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► **To cite this version:**

Marika Vellei, Jérôme Le Dréau, Jérôme Nicolle, Manon Rendu. Thermal alliesthesia under whole-body cyclical conditions. 18th Healthy Buildings Europe Conference, Jun 2023, Aachen, Germany. hal-04195083

HAL Id: hal-04195083

<https://hal.science/hal-04195083>

Submitted on 4 Sep 2023

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Thermal alliesthesia under whole-body cyclical conditions.

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Abstract. A better understanding of how thermal alliesthesia affects human thermal perception during dynamic conditions is important in view of the emerging “smart grid” paradigm and associated demand-response (DR) programs that call for the implementation of set-point temperature modulations in buildings. In this paper, we report the results of an experiment exploring the subjective responses of 44 males and 76 females to four different whole-body warm and cool cyclical temperature modulations at different moments of the day (morning/afternoon) and in distinct seasons (summer/autumn). The study aimed to better understand how the relationship between thermal comfort and thermal sensation is framed by thermal alliesthesia. We found that temporal thermal alliesthesia significantly affects thermal comfort. This alliesthesial effect depends on both previous and actual thermal sensations and gets stronger as we move far from neutrality. The season was also found to significantly modify the relationship between thermal comfort and thermal sensation which confirms the existence of seasonal alliesthesia.

Keywords. thermal comfort, thermal alliesthesia, dynamic, season, time-of-day, sex

1. Introduction

The term “alliesthesia” refers to “the property of a given stimulus to arouse pleasure or displeasure according to the internal state of the subject” (Cabanac, 1979). Cabanac’s conventional notion of thermal alliesthesia considers that pleasure is driven by “thermoregulatory load errors” emanating from the body core. Any thermal stimulus that minimizes the load error is perceived as pleasant (“positive alliesthesia”), while any stimulus that exacerbates the discrepancy is perceived as unpleasant (“negative alliesthesia”) (Cabanac, 1979). However, the alliesthesial thermal pleasure is not necessarily predicated on a deviation in body core temperature (de Dear, 2011; Parkinson & de Dear, 2017; Parkinson & De Dear, 2016). Extant empirical evidence now shows that “spatial” thermal alliesthesia can be induced in the thermoneutral zone when the mean skin temperature is displaced from its “neutral threshold” and one or more body parts are heated or cooled to reduce/increase the whole-body discomfort (H. Zhang et al., 2010a, 2010b, 2010c). In absence of localized thermal stimuli, “temporal” thermal alliesthesial can arouse during environmental or metabolic transients when the whole-body thermal

discomfort is suddenly removed/increased (Parkinson et al., 2016). The emerging “smart grid” paradigm with associated demand-response (DR) programs calls for the implementation of heating and cooling set-point temperature modulations in buildings. Designing and controlling comfortable DR-induced set-point variations have the potential to induce positive temporal alliesthesial responses, but research is needed to avoid incurring unpleasant thermal states.

Traditional thermal comfort models and indices, such as Fanger’s Predicted Mean Vote PMV (Fanger, 1972) and Gagge’s Standard Effective Temperature SET* (Gagge et al., 1986), are only valid under uniform and static thermal conditions and, thus, do not incorporate any effect of either spatial or temporal alliesthesia. The ABC Advanced Berkeley Comfort model (also known as Zhang’s model) is one of the best-known and most often used physiological-based thermal comfort models which can predict thermal sensation and comfort under non-uniform and dynamic thermal environments (H. Zhang et al., 2010a, 2010b, 2010c). In this model, the thermal comfort of individual body parts is predicted from both local and whole-body thermal sensations based on an analytical model that accounts for the effect of spatial thermal alliesthesia.

Overall thermal comfort is, in turn, predicted from local thermal comfort signals by following a set of rules. As specified by Rule 1, overall thermal comfort is the average of the two minimum local thermal comfort votes unless Rule 2 applies. Rule 2 is to be used when the person has some control over his/her thermal environment and/or when the thermal condition is transient. According to Rule 2, overall thermal comfort is the average of the two minimum thermal comfort votes plus the maximum one. Thus, Rule 2 assigns higher comfort to transient conditions due to the thermal comfort overshoot observed when removing heat stress. However, this rule is the result of a quality assessment rather than a quantitative estimation. Indeed, the relationship between thermal comfort and thermal sensation has not been mathematically described yet within the psychophysiological framework of temporal thermal alliesthesia. Furthermore, most of the works on temporal alliesthesia have focused on step-change transients, while the effect of milder cyclical thermal transients has been less often addressed.

In this paper, we report the results of an experiment exploring the subjective responses in terms of Thermal Sensation Vote (TSV), Thermal Preference Vote (TPV), and Thermal Comfort Vote (TCV) of 120 adults to four different whole-body warm and cool cyclical temperature sequences in summer and winter respectively. The study aims to better understand how the relationship between thermal comfort and thermal sensation (the affective and descriptive dimensions of thermal perception respectively) is framed by positive and negative temporal alliesthesia and whether contextual and interindividual factors, in particular, season, time-of-day and sex, affect thermal perception.

2. Methods

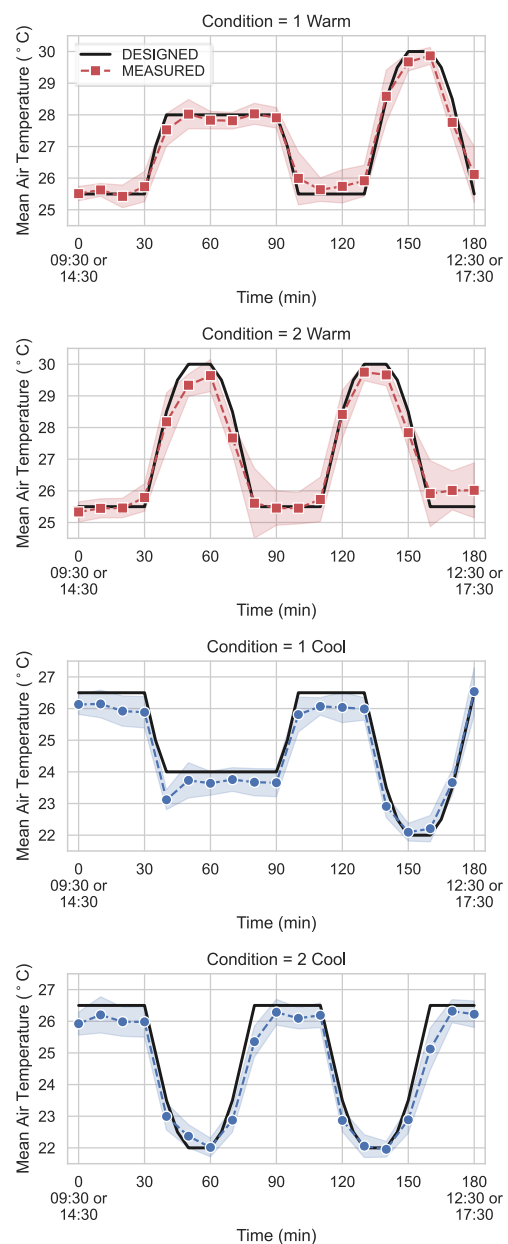
2.1 Experimental procedure

The laboratory experiment consisted in exposing 120 human participants to four different cyclical sequences of whole-body cooling and warming over 180 min. For the first 30 min of the exposure, the thermal conditions were kept constant to allow the occupants to reach steady-state thermal conditions before the start of the air temperature fluctuations. Both environmental and subjective (thermal sensation, thermal preference, and thermal comfort) data were collected during each exposure. A part of this dataset has already been analysed and published elsewhere (Vellei et al., 2022), but without including an analysis of thermal alliesthesia which is the subject of the present contribution. The four cyclical sequences include two warm conditions (“1 Warm” and “2 Warm”) and two cool conditions (“1 Cool” and “2 Cool”) as shown in Figure 1. The corresponding rates of change of the air temperature are similar in

intensity to those typically found during DR events in buildings (F. Zhang et al., 2016) and are outside the maximum allowable temperature variations set by the standards (ASHRAE, 2017; ISO, 2005). The study was conducted during one week of July 2021 (for the warm conditions) and one week of October 2021 (for the cool conditions) over the northern hemisphere summer and autumn, respectively.

Figure 1

Designed and measured mean indoor air temperature throughout the four experimental conditions. Shaded bands represent one standard deviation.



The experiments commenced at either 09:30 or 14:30 hours, in the morning and afternoon respectively. The mean outdoor temperature during the experiments was 25.3°C in the morning and 31.9°C in the afternoon

in July and 12.8°C in the morning and 17.2°C in the afternoon in October. The participants were asked to arrive 30 min before the beginning of the experiment (i.e., at either 09:00 or 14:00 hours) and remained standing in a large waiting room before being transferred to the experimental room. During this time, they were briefed verbally about the study's requirements (without detailing the thermal conditions that they were going to experience) and allowed to ask any questions. They were also provided with written instructions and an information sheet. Each participant gave their written informed consent to participate in the study. Participants were then accompanied to the experimental room where they stayed in groups of 2, 3 or 4 at most. They were randomly assigned to different experimental conditions. Participants were explicitly asked to not talk about their subjective answers with the other occupants in the room.

The research protocol was approved by the Ethics Committee at the University of Tours and Poitiers in France (Protocol No. CER-TP 2021-06-02).

2.2 Experimental platform

The experimental platform consists of four experimental rooms located at TIPEE's experimental facilities on the outskirts of La Rochelle (France). For the warm conditions ("1 Warm" and "2 Warm"), we used the experimental rooms of both the "Façade Test" and the "Maison Eurêka", while for the cool conditions ("1 Cool" and "2 Cool") only those of the "Maison Eurêka".

The "Façade Test" is a building equipped with five test rooms mainly conceived for testing buildings' envelopes. For a full description of the facility, see (Favoio et al., 2018). The two employed test rooms are equipped with an air inlet and an air outlet for ventilation, a fan coil unit for air conditioning and an electric convector unit for heating. Their internal dimensions are 5.64 m (length) x 3 m (width) x 3 m (height). At the time of the experiments, the test rooms were illuminated by natural lighting; hence the electric lighting was switched off. The ventilation rate was set to approximately 50 m³/h.

The "Maison Eurêka" is a stand-alone test house or living lab with a surface area of 150 m². It consists of two levels with a kitchen/living room, an office room and a WC located on the ground floor and three bedrooms and a bathroom on the first floor. For a full description of the facility, see (Paquet et al., 2017). The office room (ground floor) and one of the three bedrooms (first floor) were used for the experiments as test rooms. Both test rooms are equipped with convection heating and cooling units that can be controlled automatically. During the tests, windows were kept closed and sunscreens were used to avoid direct sunlight entering the rooms; hence the

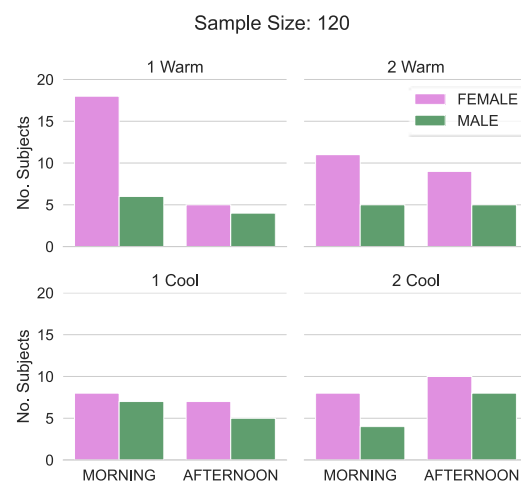
electrical lighting system was switched on. The test rooms were ventilated with 100% outdoor air with a ventilation rate set to approximately 30 m³/h.

2.3 Participants

One hundred and twenty (44 males and 76 females) adults participated in the experiment. Each participant took part in only one test in the summer and one test in the autumn. Twenty-three participants participated in both sessions, thus experiencing both one warm and one cool condition but at a distance of three months. Given the three-month gap, we considered the study design as "between-subjects" and adapted the statistical analysis accordingly. The participants were Western Europeans between 20 and 60 years old recruited by a professional recruiting agency in southwest France. The distribution of male and female participants over the four experimental conditions and according to the time of day is given in Figure 2. The anthropometric characteristics of the participants are reported in Table 1.

Figure 2

Distribution of male and female participants over the four experimental conditions according to the time of day.



The participants were asked to wear similar light clothing consisting of short trousers or a skirt, a shirt with short sleeves, ankle-length socks and shoes with total clothing insulation estimated to be about 0.6 clo (including the insulation of the chair), based on the tabulated clo values given in ANSI/ASHRAE Standard 55 (ASHRAE, 2017). During the experiments, they were allowed to drink water (bottled water was provided) and perform office tasks (reading or studying, using their mobile phones, working at the computer or performing other non-physical activities) but were not permitted to move around the room. Their metabolic rate was estimated to be approximately 1 met. For at least 24 hours before the experiment, they were requested to:

- avoid heavy exercise,

- avoid alcoholic or stimulating drinks,
- avoid eating large meals,
- and maintain a regular sleep schedule (do not stay overnight the night before).

All the participants were paid for their participation.

Table 1

Anthropometric characteristics (mean±SD) of the participants.

	Age (years)	
	MALE	FEMALE
1 Warm	35.9± 9.3	37.3± 7.6
2 Warm	44.1± 4.6	36.6± 6.6
1 Cool	42.4± 8.7	38.6± 6.0
2 Cool	34.5±10.3	38.5±11.0
	Height (cm)	
	MALE	FEMALE
1 Warm	175.8±6.5	164.5±6.6
2 Warm	177.9±7.1	167.3±3.5
1 Cool	177.2±5.7	164.1±4.7
2 Cool	179.2±6.9	165.9±4.9
	Weight (kg)	
	MALE	FEMALE
1 Warm	72.9±12.2	62.0±10.0
2 Warm	78.7± 10.0	68.4±13.4
1 Cool	79.2±11.4	61.7±12.0
2 Cool	77.2±11.9	65.9±13.6

2.4 Measurements

Air temperature T_a , globe temperature T_g , relative humidity RH , and air velocity V_a were measured with laboratory-grade equipment according to the ISO standard (ISO, 2017). The characteristics of the equipment used are reported in our previous work (Vellei et al., 2022). The air temperature was recorded at 0.1, 0.6, and 1.1 m height (ISO, 1998) close to the participants (at a distance of a maximum of 1 m). Carbon dioxide CO_2 and illuminance ILL were also recorded. The mean radiant temperature was computed using the function `psychrometrics.t_mrt` from the `pythermalcomfort` Python package (Tartarini & Schiavon, 2020). Fanger's PMV index was also computed using the same package. The sampling time step for all the monitoring equipment was set to 60 s.

The participants filled in a questionnaire describing their whole-body thermal perception at 10 min intervals starting from either 09:30 (morning tests) or 14:30 (afternoon tests). The questionnaire was paper-based and translated into French which was the language spoken by all the participants. The participants were provided with a QR code of a browser-based timer to keep the timing of the

questions. However, most participants directly used the timer available on their smartphones. The time was also noted on each questionnaire. The questionnaire included three questions. The first question was the Thermal Sensation Vote on the classical ASHRAE 7-point scale: "Hot" (+3), "Warm" (+2), "Slightly Warm" (+1), "Neutral" (0), "Slightly Cool" (-1), "Cool" (-2), and "Cold" (-3) (ASHRAE, 2017). The second question was the Thermal Comfort Vote on a 6-point scale, including "Very Comfortable" (+3), "Comfortable" (+2), "Slightly Comfortable" (+1), "Slightly Uncomfortable" (-1), "Uncomfortable" (-2), and "Very Uncomfortable" (-3). The third question was the Thermal Preference Vote on a 7-point scale, including "Much Cooler" (-3), "Cooler" (-2), "Slightly Cooler" (-1), "No Change" (0), "Slightly Warmer" (+1), "Warmer" (+2), and "Much warmer" (+3). To facilitate comparisons with previous works and datasets (Schweiker & et al, 2020), the French translation of the three questions is based on the French version of EN ISO 10551 (ISO, 2019) except for the thermal comfort question which was slightly modified to include the "Very Comfortable" and "Very Uncomfortable" votes.

2.5 Statistical analysis

Due to the longitudinal nature of the collected time-series data, a Mixed-effects Linear Model (MLM) is employed for all the statistical analysis by treating the participants as a random factor. The participants represent our particular experimental unit and constitute a deviation from the overall mean. The adopted random-effects structure is a random intercept for each group. The maximum likelihood is the chosen estimation method for the parameters in the MLM model. A "top-down" modelling strategy is used, starting with the maximum model followed by a stepwise backward elimination procedure with only significant covariates kept in the model at the end of the procedure. The open-source Python package `scipy.stats` is used for all the analyses. Differences at $p \leq 0.05$ are considered statistically significant.

3. Results

3.1 Overview

The mean measured environmental conditions during the four experimental exposures are reported in Table 2. While the mean relative humidity was quite uniform (nearly 50%) across the different conditions, there was a marked difference in the level of air quality and illuminance between the warm and the cool tests. The air quality in terms of CO_2 was better controlled in the warm tests due to the higher employed ventilation rates per occupant given that there were on average fewer occupants in the test rooms. Furthermore, the illuminance was higher in the cool tests because the electrical lighting system

was switched on. It is also to be noticed that the mean air velocity was equal to 0.2 m/s during the tests due to the decentralised convection thermal systems employed. To account for all the environmental variables, Figure 3 gives an overview of the four tested conditions in terms of Fanger’s PMV which is compared to the measured TSV.

Figure 3

Mean Fanger’s PMV and measured TSV throughout the four experimental conditions. Shaded bands represent one standard deviation.

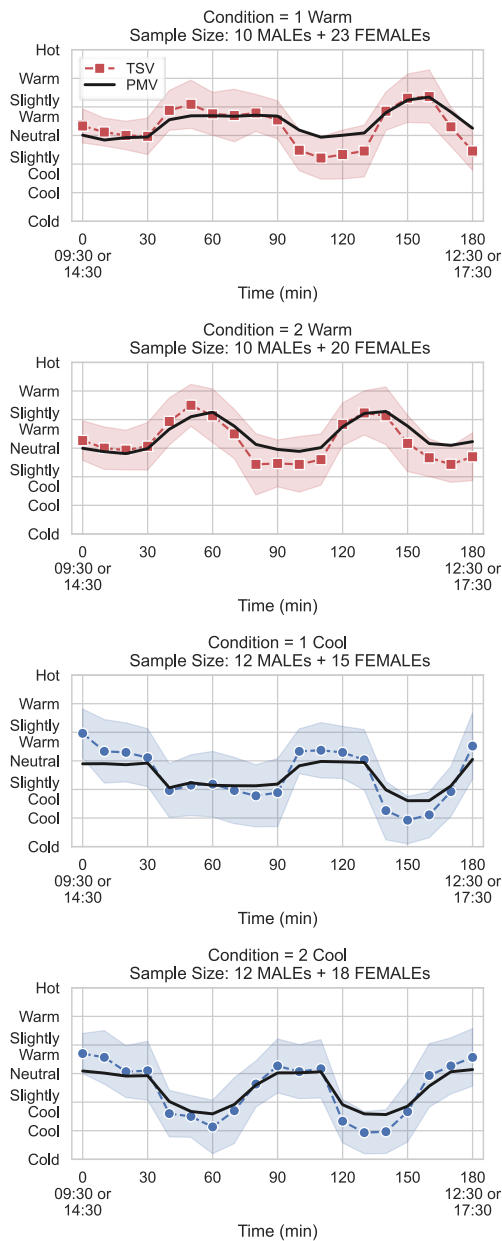


Table 2

Measured environmental conditions (mean±SD).

	T_a (°C)	T_r (°C)
1 Warm	27.1±1.5	27.8±1.4
2 Warm	27.0±1.8	27.8±1.5
1 Cool	24.6±1.5	25.5±1.0
2 Cool	24.5±1.8	25.4±1.1
	RH (%)	V_a (m/s)
1 Warm	49.8±6.3	0.2±0.2
2 Warm	47.3±5.2	0.2±0.2
1 Cool	50.4±7.1	0.2±0.1
2 Cool	49.5±6.0	0.2±0.1
	CO_2 (ppm)	ILL (lux)
1 Warm	657±116	274±226
2 Warm	687±165	245±177
1 Cool	1118±292	664±373
2 Cool	1130±240	608±203

3.2 Relationship between TSV and PMV

In this section, we analyse whether sex and time-of-day affect the relationship between the Thermal Sensation Vote and Fanger’s Predicted Mean Vote. We employ MLM with possible two-way interactions to model TSV as a function of PMV (as a continuous fixed effect), sex, and time of day (as categorical fixed effects: female/male and morning/afternoon). The participants are treated as a random factor. For this analysis, all timesteps are included (2280 observations and 120 groups). The key assumptions of MLM (normality, homoscedasticity and no autocorrelation of the residual errors, no multicollinearity of the independent variables) were checked and met. Time-of-day was not found to affect the relationship between TSV and PMV. However, sex was found to be a significant predictor of the MLM model (see Table 3). As illustrated in Figure 4, at equal PMV females felt significantly cooler than males. These observations are in line with our previous study in which we observed that females respond to cooling with a higher rate of cooling of skin temperature and correspondingly stronger thermal overshoot responses compared to males (Vellei et al., 2022).

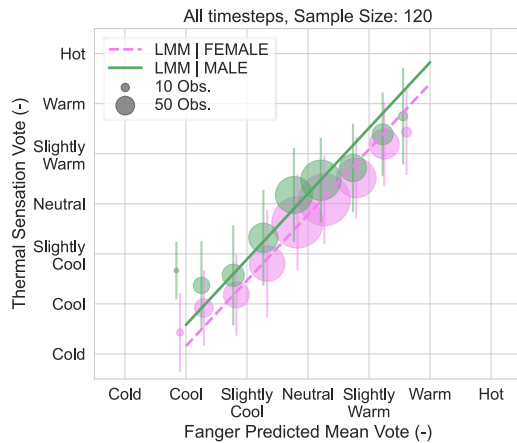
Table 3

Regression coefficients for the significant predictors of the TSV in the MLM. All timesteps are included.

	Coef.	Std. Err.	z	P> z
Intercept	-0.222	0.061	-3.633	0.000
Sex[MALE]	0.425	0.101	4.208	0.000
PMV	1.311	0.029	45.73	0.000
Subject Var	0.253	0.051		

Figure 4

Relationship between the TSV and Fanger's PMV for female and male participants. Error bars represent one standard deviation.



3.3 Relationship between TPV and TSV

In this section, we analyse whether sex, season, and time-of-day affect the relationship between thermal preference and thermal sensation. We employ MLM with possible two-way interactions to model TPV as a function of TSV (as a continuous fixed effect), sex, season, and time of day (as categorical fixed effects: female/male, summer/autumn, and morning/afternoon). The participants are treated as a random factor. For this analysis, all timesteps are included (2280 observations and 120 groups). The key assumptions of MLM were checked and met. Sex was not found to affect the relationship between the Thermal Preference Vote and the Thermal Sensation Vote. However, time-of-day and season were found to be significant predictors of the MLM model (see Table 4). Warm thermal sensations were preferred in the morning and autumn, while cool thermal sensations were preferred in the afternoon and summer. Seasonal effects in the relationship between thermal preference and thermal sensation have been previously observed and attributed to a form of seasonal alliesthesia (Schweiker et al., 2020). The observed effect of time-of-day on thermal perception was small but significant. It could be either related to the circadian fluctuation of the body temperature (Vellei et al., 2021, 2023) or attributed to a form of diurnal alliesthesia grounded on the prevailing cool thermal conditions experienced in the morning than in the afternoon so that warm conditions are more likely to be preferred in the morning. Further research is needed to better understand time-of-day effects on thermal comfort.

Table 4

Regression coefficients for the significant predictors of the TPV in the MLM. All timesteps are included.

	Coef.	Std. Err.	z	P> z
Intercept	0.359	0.048	7.403	0.000
Time [MOR]	0.119	0.056	2.109	0.035
Season [SUMMER]	-0.436	0.057	-7.711	0.000
TSV	-0.698	0.012	-57.92	0.000
TSV * Season[SU]	-0.044	0.019	-2.328	0.020
Subject Var	0.079	0.026		

3.4 Relationship between TCV and TSV

In this section, we model the relationship between thermal comfort and thermal sensation considering the effect of thermal alliesthesia. Temporal thermal alliesthesia is only experienced in transitional environments. Hence, we assume that only those timesteps characterized by a change in thermal sensation are affected by temporal thermal alliesthesia. It has been previously observed that during transitional thermal states, the alliesthesial thermal comfort overshoot is dependent upon the corrective potential of the peripheral heat transfer (Parkinson et al., 2016). The corrective potential of the peripheral heat transfer at any given thermal sensation depends on the previous thermal sensation. For example, if the previous thermal sensation is cool, then a warm thermal sensation is counteracting the whole-body discomfort. Thus, if any alliesthesia exists then the previous thermal sensation should be found to significantly affect the relationship between TCV and TSV. Based on this information, we model thermal comfort as a function of both the actual thermal sensation vote (TSV) and the previous one (pTSV). We employ MLM with TCV as the dependent variable, TSV and pTSV as a continuous fixed effect and sex, time of day, and season as categorical fixed effects. We fit two separate MLM models for both the cool and warm side and obtain the significant regression coefficients shown in Table 5 and Table 6. Sex and time-of-day were not found to affect the relationship between the TCV and the TSV. However, the season was found to be a significant predictor for both MLM models. Warm thermal sensations were considered more comfortable in the autumn, while cool thermal sensations were regarded as more comfortable in the summer. The previous thermal sensation was found to be a significant predictor both on the cool and warm side, but with significant interaction with TSV only on the warm side. From Figure 5 and Figure 6, we can also observe that the effect of thermal alliesthesia is stronger as we move far from neutrality.

Table 5

Regression coefficients for the significant predictors of the TCV on the cool side ($TSV \leq 0$) in the MLM (824 observations and 120 groups).

	Coef.	Std. Err.	z	P> z
Intercept	4.751	0.061	78.04	0.000
Season [SUMMER]	0.185	0.080	2.328	0.020
pTSV	0.066	0.018	3.617	0.000
TSV	1.187	0.027	44.16	0.000
Subject Var	0.118	0.042		

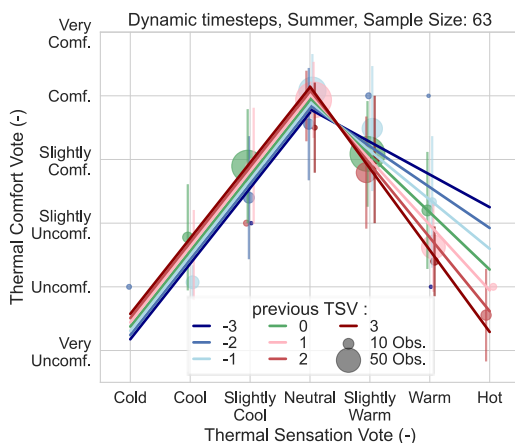
Table 6

Regression coefficients for the significant predictors of the TCV on the warm side ($TSV \geq 0$) in the MLM (787 observations and 119 groups).

	Coef.	Std. Err.	z	P> z
Intercept	4.867	0.073	67.09	0.000
Season [SUMMER]	0.100	0.098	1.018	0.309
pTSV	0.059	0.029	2.047	0.041
TSV	-0.509	0.060	-8.525	0.000
TSV * Season [SUM]	-0.390	0.077	-5.080	0.000
pTSV * TSV	-0.129	0.030	-4.337	0.000
Subject Var	0.117	0.039		

Figure 5

Summer relationship between TCV and TSV. Error bars represent one standard deviation.



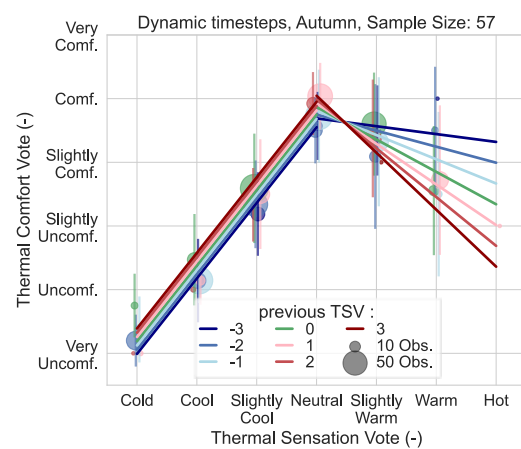
4. Conclusion

By studying whole-body cyclical thermal transients, we observed that the relationship between thermal sensation and Fanger's PMV significantly differs between sex, with females feeling cooler than males.

Season and time-of-day were identified as factors significantly affecting the relationship between thermal preference and thermal sensation which confirms the existence of seasonal alliesthesia and points to the importance of further investigating the time-of-day variable. Finally, we found that the impact of temporal alliesthesia on thermal comfort can be modelled as a function of the previous thermal sensation and gets stronger as we move far from neutrality.

Figure 6

Autumn relationship between TCV and TSV. Error bars represent one standard deviation.



5. Acknowledgements

This project has received funding from the European Union's Horizon 2020 programme under the Marie Skłodowska-Curie grant agreement No 884556. We also thank the French Ministry of Ecological and Solidarity Transition for funding it within the frame of the Smart-Reno project (2019-2021).

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