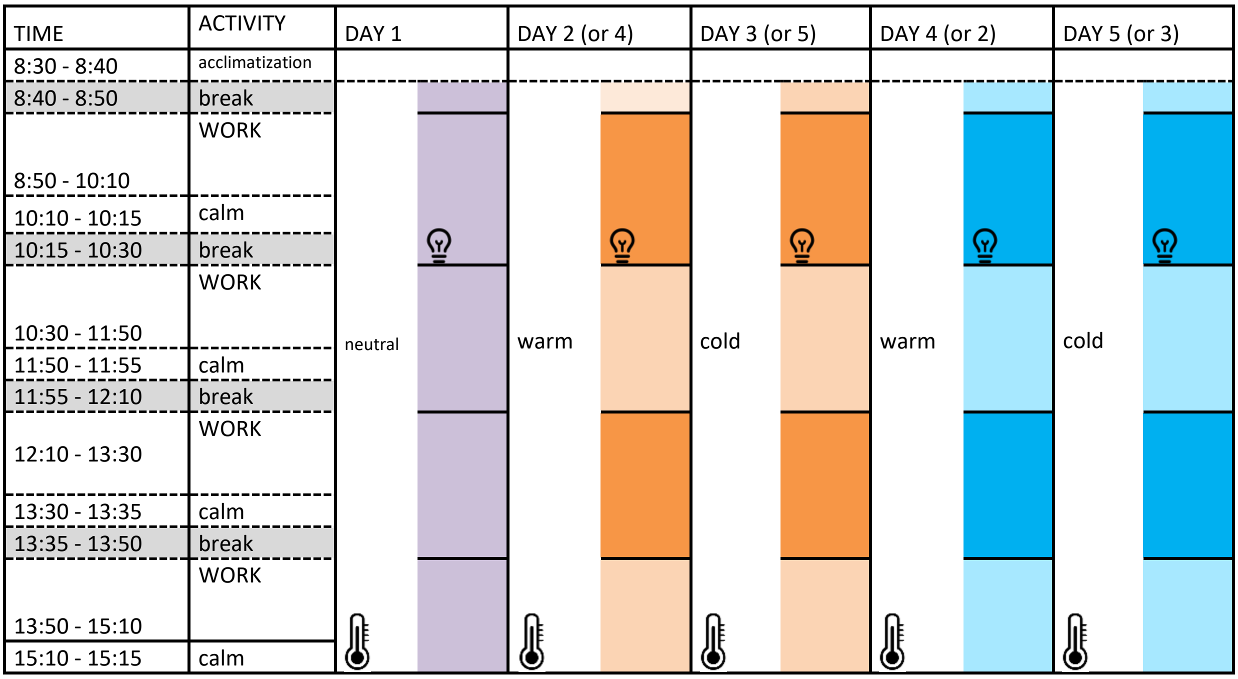

Figure 2. Experimental schedule

2.3. *Measurements*

Air temperature and relative humidity were monitored by a sensor, placed on the working desk, close to the participant. A spectroradiometer and five lux meters were used to monitor the horizontal and vertical spectral power distribution and illuminance near the participant and around the room to capture the distribution and quality of light in the office. In this paper, we have only included results from the spectrometer and lux meter at the eye level in the horizontal gaze direction.

Participant response was monitored using wearable sensors. Empatica EmbracePlus, a wristwatch-like device was used to measure participants' heart rate, skin temperature, electrodermal activity, and movement.

Subjective responses to office environment conditions were collected using a pop-up survey. Participants answered questions regarding all indoor quality domains, due to possible interactions, but also to not reveal the main goal of the study. The survey also included a question on the psychological state of the participant. The analysis in this paper focuses on answers regarding thermal sensation. The participants answered it on a 7-point scale with the following descriptions: cold (-3), cool (-2), slightly cool (-1), neutral (0), slightly warm (1), warm (2) and hot (3). At specified times, the survey automatically appeared on an extra screen located close to the screen, that participants were working on. An experiment schedule was reported automatically on the same screen.

2.4. *Participants*

As the research focuses on the development of personal models of thermal comfort, the group of participants was heterogeneous. The study included 5 participants aged between 24 and 47 years. There were 2 men and 3 women. All participants were in general good health and had no major visual abnormalities.

2.5. *Ethical considerations*

The study was conducted under ethical guidelines, with participants providing informed consent before participation. The participants were informed of their right to withdraw from the study at any time without penalty. The study protocol was approved by the University of Primorska ethics committee.

3. Results

3.1. *Environmental conditions*

The blackout of the office windows ensured precise light control, using spectrally adjustable luminaires. One experimental week's measurements are shown in Figure 3. In the top three charts, lux meter measurements are presented. The left chart presents the lighting intensity of the first, neutral-white light, day (in purple). The right two charts present the measurements of the two warm and two cold days. Nearly the same illuminance intensities were measured for warm-white (in orange) and cool-white light (in blue). The bottom three charts present spectroradiometer measurements converted to melanopic lux. The difference between the warm-white (in orange) and cool-white light (in blue) is visible. Melanopic lux values for warm-white light at high intensity are much lower than values for cool-white light but are similar to the melanopic values of the neutral-white light from the first day.

As the experiment took place in a real office environment, the temperature conditions in the room were not completely uniform. They were influenced by external conditions. In addition, the room was heated and cooled by the heating and cooling units present in the room and intended for everyday office use (central heating and air conditioning), which do not provide very precise temperature control. The temperature variation and the differences between the conditions for all 5 participants are shown in the lower part of Figure 4.

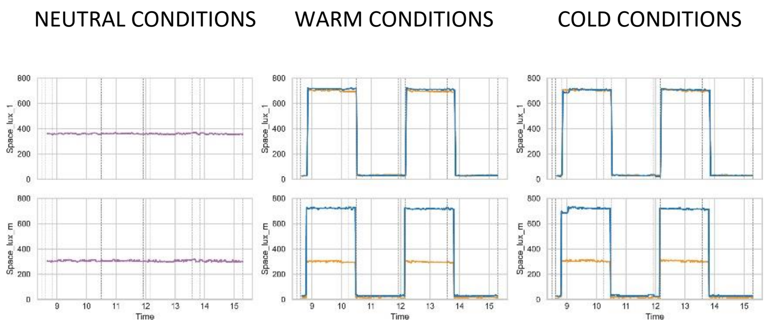

Figure 3. Lighting conditions. On the top: Luxmeter measurements. On the bottom: Spectrometer measurements, converted to melanopic lux. Violet for neutral-white light, orange for warm-white light, and blue for cool-white light.

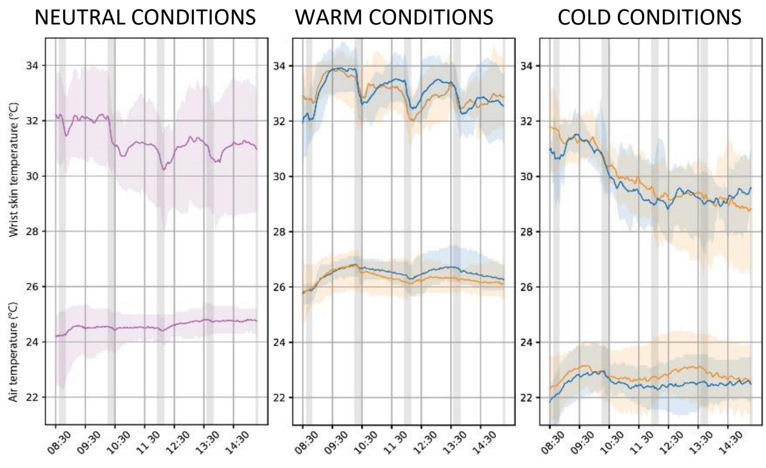

Figure 4. Mean wrist skin temperature fluctuations during the day (on the top) and corresponding air temperature in the office (on the bottom). Violet for neutral-white light, orange for cool-white light, and blue for cool-white light. Shaded areas represent the minimum and maximum values for all the participants.

3.2. *Daily skin temperature fluctuations*

The upper part of Figure 4 shows the variation of the wrist skin temperature of 5 participants during the experiment. Skin temperature was higher at higher ambient temperatures and was about 6 degrees higher than the office air temperature in all experiments. Generally, skin temperature dropped from the beginning till the end of the experiment, but the difference between the initial and end skin temperature was greater in cold (up to 3 degrees) than in warm conditions (less than 2 degrees). Fluctuations in skin

IOP Conf. Series: Earth and Environmental Science **1402** (2024) 012008 doi:10.1088/1755-1315/1402/1/012008

temperature were also strongly influenced by exits from the office, which is particularly noticeable in neutral and warm conditions. Consequently, only measurements taken half an hour after the start of each of the new condition were considered for further analyses. Based on our results, this duration seems reasonable, while similar acclimatization times are often used in studies by other researchers.

3.3. *Thermal response of the group*

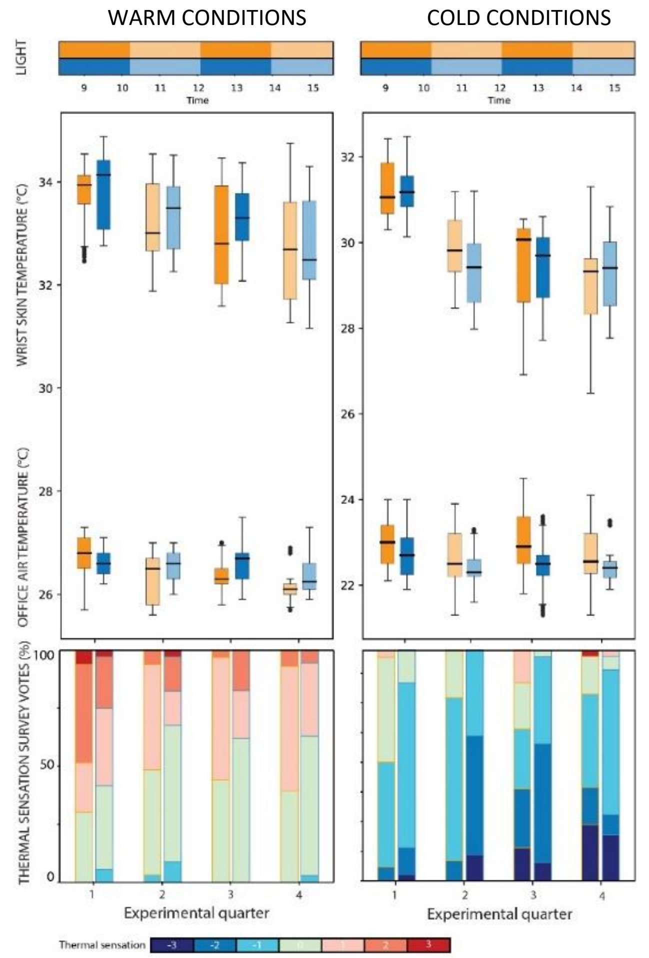

Figure 5. Group thermal response to different lighting conditions. Above: wrist skin temperature fluctuations and the air temperature in the office. On the bottom: Subjective thermal responses. The colors of the boxes (temperature chart) and borders (survey votes chart) represent the type of light: orange for days with warm-white light and blue for days with cold-white light.

Figure 5 shows the mean thermal response of all 5 participants to different lighting conditions on warm and cold days of the experiment. Only data from the working parts, excluding data of the first hour of each of the new condition was used. In warm conditions with cool-white light and warm-white light, the skin temperature dropped during the day. Skin temperature was not affected by light intensity that changed throughout the one day, while mean skin temperature was higher on the days with cool-white light in the first three parts of the experiment. Due to the variation in room temperature, it cannot be concluded with certainty that the result is solely based on the change in light. The proportion of thermal sensation responses indicating that participants were warm was higher in warm-white light. There seemed to be no influence of light intensity on the subjective perception of thermal sensation.
In cold conditions, skin temperature was higher during high light intensity in both cool-white and warm-white light. As the room temperature fluctuated similarly, it is not certain if it is the consequence of the change in light. The room air temperature was on average higher under warm-white light, but the same difference is not observed in the skin temperature fluctuations throughout the experiment. The proportion of thermal sensation responses indicated that participants felt colder in

IOP Conf. Series: Earth and Environmental Science **1402** (2024) 012008 doi:10.1088/1755-1315/1402/1/012008

cool-white light. The results also show that there were slightly fewer responses lower than a neutral thermal sensation in low-intensity warm-white light. The feeling of coldness increased during the day.

3.4. *Comparison of thermal responses of the individuals*

As the goal of the broader research is to develop personal thermal comfort models that respond to the needs of individuals, a comparison of thermal responses between individuals was made to see if differences do exist, as shown in Figure 6. Although not all participants had the exact same conditions, it is noticeable that the thermal responses vary considerably between them. Differences are noticeable in the range of skin temperature fluctuations, especially in cold conditions, as well as in the subjective thermal responses collected by the survey. In warm conditions, individual temperature fluctuations ranged from less than 3°C to less than 4°C per individual, while in cold conditions the difference range was between less than 2°C to around 6°C. The results of the survey on thermal sensation show that some participants chose a wider range of answers than others.

In warm conditions, office air temperature was highest for participant C, who also had the highest mean skin temperature and the highest proportion of subjective thermal responses higher than neutral. Air temperature was lowest for participant A, while B had the lowest mean skin temperature and lowest proportion of subjective thermal responses higher than neutral. In cold conditions, the office air temperature for participant B stands out, by being the highest. However, person C found the conditions the least cold, while participant D had the highest skin temperature.

Conditions were most similar for participants D and E, while this was not the case for thermal responses. Figure 7 shows a more detailed analysis of these two participants.

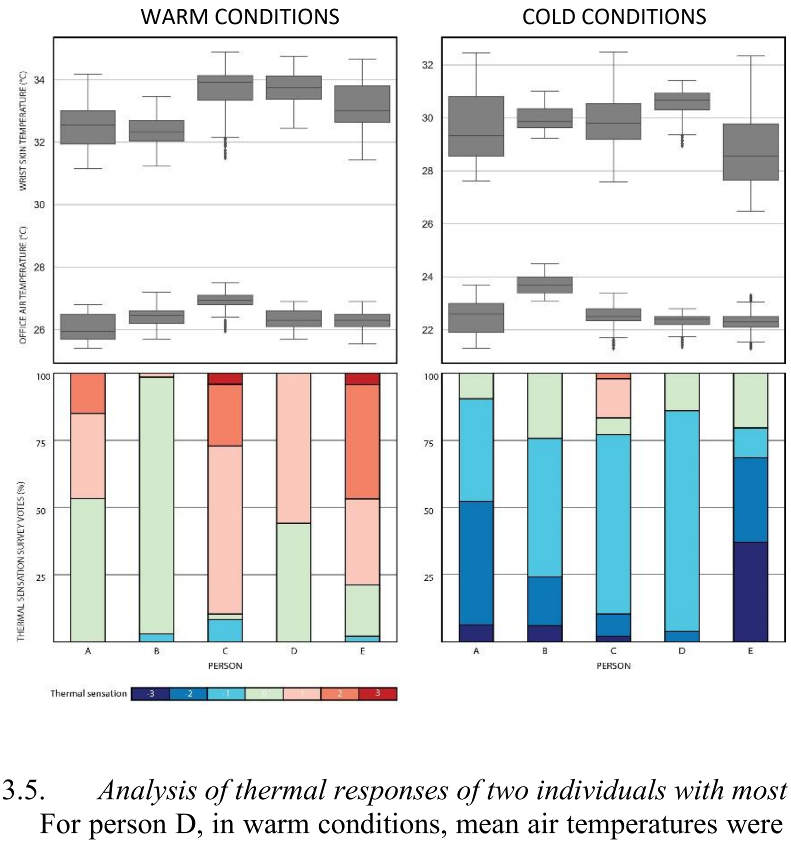

Figure 6. Comparison of all 5 participant's thermal responses. On the top: Office air and wrist skin temperature. On the bottom: Subjective thermal response.

3.5. *Analysis of thermal responses of two individuals with most similar environmental conditions*

For person D, in warm conditions, mean air temperatures were 26,4°C and 26,2 °C on warm-white and cool-white light days. Mean humidities were 34,7% and 31,3% on warm-white and cool-white light days. Thermal conditions were therefore very similar. Mean wrist skin temperature was higher in warm-white light conditions in the last three quarters of the experiment. Mean skin temperature was higher when the light intensity was higher, however, the air temperature follows a similar pattern in both lighting conditions. A higher percentage of warm thermal sensation votes was chosen in warm-white light conditions in the last three quarters of the experiment. The light intensity did not affect thermal votes. In cold conditions mean air temperatures and humidites were 22,3°C and 41% and 22,2 °C and 34,5% on warm-white and cool-white light days. Mean wrist skin temperature was lower in warm-white light conditions in the first three quarters of the experiment. The mean skin pattern does not follow light intensity. Thermal sensation votes do not correspond to lighting conditions.

For person E, in warm conditions mean air temperatures and humidities were 26,3°C and 33,6% and 26,3 °C and 30,3% on warm-white and cool-white light days. In cold conditions mean air temperatures and humidities were 22,4°C and 33,5% and 22,3°C and 36,1% on warm-white and cool-white light days. Mean wrist skin temperature was higher in cool-white light conditions in the first three quarters of the experiment on warm days. The light intensity did not influence it. In warm conditions, a person felt warmer on a cool-white light day. In cold conditions, wrist skin temperature was higher in warm-white conditions in the first half of the experiment. The pattern follows air temperature changes. The person felt warmer at warm-white light conditions in three quarters of the experiment, excluding the third quarter of the experiment, which might be due to the sudden unintended air temperature drop at that time.

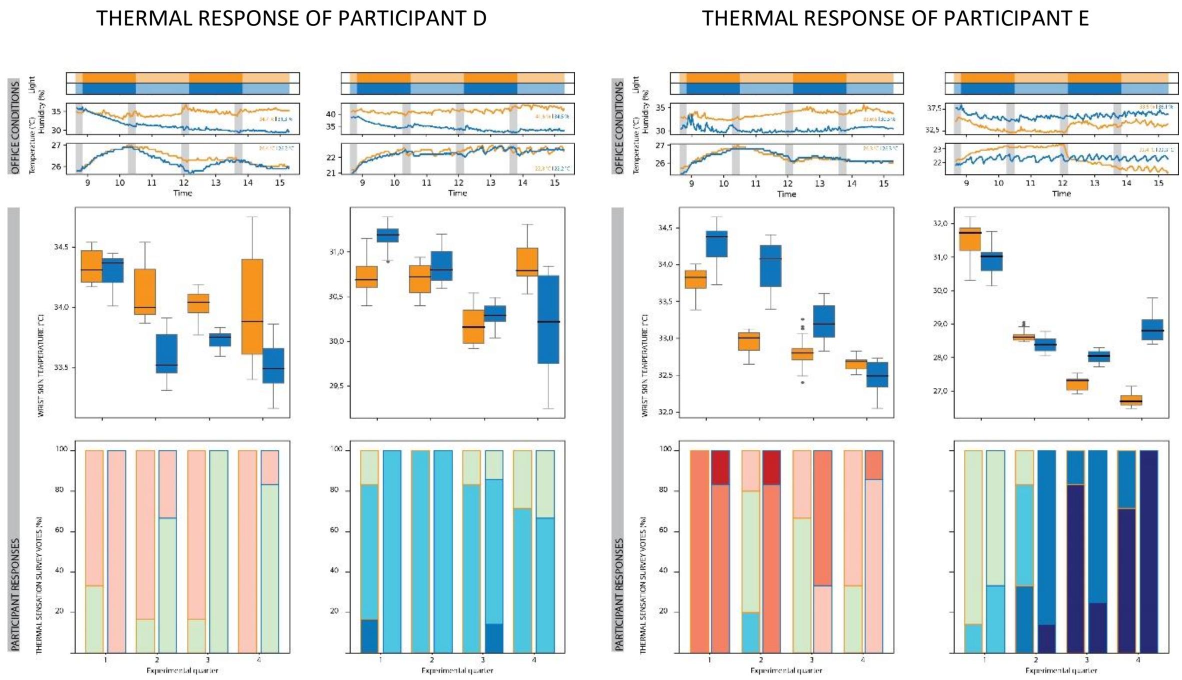

Figure 7. Thermal responses of participants D and E

4. Discussion

Wrist skin temperature corresponds to air temperature and is higher when the air temperature is higher. The result was expected, as research on thermal comfort models shows that skin temperature is one of the best indicators of thermal comfort. Wrist skin also depends on the time of day because of circadian rhythm [10].

The results also showed that physiological and subjective responses to thermal and lighting conditions varied considerably between the participants.

Analysis of the results from 5 participants showed that mean wrist skin temperature was mostly higher in warm conditions in cool-white light. The individual analysis of two individuals showed that the first participant had higher skin temperature in cool-white light as well, while the opposite was true for the second participant. No effect of light intensity was detected, except in the case of the first participant in the warm conditions, which might have been affected by space temperature fluctuations. Subjective responses showed that participants felt slightly warmer in the warm-white light conditions, which was also the case for the first participant, while the results for the second participant were the opposite.

In cold conditions, the results of the cluster analysis showed that light intensity positively correlated with skin temperature on the wrist, while the air temperature followed a similar pattern, therefore the effect of light is not conclusive. The effect of air temperature variation on skin temperature was also detected in the second participant, while the first participant showed mainly higher body temperature in cool-white light. Subjective responses in the group analysis showed that a higher proportion of high votes on thermal sensation were obtained during the warm white light conditions. The same result was evident for the second participant, while for the first one, the influence of light on subjective thermal perception was not observed.

Group analysis of subjective responses is promising and consistent with past research. The review article [6], based on 18 papers, states that from a psychological point of view, most of the results confirm the influence of light color on the perception of thermal comfort, with warm tones of light resulting in warmer temperature perception. However, our analysis of the answers of two individuals does not show the same results. In addition to the light itself, the subjective perception of thermal comfort can also be affected by distractions from work [11], visual comfort preference [12], or high thermal discomfort [13], which can override the effect of the light.

5. Conclusion

Our research on the effect of light on thermal comfort does not provide definitive conclusions. The findings suggest that skin temperature followed air temperature, which was not constant, as is the case in real-life conditions. Skin temperature varied also due to circadian rhythm. Subjective thermal response results are promising but not conclusive either. Since thermal comfort can be influenced by many factors, which can be environmental (air speed, humidity, etc.) or personal (influence of sleep, body temperature fluctuations because of the menstrual cycle, influence of psychological state, etc.), it is necessary to take these into account in the analyses. Our future study will expand the scope by incorporating additional physiological measurements, including measurements of skin temperature in distinct locations on the body. The development of thermal comfort models that consider all the most important factors influencing thermal comfort can contribute to a more efficient use of heating and cooling energy. Adaptation of existing systems would be a particularly useful solution for heritage buildings where building interventions are limited.

Conducting research in a real-life environment, rather than a highly controlled environmental chamber, is a pre-step to conducting similar research in actual heritage buildings and different historical environments. The study's findings, while not definitive, highlight the need for further investigation. The partially promising effect of light on subjective thermal perception suggests that light adaptation may have potential as an energy-saving solution in heritage buildings, however, research conducted in heritage buildings is needed to validate the results and develop more comprehensive thermal comfort models.

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