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► **To cite this version:**

Marika Vellei, Richard de Dear, Jérôme Le Dréau, Jérôme Nicolle. Thermal alliesthesia under whole-body step-change transients. The 11th International Conference on Indoor Air Quality, Ventilation & Energy Conservation in Buildings (IAQVEC2023), May 2023, Tokyo, Japan. pp.01003, 10.1051/e3sconf/202339601003 . hal-04195093

HAL Id: hal-04195093

<https://hal.science/hal-04195093v1>

Submitted on 4 Sep 2023

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Thermal alliesthesia under whole-body step-change transients

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Abstract. A better understanding of the psycho-physiological mechanisms driving human thermal perception during dynamic conditions is important to improve physiological-based thermal comfort models. During thermal transients, the two phenomena of thermal overshoot and thermal alliesthesia concurrently affect thermal comfort. However, they have to date been analysed separately. In this paper, we report the results of an experiment exploring the subjective responses of 16 males and 48 females to four different whole-body warm and cool step-change transients at different times of day (morning/afternoon) and in distinct seasons (summer/autumn). We found that time of day and season both significantly affect the relationship between thermal comfort and thermal sensation. This relationship was then used to predict the thermal comfort overshoot which was compared to the actual comfort vote during the step-change transients. This allowed us to separate the contribution to thermal comfort due to thermal overshoot from that attributed to thermal alliesthesia. We could show that, during the step-change transients, positive alliesthesia increases the level of thermal comfort proportionally to the perceived corrective potential of the whole-body discomfort, and this effect gets stronger as we move away from thermal neutrality.

1 Introduction

Temperature step-change transients are discrete changes in thermal conditions that can be typically encountered during transitions between different building thermal zones, or between a building and the outdoors, and can especially occur in temporarily occupied spaces. A better understanding of the psycho-physiological mechanisms driving the dynamic thermal sensation and comfort during these rapidly changing thermal conditions is important to improving models of dynamic thermal perception in physiological-based thermal comfort simulations.

During step-change thermal transients, thermal sensation anticipates body temperature responses and can both predict [1] and initially exaggerate [2] the final steady-state sensory perception. This anticipatory behaviour has been referred to as “thermal overshoot” and depends primarily on the ability of sensory neurons to detect the rate of change in the skin temperature and to send this information to the brain through a burst in their firing rate [3,4]. However, thermal overshoot is not the only psycho-physiological phenomenon affecting thermal perception during step-change transients. Pleasurable and unpleasant thermal states can be aroused during environmental transients when whole-body thermal discomfort is suddenly diminished and increased. Cabanac referred to this “property of a given stimulus to arouse pleasure or displeasure according to the internal state of the subject” as “thermal alliesthesia” [5]. Cabanac’s conventional notion of thermal

alliesthesia considers that pleasure is driven by “thermoregulatory load errors” emanating from the body core [5]. 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”) [5]. However, empirical evidence now shows that positive/negative alliesthesia can also be induced within 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 peripheral load error [6–14].

Until now, the two phenomena of thermal overshoot and thermal alliesthesia have been analysed separately, although they occur simultaneously during transient conditions and, therefore, are closely intertwined, with one affecting the descriptive dimension of thermal perception (thermal sensation) and the other the affective property (thermal comfort).

One of the best-known and most often used physiological-based thermal comfort models is the ABC Advanced Berkeley Comfort model (also known as the Zhang model) which predicts thermal sensation and comfort based on body temperature conditions [12–14]. In this model, overall thermal comfort is modelled based on the knowledge of thermal comfort signals coming from localized body parts 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 (out of 15 body parts) unless Rule 2 applies. Rule

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2 is to be used when the person has some control over the thermal environment and/or when the thermal conditions are 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 alliesthesial phenomenon observed when removing heat stress. However, this rule is the result of a qualitative rather than quantitative assessment. Indeed, the relationship between thermal overshoot and thermal alliesthesia has not been quantitatively examined to date.

In this paper, we report the results of an experiment exploring the subjective (thermal sensation, thermal preference, and thermal comfort) responses of 64 adults to four different repeated whole-body warm and cool step-change transients in the summer and winter respectively. The study aims to better understand how the two psycho-physiological phenomena of thermal overshoot and thermal alliesthesia influence the relationship between thermal comfort and thermal sensation during rapid skin temperature variations. It also aims to investigate whether interindividual and contextual factors, such as sex, time-of-day, and season, have any bearing on this relationship.

2 Methods

2.1 Experimental procedure

The laboratory experiment involved exposing the participants to four different sequences of repeated whole-body temperature step-change transients including two warm exposures (“1 Warm” and “2 Warm”) and two cool exposures (“1 Cool” and “2 Cool”) as shown in Fig. 1. The temperature step-change transients were realised by making the participants move between two identical rooms kept at constant thermal conditions. After each transient, the occupants remained for 30 min in the room to reach steady-state thermal conditions. Both environmental and subjective (thermal sensation, thermal preference, and thermal comfort) data were collected during each exposure.

The study was conducted during one week of July 2021 (for the warm conditions) and one week of October 2021 (for the cool conditions) during the French summer and autumn respectively. 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. Each participant took part in only one test in the summer and one test in the autumn. Five 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. 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).

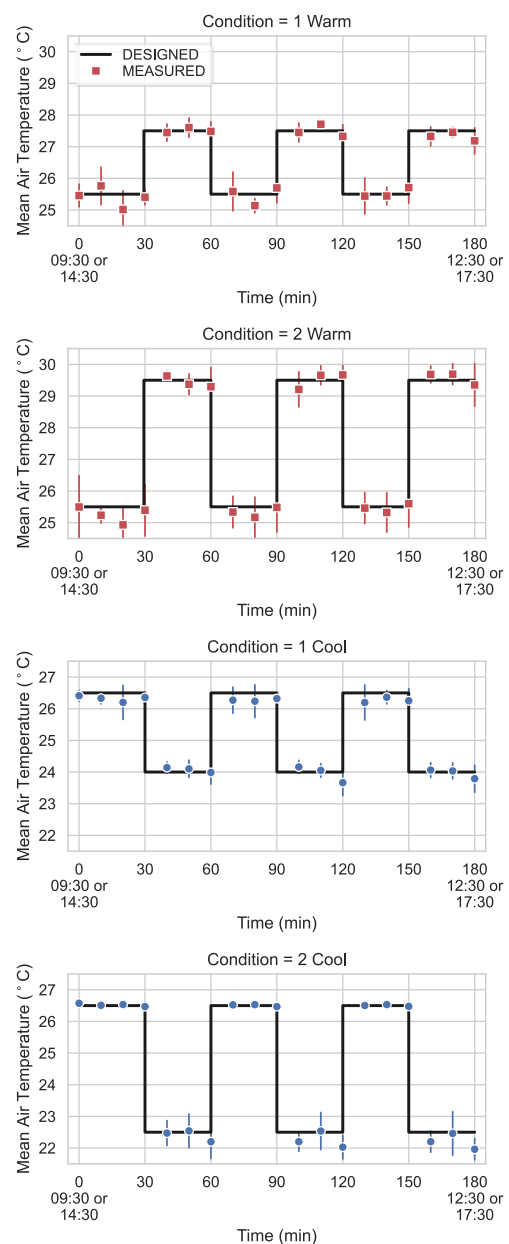


Fig. 1. Designed and measured indoor air temperature throughout the four experimental conditions. Error bars represent one standard deviation.

2.2 Experimental platform

The experimental platform consisted of two identical experimental rooms located within the “Maison Eurêka” at the TIPEE’s experimental facilities on the outskirts of La Rochelle (France). The “Maison Eurêka” is a two-floors stand-alone test house or living lab with a total surface area of 150 m². For a full description of the facility, see [15]. Two of the three bedrooms on the first floor were used for the experiment as test rooms. Both rooms are equipped with convection heating and cooling units that can be controlled automatically, and their windows are oriented northwest. Windows were kept closed and sunscreens were used to avoid direct sunlight entering the rooms. The electrical lighting system was switched on. The test rooms were ventilated with 100% outdoor air at a rate of approximately 30 m³/h.

For the experiment, the test rooms were furnished with desks and chairs. The schematic representation of the configuration of the test rooms is shown in Fig. 2. This configuration implied that the thermal environments were not perfectly uniform spatially, but were more similar to what can be expected in real buildings.

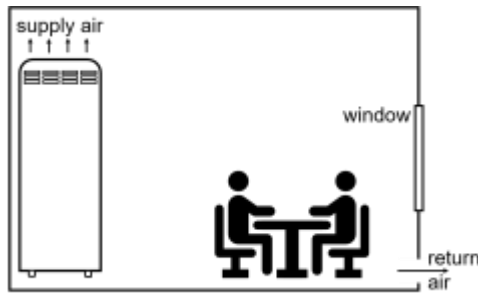


Fig. 2. Schematic representation of the configuration of the test rooms.

2.3 Participants

Sixty-four (16 males and 48 females) adults participated in the experiment. The participants were Western Europeans between 20 and 60 years old recruited by a professional recruiting agency in southwest France. They 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 in ANSI/ASHRAE Standard 55 [16].

During the experiment, participants were allowed to drink bottled water ad libitum 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. The 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,
- maintain a regular sleep schedule.

All the participants were paid for their participation. The distribution of male and female participants over the four experimental conditions and according to the time of day is given in Fig. 3. The anthropometric characteristics of the participants are reported in Table 1.

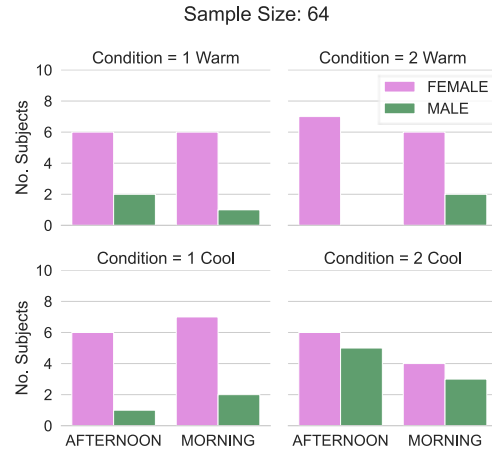


Fig. 3. Distribution of male and female participants over the four experimental conditions according to the time of day.

Table 1. Anthropometric characteristics (mean±SD) of the participants.

	Age (years)	
	MALE	FEMALE
1 Warm	34±14	34±8
2 Warm	40±14	38±8
1 Cool	45±23	38±13
2 Cool	34±11	41±10
	Height (cm)	
	MALE	FEMALE
1 Warm	181.7±2.9	164.0±5.5
2 Warm	186.0±2.8	166.5±4.4
1 Cool	175.7±4.5	163.1±6.6
2 Cool	177.3±4.5	167.4±8.0
	Weight (kg)	
	MALE	FEMALE
1 Warm	91.7±7.8	64.1±14.8
2 Warm	111.0±48.1	72.4±18.4
1 Cool	84.7±5.5	63.5±8.3
2 Cool	79.6±10.0	69.3±13.7

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 ISO 17772 [17]. The characteristics of the equipment used are reported in Table 2. The air temperature was recorded at 0.1, 0.6, and 1.1 m height [18] close to the participants

(at a maximum distance 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 [19]. Fanger’s PMV index was also computed using the same package. Furthermore, a fully equipped weather station measuring the outdoor conditions was located on the façade of a building nearby. The sampling time-step for all monitoring equipment was set to 60 s.

Table 2. Characteristics of the equipment used for the environmental measurements.

	Model	Range	Accuracy	Resolution
T_a	Thermo-	-50 to 400°C	$\pm 0.2^\circ\text{C}$	0.01°C
	couples Type T (TCSA)			
T_g	Thermo-	-50 to 400°C	$\pm 0.2^\circ\text{C}$	0.01°C
	couples Type T (TCSA)			
RH	HMP155 (Vaisala)	0 to 100%	$\pm 1\%$	0.1%
V_a	8475	0 to 2.5 m/s	$\pm (3\%$ of reading +1%	0.07% of range)
	(omnidirecti onal TSI)		of range)	
CO_2	GMP222 (Vaisala)	0 to 3000 ppm	$\pm (1.5\%$ of range +2% of reading)	1 ppm
ILL	HD2021T (DeltaOHM)	20 to 2000 lux	$\pm 4\%$ of reading	0.1 lux

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). During the step-change transients, the questionnaire was filled in right after changing the room (see top two plots of Fig. 4). Only for the cool tests, we collected an additional questionnaire right before changing the room to better detect the thermal overshoot (see bottom two plots of Fig. 4). 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 (TSV) on the classical ASHRAE 7-point scale: “Hot” (+3), “Warm” (+2), “Slightly Warm” (+1), “Neutral” (0), “Slightly Cool” (-1), “Cool” (-2), and “Cold” (-3) [16]. The second question was the Thermal Comfort Vote (TCV) 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 (TPV) 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 [20], the French translation of the three questions is based on the French version of EN ISO 10551 [21] except for the thermal comfort question which was slightly modified to include the “Very Comfortable” and “Very Uncomfortable” votes. We judged that these more extreme votes were relevant for the dynamic conditions studied that could induce thermal alliesthesia [7].

All the raw measured data can be accessed online at <https://doi.org/10.6084/m9.figshare.21552441.v3>.

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 adopted random-effects structure is a random intercept for each group. 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 predictors kept in the model at the end of the procedure. The open-source Python package `scipy.stats` is used for all the statistical 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 3. 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 higher ventilation rates per occupant given that there were fewer occupants per test room. Furthermore, the illuminance was higher in the cool tests because the sunscreens were kept slightly more open. It is also to be noticed that the air velocity was always above 0.1 m/s during the tests due to the decentralised convection thermal systems employed. To account for all the environmental variables, Fig. 4 gives an overview of the four tested conditions in terms of Fanger’s Predicted Mean Vote (PMV) which is compared to the measured Thermal Sensation Vote. The difference between the mean predicted and measured thermal sensation was always kept within one vote, while the standard deviation of the measured thermal sensation was observed to be larger than one vote. In the next section, we investigate contextual and interindividual factors contributing to such variation.

Table 3. Measured environmental conditions (mean±SD).

	T_a (°C)	T_r (°C)	RH (%)
1 Warm	26.4±1.1	27.6±1.0	50±3
2 Warm	27.3±2.2	28.3±1.6	49±4
1 Cool	25.2±1.2	25.3±1.3	48±4
2 Cool	24.6±2.1	25.3±1.7	47±3
	V_a (m/s)	CO_2 (ppm)	ILL (lux)
1 Warm	0.22±0.09	804±202	356±210
2 Warm	0.30±0.09	777±210	259±102
1 Cool	0.18±0.06	921±178	514±325
2 Cool	0.16±0.06	1065±184	689±338

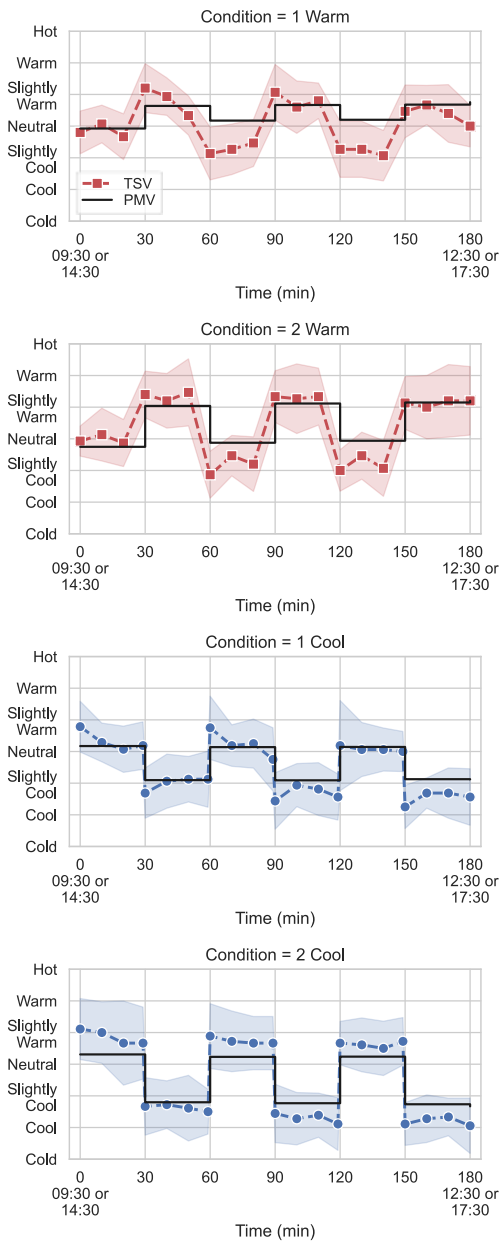


Fig. 4. Fanger's Predicted Mean Vote (PMV) and Thermal Sensation Vote (TSV) throughout the four experimental conditions. Shaded bands represent one standard deviation.

3.2 Thermal overshoot

In this section, we analyse whether the sex and time-of-day factors affect the thermal sensation overshoot during step-change transients. We first employ MLM with possible two-way interactions to model the actual Thermal Sensation Vote as a function of Fanger's Predicted Mean Vote (as a continuous fixed effect) and 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 except the step-change timesteps are included (1059 observations and 64 groups). The regression coefficients of the resulting linear model are shown in Table 4. Secondly, we use MLM to test whether sex and time of day affect the relationship between the step-change of TSV and that of Fanger's PMV when passing from one test room to another, i.e., during the step-change timesteps at 30, 60, 90, 120, and 150 min (320 observations and 64 groups). The regression coefficients of the resulting linear model are shown in Table 5. The key assumptions of MLM (normality, homoscedasticity and no autocorrelation of the residual errors, no multicollinearity of the independent variables) have been checked and met for both models.

Table 4. Regression coefficients for the significant predictors of the TSV in the MLM. All timesteps except the step-change timesteps are included.

	Coef.	Std. Err.	z	P> z
Intercept	-0.187	0.066	-2.835	0.005
Sex[MALE]	0.419	0.132	3.178	0.001
PMV	1.365	0.042	32.176	0.000
PMV * Sex[MALE]	-0.170	0.075	-2.259	0.024
Subject Var	0.173	0.052		

Table 5 Regression coefficients for the significant predictors of the step-change of TSV in the MLM. Only step-change timesteps are included.

	Coef.	Std. Err.	z	P> z
Intercept	0.012	0.069	0.170	0.865
Sex[MALE]	0.131	0.140	0.935	0.350
PMV	1.649	0.058	28.479	0.000
PMV * Sex[MALE]	-0.340	0.106	-3.223	0.001
Subject Var	0.000	0.046		

Time-of-day was found to not affect the relationship between the Thermal Sensation Vote and Fanger's Predicted Mean Vote and between the step-change of TSV and that of Fanger's PMV. However, sex was found to be a significant predictor for both MLM models (see Table 4 and Table 5). At equal PMV, females felt significantly cooler than males (Fig. 5) and responded to the step-change with a greater step-change of thermal sensation both during cooling and warming transients

(Fig. 6). These observations are in line with the results of 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 [22].

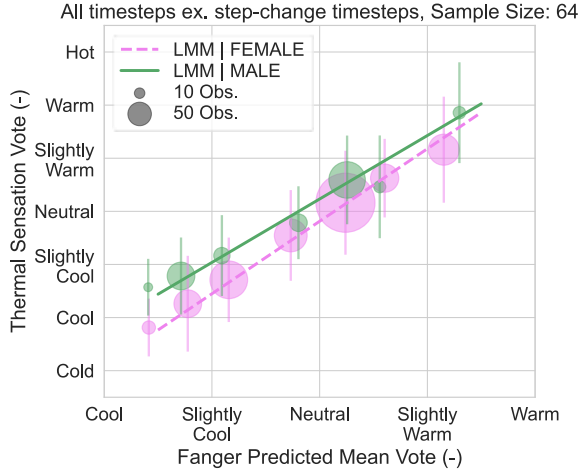


Fig. 5. Relationship between the Thermal Sensation Vote and Fanger’s Predicted Mean Vote for female and male participants. All timesteps except step-change timesteps are included. Error bars represent one standard deviation.

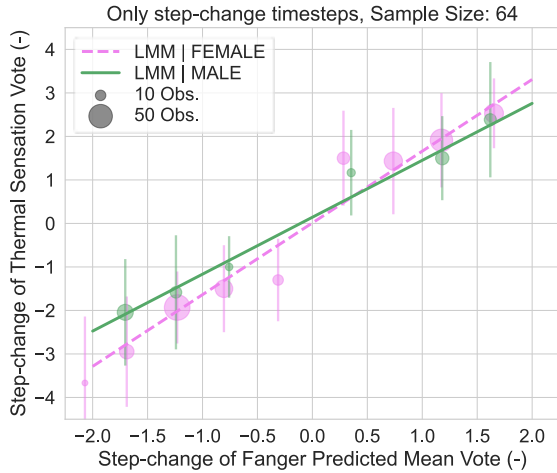


Fig. 6. Relationship between the step-change of TSV and that of Fanger’s PMV for female and male participants. Only step-change timesteps are included. Error bars represent one standard deviation.

3.3 Thermal alliesthesia

During temperature step-change transients, thermal comfort depends both on the phenomena of thermal overshoot and thermal alliesthesia. To disentangle these two effects, we first derive the quasi-steady-state relationship between thermal comfort and thermal sensation by including all timesteps except the step-change timesteps. We employ MLM with the thermal comfort vote as the dependent variable, the thermal sensation vote as a continuous fixed effect and sex, time of day (MORning/AFTernoon) and season (SUMmer/AUTumn) as categorical fixed effects. We fit two separate MLM models for both the warm and cool

side and obtains the significant regression coefficients shown in Table 6 and Table 7.

Table 6. Regression coefficients for the significant predictors of the Thermal Comfort Vote on the cool side ($TSV \leq 0$) in the MLM (769 observations and 64 groups).

	Coef.	Std. Err.	z	P> z
Intercept	5.018	0.083	60.32	0.000
Time[MOR]	-0.090	0.099	-0.914	0.360
Season[SUM]	0.074	0.099	0.744	0.457
TSV	1.340	0.045	29.78	0.000
TSV * Time[MOR]	0.153	0.059	2.603	0.009
TSV * Season[SUM]	-0.434	0.072	-5.998	0.000
Subject Var	0.089	0.038		

Table 7. Regression coefficients for the significant predictors of the Thermal Comfort Vote on the warm side ($TSV \geq 0$) in the MLM (656 observations and 64 groups).

	Coef.	Std. Err.	z	P> z
Intercept	5.113	0.095	53.67	0.000
Time[MOR]	-0.091	0.112	-0.813	0.416
Season[SUM]	-0.037	0.112	-0.335	0.737
TSV	-0.961	0.069	-14.00	0.000
TSV * Time[MOR]	0.279	0.083	3.369	0.001
TSV * Season[SUM]	-0.317	0.084	-3.785	0.000
Subject Var	0.116	0.047		

Sex was not found to affect the relationship between the Thermal Comfort Vote and the Thermal Sensation Vote. However, time-of-day and season were found to be significant predictors for both MLM models. As illustrated in Fig. 7, warm thermal sensations were considered more comfortable in the morning and autumn while cool thermal sensations were regarded as more comfortable in the afternoon and summer. Seasonal effects in the relationship between thermal comfort and thermal sensation have been previously observed and attributed to a form of seasonal alliesthesia [23]. While the effect of time-of-day on the relationship between thermal sensation and thermal comfort has been not observed previously, except in our previous works [24,25]. This diurnal effect might be related to the circadian fluctuation of the body temperature, and in particular, to the core temperature lowering down at night and raising during the morning with a peak reached in the afternoon [26]. Indeed, the observed variation in human thermal perception could be needed to favour the increase of body core temperature in the morning [24,25]. But it could be also 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 perceived as comfortable in the morning. This is similar to what happens in seasonal alliesthesia with warm conditions more likely to be perceived as comfortable in the winter. Further research is needed to better understand time-of-day effects on thermal comfort.

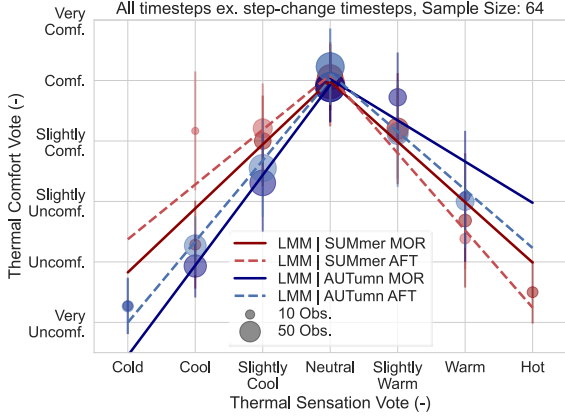


Fig. 7. Relationship between the Thermal Comfort Vote and the Thermal Sensation Vote in the morning (MOR)/afternoon (AFT) and summer/autumn. Error bars represent one standard deviation.

Now, we use the derived relationship between thermal comfort and thermal sensation to predict the “overshot” thermal comfort votes $oTCV$ during the step-change timesteps at 30, 60, 90, 120, and 150 min. As an example, in Fig 8 we show the actual compared with the “overshot” thermal comfort votes for the condition “1 Cool”. The $oTCV$ account for the thermal sensation overshoot but do not consider any effect due to the thermal alliesthesia experienced during dynamic environmental conditions. Hence, we calculate the residuals between the actual and the “overshot” thermal comfort votes $rTCV = TCV - oTCV$. These residuals incorporate the effect of thermal alliesthesia. Thus, we regress them against the rate of change of $oTCV$ ($\frac{\partial oTCV}{\partial t} = \frac{oTCV_t - oTCV_{t-1}}{\Delta t}$) that represents the “perceived” corrective potential of the whole-body peripheral load error, i.e. how much the magnitude of the perceived load error incurred in the antecedent exposure is counteracted during the transient exposure [7]. A positive value ($\frac{\partial oTCV}{\partial t} > 0$) implies that the perceived load error is decreasing (“positive alliesthesia”), while a negative value ($\frac{\partial oTCV}{\partial t} < 0$) that is increasing (“negative alliesthesia”). It is found that $\frac{\partial oTCV}{\partial t}$ is a significant predictor of $rTCV$ only for the case of positive alliesthesia ($\frac{\partial oTCV}{\partial t} > 0$) and when the thermal sensation is different than “neutral”. On the contrary, negative alliesthesia is not found to significantly modify the relationship between thermal comfort and thermal sensation during thermal transients. Significant regression coefficients for the predictor of $rTCV$ in the MLM for the case positive alliesthesia are reported in

Table 8. From Table 8, we can see that the positive effect of thermal alliesthesia is stronger as we move far from neutrality as the coefficient of $\frac{\partial oTCV}{\partial t}$ is higher for the case of $|TSV| \geq 2$.

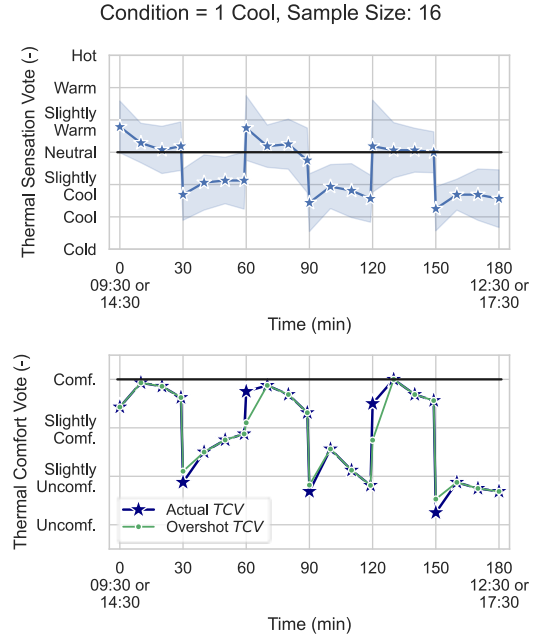


Fig. 8. The Thermal Sensation Vote (above) and the actual Thermal Comfort Vote compared with the “overshot” one (below) for the condition “1 Cool”. Shaded bands represent one standard deviation.

Table 8. The regression coefficient for the significant predictor of $rTCV$ in the MLM for the case of positive alliesthesia (131 observations and 61 groups).

$ TSV \geq 2$	Coef.	Std. Err.	z	P> z
$\frac{\partial oTCV}{\partial t}$	0.901	0.318	2.838	0.005
Subject Var	0.591	1.878		
$ TSV = 1$	Coef.	Std. Err.	z	P> z
$\frac{\partial oTCV}{\partial t}$	0.253	0.086	2.954	0.003
Subject Var	0.261	0.303		

Conclusions

This study aimed to compare the psycho-physiological phenomena of thermal overshoot and thermal alliesthesia in relation to their effect on the relationship between thermal comfort and thermal sensation at different moments of the day (morning/afternoon), in distinct seasons (summer/autumn), and based on the sex. The main findings are:

- The relationship between the thermal sensation and Fanger’s PMV differs between sex, with females feeling cooler than males during dynamic thermal conditions.
- Season and time-of-day affect the relationship between thermal comfort and thermal

sensation. This finding confirms the existence of seasonal alliesthesia and points to the importance of further investigating the time-of-day factor.

- Positive alliesthesia during step-change transients increase thermal comfort proportionally to the corrective potential of the whole-body perceived load error and this effect is stronger further we are from the neutrality.

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