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Beyond hue and heat: A multi-site experimental study of lighting–thermal interactions in human perceptions

Mateus Bavaresco [a,*], Roberta Jacoby Cureau [b,c], Ilaria Pigliautile [b], Marcel Schweiker [d,e], Veronica Martins Gnecco [b,c], Giorgia Chinazzo [f], Edit Barna [g], Zsofia Deme Belafi [g], Lorenzo Belussi [h], Agnese Chiucchiù [b], Ludovico Danza [h], Zhipeng Deng [i,j], Bing Dong [j], Natasha Hansen Gapski [k], Liége Garlet [k], Xingtong Guo [l], Peiman Pilehchi Ha [d], Hamidreza Karimian [m], Roberto Lamberts [k], Shichao Liu [l], Brenda da Costa Loeser [n], Camilla Massucci [o], Ana Paula Melo [k], Balázs Vince Nagy [p], Mohamed M. Ouf [m], Francesco Salamone [h], Anna Laura Pisello [b,c]

[a] Department of Civil Construction Engineering, Polytechnic School of the University of São Paulo (Poli-USP), São Paulo, Brazil
[b] EAPLAB at CIRIAF – Interuniversity Research Center on Pollution and Environment "Mauro Felli", University of Perugia, Perugia 06125, Italy
[c] Department of Engineering, University of Perugia, Perugia (PG), Italy
[d] Healthy Living Spaces Lab, Institute for Occupational, Social and Environmental Medicine, Medical Faculty, RWTH Aachen University, Aachen, Germany
[e] Chair of Healthy Living Spaces, Faculty of Architecture, RWTH Aachen University, Aachen, Germany
[f] Controlled, Adaptive and Responsive Environments Laboratory (CARE), Department of Civil and Environmental Engineering, Northwestern University, Evanston, IL, USA
[g] Department of Building Services and Process Engineering, Faculty of Mechanical Engineering, Budapest University of Technology and Economics, Budapest, Hungary
[h] Construction Technologies Institute, National Research Council of Italy (ITC-CNR), San Giuliano Milanese, 20098, MI, Italy
[i] Department of Mechanical and Aerospace Engineering, College of Engineering and Computer Science, University of Central Florida, Orlando, FL, USA
[j] Department of Mechanical & Aerospace Engineering, Syracuse University, Syracuse, NY, USA
[k] Laboratory of Energy Efficiency in Buildings, Federal University of Santa Catarina, Florianópolis, Brazil
[l] Department of Civil, Environmental, and Architectural Engineering, Worcester Polytechnic Institute, Worcester, MA 01609, USA
[m] Department of Building, Civil and Environmental Engineering, Gina Cody School of Engineering and Computer Science, Concordia University, Montreal, QC Canada
[n] Delft University of Technology, Faculty of Architecture and The Built Environment, Delft, the Netherlands
[o] International Centre for Indoor Environment and Energy, Department of Environmental and Resource Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark
[p] Department of Mechatronics, Optics and Engineering Informatics, Faculty of Mechanical Engineering, Budapest University of Technology and Economics, Budapest, Hungary

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ABSTRACT

This multi-site experimental study investigated the Hue-Heat Hypothesis (HHH), which posits that light hues can influence human thermal perception, as well as broader cross-modal interactions between visual and thermal domains. Across 464 experimental sessions in eight test rooms around the world, participants were exposed to varied thermal conditions (~20 °C, ~24 °C, ~26 °C, and ~28 °C) and typical white-light Correlated Color Temperatures (CCT, warm light: ~3000 K; neutral: ~4000 K; cool light: ~6000 K) from LED sources (horizontal illuminance: ~500 lx). The study assessed thermal, visual, and overall perceptions. Results revealed that thermal sensation and preference were predominantly influenced by thermal conditions, gender, and the laboratory setting, indicating that no statistically significant effects were found in support of the HHH. Similarly, visual perceptions were influenced by lighting conditions but not by the thermal environment. For instance, cool light was perceived as brighter than warm light, leading participants to prefer brighter light under warm light hues. Ultimately, this research revealed the significant challenges of interlaboratory experiments in this field, as local climate and test-room characteristics complicate both the conduct and the standardization of data analysis. Our findings highlight both the limited role of white-light CCT in shaping thermal sensations and the methodological

* Corresponding author.
E-mail address: m.bavaresco@usp.br (M. Bavaresco).

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challenges of multi-site comfort research, underscoring the need for careful data harmonization and context-aware analyses in future international collaborations.

Nomenclature

Symbol or Acronym	
CCT_h	Horizontal Correlated Color Temperature [K]
CCT_v	Vertical Correlated Color Temperature [K]
E_h	Horizontal illuminance [lx]
E_v	Vertical illuminance [lx]
MRT	Mean radiant temperature [°C]
T_a	Air temperature [°C]
RH	Relative humidity [%]
V_a	Air velocity [m/s]
TCV	Thermal comfort vote [–]
TPV	Thermal preference vote [–]
TSV	Thermal sensation vote [–]
OCV	Overall comfort vote [–]
VCV	Visual comfort vote [–]
VPV	Visual preference vote [–]
VSV	Visual sensation vote [–]

1. Introduction

Multi-domain comfort theory aims to address the limitations of current standards in human comfort assessment, which have traditionally focused on a single physical domain at a time, while people are continuously exposed to multiple stimuli simultaneously [1]. Multi-domain studies seek to deepen our understanding of human environmental perception by investigating both cross-modal and combined effects on human responses. A cross-modal effect occurs when a stimulus in one domain influences a response in an unrelated domain.

A common example of a cross-modal effect is the Hue-Heat-Hypothesis (HHH), which states that thermal responses (specifically, thermal perception) are influenced by light hues, a stimulus typically associated with the visual domain [2]. More precisely, the HHH claims that a cool light leads to a cooler thermal perception, while a warm light leads to a warmer thermal perception. Such an assumption may be linked with humans' lifetime exposures to colored symbols indicating warmth or coolness in the real world [3]. Once verified, such a cross-modal effect could unlock significant potential for developing strategies to ensure satisfactory thermal environments through light hue manipulation, a less energy-intensive approach than relying on active conditioning systems.

Although the first experimental study on the HHH dates back over a century, the scientific community has yet to reach a consensus over its validity, due to numerous contradictory or ambiguous findings reported by different research groups over the years. Among others, Better and Rey [4] in 1980 exposed 21 students to controlled thermal conditions while wearing red, blue, and clear goggles, but observed no hue-driven effect on perceived thermal comfort. Similarly, Greene and Bell [5] found that the color of interior finishes did not affect perceived temperature. Under similar boundary conditions, Wang et al. [6] reported different outcomes, observing increases in both thermal sensation and participants' heart rate as wall colors changed from cool to warm tones. More recently, Chinazzo and Andersen [7] exposed 75 participants to nine controlled conditions, combining three temperature levels with three daylighting scenarios, in which daylight passed through colored glass. Their findings revealed a cross-modal effect of the visual stimulus on psychological responses (overall comfort and thermal sensation), but not on physiological ones. Shifting the focus from daylight to artificial lighting, Winzen et al. [8] observed a trend in perceiving warmer conditions under yellow light compared to blue light, despite constant room temperatures. In contrast, the study from Baniya et al. [9] did not support the HHH, while Brambilla et al. [10] observed a statistically significant improvement in thermal comfort under warm conditions with lights of high Correlated Color Temperature (CCT, CCT > 6000 K). Similarly, Toftum et al. [11] investigated the link between the CCT of white LED lighting and subjective perception at different operative temperatures and found a significant inverse correlation between CCT and thermal sensation, with stronger effects observed under neutral thermal conditions.

Recent literature reviews have provided a comprehensive overview of experimental studies on how lighting manipulations influence thermal perception. Mayes et al. [12] highlighted the methodological heterogeneity across these experiments, which obscures the effects of the visual domain on thermal perception. Li et al. [13] focused on the influence of CCT on thermal sensation, identifying specific conditions under which the HHH applies, while also emphasizing the significant role of methodological differences observed in the studies. Differences in sample characteristics, exposure durations, lighting conditions, and experimental protocols make it difficult to draw generalizable conclusions. Indeed, different protocols may bring different biases in the analysis, which must be properly identified through rigorous reporting practices to ensure comparability of results [14]. To achieve a better understanding of the HHH and potential cross-modal interactions, it is crucial to gather a substantial amount of data that accurately represents the target population, using a standardized, replicable experimental procedure and a consistent reporting process. To this end, a multi-site experiment was conducted across eight research institutes within the framework of the IEA-EBC Annex 79 project [15]. The initiative focused on the development and implementation of a shared experimental protocol, replicated across participating laboratories. Our primary research question was to investigate if and how varying white-light CCT affects people's thermal and visual responses, while also exploring the broader cross-modal interactions between these two domains.

A coordinated effort like this allows, for the first time, to target human comfort using a consistent methodology across diverse national and climate contexts. Such an approach enables the exploration of contextual variables affecting human responses, factors that cannot be addressed through experimental campaigns conducted in a single location. This contribution presents the outcomes of a multi-site experimental campaign, highlighting the challenges related to interlaboratory experiments on multi-domain human comfort research.

2. Method

This research is based on a shared experimental protocol followed by eight research institutes, specifically designed to investigate the HHH. The protocol received ethical approval from institutional and national review boards when required, and all participants provided their consent before taking part in the experiment. A total of 464 experimental sessions were considered in the data analysis. Ultimately, this study investigated indoor conditions representative of real-world office environments, in terms of both air temperature and CCT.

2.1. Test room characteristics

This subsection provides an overview of each test room participating in the multi-site experimental campaign for HHH testing. As summarized in Table 1, the test rooms involved vary in size, design, boundary conditions, location, conditioning, and lighting systems, providing a diverse set to answer the research questions formulated in this project. Scenario photos are provided in Table A.1 (Appendix A), while additional information about these facilities is provided in [16], and their respective Technical Sheets are included in [17]. Given the reported differences, the lighting conditions tested also vary slightly among laboratories despite targeting the same values. Table 2 presents the illuminance (E) and CCT values for the lighting conditions in each test room.

2.2. Synthesis of the experimental protocol

This subsection describes the experimental protocol adopted in this study, covering environmental control and monitoring, physiological signal measurements, questionnaires, and ethical consent. All datasets, along with detailed information on the test rooms, experimental protocol, and questionnaires (available in English, Italian, German, and Portuguese), are publicly accessible [16,17].

2.2.1. Environmental control and measurements

During the experiments, participants were exposed to various thermal and visual conditions in both summer and winter, as detailed in Table 3. One experimental session corresponds to a 110-min period during which participants stayed inside the test room under fixed thermal conditions and alternating lighting (Fig. 1). The experiment began with a 40-min exposure to neutral light for acclimation, followed by a 30-min exposure to the first lighting condition (either cool or warm light), a 10-min rest period in neutral light, and another 30-min exposure to the second lighting condition (either warm or cool light, being the opposite of the previous session). During the sessions, they remained seated and could read a document provided by them on an e-book reader with a non-backlit display, except when they were asked to walk inside the test room during the neutral light exposure between the cool and warm lights. This was done to avoid reducing their metabolic rate due to prolonged sitting. Counterbalanced initial lighting conditions and gender balance were targeted, and each participant repeated the experiment twice per season under different thermal conditions on two non-consecutive days. Summer participants were not necessarily the same involved in the winter sessions.

During the experimental sessions, thermal factors (i.e., air temperature, air velocity, relative humidity, and globe temperature) were recorded every minute. Only artificial light was used for the experiments, so test rooms with windows facing outdoors required shutters, curtains, or other shading to block natural light. This ensured equal lighting conditions for all tests performed in the same test room and, for this reason, visual factors (CCT and illuminance) were either measured every minute during the session or monitored beforehand for the three lighting conditions (cool light, warm light, and neutral). Illuminance was set around 500 lx on the horizontal plane (desk) and 300 lx on the vertical plane (sight level at 120 cm). Finally, to ensure consistency across participants, all sessions were conducted in the morning, as previous studies have shown that thermal perceptions and physiological responses may vary throughout the day [18].

2.2.2. Physiological measurements

Participant skin temperature (10-point method [19,20]) and heart rate were also continuously monitored during the sessions (1-min

Table 1
Summary of the test rooms involved in the experimental campaign.

TR	Location	Climate class	Dimensions	Boundary conditions	Finishing	Conditioning system(s)	Lighting system(s)
1	Worcester, USA	Dfb	4.60 m x 5.90 m x 3.60 m	Room in a building	Walls: white paint; floor: cool grey cover; ceiling: coated with steel fireproof spray	HVAC system (centralized air conditioning, ceiling-mounted heater, and fans)	4 suspended LED lights with CCT control
2	San Giuliano Milanese (Milan), Italy	Cfa	6.40 m x 3.70 m x 2.95 m	Room in a building	Walls: plaster, white paint; floor: dark grey steel tiles with satin finish and calamine texture; ceiling: white soundproof tiles	Radiant system (radiant floor modules for heating and cooling), HVAC system (cooling and heating supply with air-to-water mechanical ventilation with recovery system that includes a heat pump)	1 suspended LED panel with CCT control, 1 LED lamp, 1 halogen lamp
3	Aachen, Germany	Cfb	3.00 m x 4.00 m x 2.55 m	Room in a building	Walls: white colored punched metallic boards (thermal radiators), white painted plasterboards, black-colored metal strips dividing these surfaces; ceiling: white colored punched metallic boards; floor: dark grey vinyl flooring.	Radiant system (15 heating and cooling panels distributed on the ceiling and right and left walls), HVAC system (heat supply through district heating system, cooling supply through air-to-water heat pump, humidification through steam humidifier)	2 free-standing LED panels with direct and indirect light output (2700–6000 K), 1 LED strip with tunable white light and RGB colors (2300–6500 K)
4	Syracuse, USA	Dfb	10.97 m x 5.10 m x 3.20 m		Walls: white painting; floor: fabric carpet; ceiling: white partitions	HVAC system (mixed and displacement ventilation)	4 panel luminaires, LED desk lamps with CCT control
5	Budapest, Hungary	Dfb	4 m x 4 m x 3 m	Independent volume inside a building	Walls: 3 white-painted, 1 black-painted (enables visualizing airflows); floor: floor tiles; ceiling: cassette type	Radiant system (panels on the walls, floor, and ceiling), HVAC system (compact air handling unit)	4 LED bulbs (2700 K), 4 classic LED bulbs (6500 K), 2 + 2 LED bulbs (4000 K), 12 LED fixture + RGB LED reflectors
6	Florianópolis, Brazil	Cfa	2.80 m x 3.50 m x 2.62 m	Independent volume inside a building	Walls and ceiling: gypsum board, white painting; floor: light brown vinyl flooring	HVAC system (Variable Refrigerant Flow system)	4 LED panels with CCT control
7	Montreal, Canada	Dfb	2.80 m x 3.80 m x 2.70 m	Independent volume inside a building	Walls: polished chrome plasterboard; floor: grey; ceiling: suspended panels	Perimeter heating system (2 convectors with high heat output), HVAC system (Air Handling Unit + Variable Air Volume system)	4 LED panels, RGB reflectors
8	Perugia, Italy	Cfa	4.0 m x 4.0 m x 2.7 m	Independent volume inside a building	Walls, floor, and ceiling: grey plasterboard; dark grey strip in the middle of walls for visualizing the radiant system	Radiant system (heating/cooling in all surfaces), HVAC system (air-to-air heat pump, active heat recovery)	4 LED panels, 2 RGB reflectors (14 emission colors)

Table 2
Average E_h and E_v (120 cm height) [lx] and CCT_h and CCT_v [K] for the lighting conditions in each test room (TR).

TR	Cool light				Neutral				Warm light			
	E_h	E_v	CCT_h	CCT_v	E_h	E_v	CCT_h	CCT_v	E_h	E_v	CCT_h	CCT_v
1	510	301	5677	5677	510	301	4068	4068	510	301	2912	2912
2	512	353	6233	6165	516	333	4228	4282	503	307	2992	2989
3	386	194	6091	6022	369	196	3973	3965	378	196	3173	3205
4	500	300	6500	6500	500	300	4500	4000	500	300	2800	3000
5	546	377	6268	6028	522	328	3992	3942	502	330	2723	2712
6	509	337	5688	5502	499	342	3928	3850	486	328	2850	2826
7	504	NR	6000	NR	491	NR	4000	NR	492	NR	2800	NR
8	487	227	6453	6412	474	240	4000	3839	534	267	2906	2894

Note 1: E_h: Horizontal illuminance; E_v: Vertical illuminance; CCT_h: Horizontal Correlated Color Temperature; CCT_v: Vertical Correlated Color Temperature; NR: Not Reported.
.Note 2: Correlated Color Temperatures were characterized through proper lab tools, specified in corresponding technical sheets available in [17]. In two out of eight cases, manufacturer specifications were assumed as reference.

Table 3
Conditions adopted during the experimental sessions.

Domain	Factors	Levels			
Thermal	T_a [°C]	Cool		Warm	
		20[a]	24[b]	26[a]	28[b]
	V_a [m/s]	Constant (< 0.1)			
Visual	CCT [K]	Warm light	Neutral	Cool light	
		2700–3000	~4000	6000–6500	
	E_h [lx]	~ 500 (on the desk)			
	E_v [lx]	~ 300 (at the sight level)			

[a] Temperatures for winter sessions.
[b] Temperatures for summer sessions.
Note: T_a: Air temperature; V_a: Air velocity; CCT: Correlated Color Temperature; E_h: Horizontal illuminance; E_v: Vertical illuminance.

interval). Additional details regarding the experimental procedure, its design, and physiological monitoring system specifics per laboratory are provided in [16]. Recruited participants were asked not to smoke, drink any beverage, or eat any type of food at least two hours before the test to avoid corresponding influences on their responses. Some of the participating laboratories had the opportunity to provide garment ensembles corresponding to the standard clothing levels for the heating (1.0 clo) and cooling (0.5 clo) seasons. In contrast, others relied on participants' preferred attire for the season that was expected to be similar to the standard one. Regardless of the approach, participants' clothing levels were reported for all experimental sessions. Skin temperature and heart rate were continuously monitored to build a broader dataset on physiological responses to environmental conditions. The current paper focuses on perceptual responses; therefore, the physiological data are not analyzed here and will be addressed in future work.

2.2.3. Questionnaires used

Two different questionnaires were used, the general questionnaire answered at the beginning of each experimental session, and the perceptual survey answered three times during each session at the end of each lighting exposure (cool and warm light), as shown in Fig. 1. The general survey asked for participants' age, gender, height, weight, clothing, highest level of education, employment status, visual problems, and in which city they were currently living and for how long. They also reported on their sleep quality and stress level (5 points ranging from worst to best), as well as eating and exercise habits (5 points ranging from uncommon to regular). City of residence and duration of stay were collected in broad ordinal categories to characterize the sample. Because these categories do not allow a continuous climatic exposure metric, they were not included in the inferential models. Individual differences were accounted for by including Participant ID as a random effect in the models.

After the acclimation period (neutral light) and at the end of warm light and cool light exposure, participants answered to the perceptual survey. This included questions on thermal and visual sensations, comfort, preferences, and acceptability; localized thermal sensation at hands, trunk, and feet; and overall comfort. The scales used for each question are detailed in Table 4. Additional details and the complete survey used in the study are provided in the questionnaire available at [17].

2.2.4. Ethics and consent

Ethical approval was obtained from the institutional or national review board when required (WPI: Institutional Review Board (IRB-20–0001); ITC: CNR Ethics and Research Integrity Commission (0053,590/2022); RWTH: The Ethics Committee at the RWTH Aachen University Faculty of Medicine (EK 23–046); Syracuse: Institutional Review Board (22–161); BME: United Ethical Review Committee for Research in Psychology (2022–123); UFSC: Research Ethics Committee Involving Human Subjects (5.993.216); Concordia: Human Research Ethics Committee (30,016,771)).

2.3. Data cleaning and preparation

A comprehensive data cleaning and preparation process was conducted to ensure that the final dataset conformed to the protocol's defined boundaries. Experimental sessions with extreme indoor conditions were initially excluded, such as air velocities above 1 m/s and relative humidity outside the 10 %–80 % range. The protocol defined

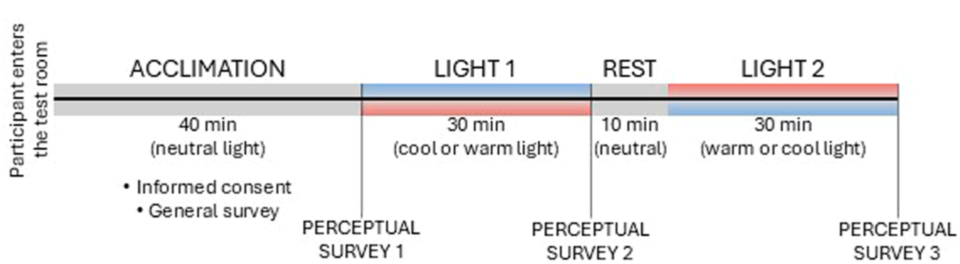

Fig. 1. Overview of the experimental protocol.

Table 4
Subjective assessment scales used in the perceptual survey.

Subjective perception	Scale
Thermal sensation (overall body (TSV), hands, trunk, and feet)	1: Cold 2: Cool 3: Slightly cool 4: Neutral 5: Slightly warm 6: Warm 7: Hot
Thermal preference (TPV)	1: Much cooler 2: Cooler 3: Slightly cooler 4: Without change 5: Slightly warmer 6: Warmer 7: Much warmer
Visual sensation (VSV)	1: Too dark 2: Dark 3: Slightly dark 4: Neutral 5: Slightly bright 6: Bright 7: Too bright
Visual preference (VPV)	1: Much darker 2: Darker 3: Slightly darker 4: Without change 5: Slightly brighter 6: Brighter 7: Much brighter
Comfort (thermal (TCV), visual (VCV), and overall (OCV))	1: Comfortable 2: Slightly uncomfortable 3: Uncomfortable 4: Very uncomfortable 5: Extremely uncomfortable
Acceptability (thermal and visual)	1: Clearly acceptable 2: Just acceptable 3: Just unacceptable 4: Clearly unacceptable

target air temperatures based on season and condition (Summer–Cool, SC: 24 °C; Summer–Warm, SW: 28 °C; Winter–Cool, WC: 20 °C; Winter–Warm, WW: 26 °C). For data analysis, only experiments within the 18 °C–30 °C range were considered. Additionally, sessions with horizontal illuminance below 350 lx were excluded. These criteria aimed to balance methodological precision with the practical limits of achievable indoor conditions across all test rooms.

During the dataset review, temperature ramps and drifts were observed. Thus, experiments not complying with the ASHRAE 55 criteria [21]—specifically, operative temperature variations limited to a peak-to-peak amplitude of no more than 1.1 °C within any 15 min, 1.7 °C within 30 min, and 2.2 °C within 60 min—were excluded from the final database. For each experimental session, the time series of operative temperature values was evaluated using rolling windows of 15, 30, and 60 min. The peak-to-peak amplitude (the difference between the maximum and minimum temperatures) was calculated within each window, and any violation resulted in exclusion of the entire session to ensure steady-state conditions across tests. The final quality control step involved comparing PMV values during contrasting lighting exposures (cool vs. warm light). A threshold of $|\Delta PMV| < 0.5$ was set; no tests violated this criterion. Fig. 2 illustrates the full cleaning process adopted in this study. The final sample comprised 464 experimental sessions distributed across the labs as follows: lab 1: 50; lab 2: 86; lab 3: 20; lab 4: 39; lab 5: 92; lab 6: 60; lab 7: 12; and lab 8: 105.

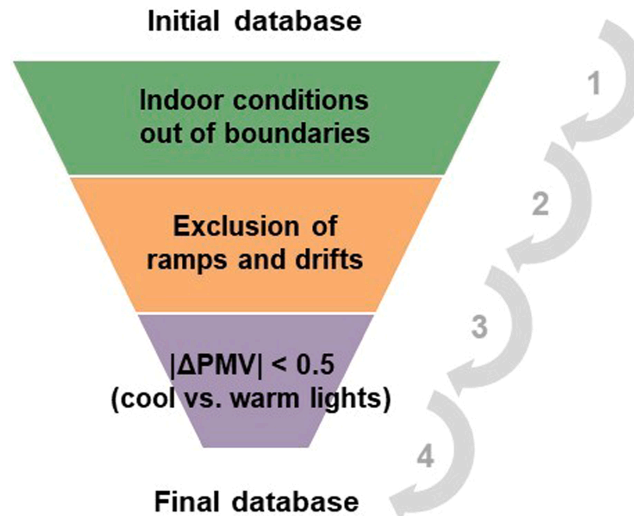

Fig. 2. Recursive cleaning process adopted.

2.4. Statistical modeling and analyses

This study assesses thermal and visual perceptions, as well as overall comfort, reported during the experiments. We specifically focused on perceptions reported under cool and warm light conditions, as these contrasting conditions were specified to explore the HHH. To investigate factors influencing human perceptions, we developed a series of linear mixed-effects models using the *statsmodels* library in Python [22]. Table 5 provides an overview of the models designed to test thermal sensation. The approach involved recursively adding factors that may explain the participants' thermal sensation beyond the air temperature measured during the experiment. Similar steps were performed to analyze thermal comfort and thermal preference votes. For visual perceptions, factors were incrementally added to E_h and CCT_h, measured during the experiments. Given that most laboratories measured the CCT_h for the three lighting conditions before starting their experimental campaign, CCT_h was considered a categorical value in the models. The "*" symbol between predictors indicates that the model also incorporates the interaction effects between them. Three criteria guided the selection of the best model for each scenario: first, the lower Akaike Information Criterion (AIC) [23]; second, a higher (less negative) Log-Likelihood; and third, the significance levels of fixed effects included in the model. For instance, if a more complex model (e.g., with an additional factor included as a predictor) had similar performance to a simpler one, but the added factor was not statistically significant, the simpler model was preferred.

Appendices C, D, and E provide comprehensive details regarding each model tested, comprising thermal sensation, comfort, and preference votes (TSV, TCV, and TPV, respectively), visual sensation, comfort, and preference votes (VSV, VCV, and VPV, respectively), as well as overall comfort votes (OCV). For each group of models, only data subsets with complete values for all variables included in any model of that

Table 5
Example of a series of mixed-effects models created to assess thermal sensation vote (TSV).

Model	Fixed effects*
M1	$TSV \sim T_a$
M2	$TSV \sim T_a + Gender$
M3	$TSV \sim T_a + Lab$
M4	$TSV \sim T_a + Gender + Lab$
M5	$TSV \sim T_a + CCT_h$
M6	$TSV \sim T_a * CCT_h$
M7	$TSV \sim T_a + E_h$
M8	$TSV \sim T_a + CCT_h + Lab$
M9	$TSV \sim T_a + CCT_h + Lab + E_h$
M10	$TSV \sim T_a * CCT_h * E_h + Lab$

*In all models, the participant ID was included as a random effect of the intercept.

group were considered. For example, in the visual sensation group, all records with missing values for PMV were excluded—even from models that did not explicitly include PMV—ensuring consistent sample sizes and minimizing bias due to varying sample sizes when selecting the best models according to AIC values.

3. Results

This section synthesizes the experimental results across all laboratories, considering both measured environmental parameters and multi-domain perceptual outcomes. We examine how visual conditions influence thermal perceptions, how thermal conditions influence visual perceptions, and how both domains jointly affect overall comfort.

The final database includes data from 464 experimental sessions, of which 53.7 % involved male participants and 45.9 % female participants. One participant, who took part in two sessions, preferred not to disclose their gender. Table B.1 (Appendix B) presents the gender distribution of participants across laboratories. Importantly, given the variability in sample size and gender distribution in each laboratory, no models involving the interaction of these effects (Gender and Lab) were considered. Most sessions were conducted with participants aged 21–25 years (41.0 %) and 26–35 years (44.2 %). The remaining sessions involved people younger than 21 years (7.3 %) and some aged 36–55 years (7.5 %). Table B.2 (Appendix B) presents the gender distribution of participants across laboratories. The average height was 1.7 ± 0.1 m (ranging from 1.5 to 2.0 m), and the average weight was 69.9 ± 14.8 kg (from 43.0 to 134.0 kg). Although personal variables such as age and BMI have been reported to influence thermal perception in previous research [24–26], they were not included as fixed effects in the present models. This decision reflects both the categorical nature of some individual data in our sample and the inclusion of Participant ID as a random effect, which accounts for between-subject variability without over-parameterizing the models. This follows the parsimonious modeling strategy adopted in the study. Future work may explicitly explore individual-level effects on multi-domain perceptions.

3.1. Overview of the experimental sessions

This subsection presents a characterization of the indoor conditions measured during each experimental session included in the final analyses. Fig. 3 illustrates air temperatures, relative humidities, air velocities, mean radiant temperatures (MRT), clothing levels, and PMV values observed across experimental conditions in each laboratory. Key observations include:

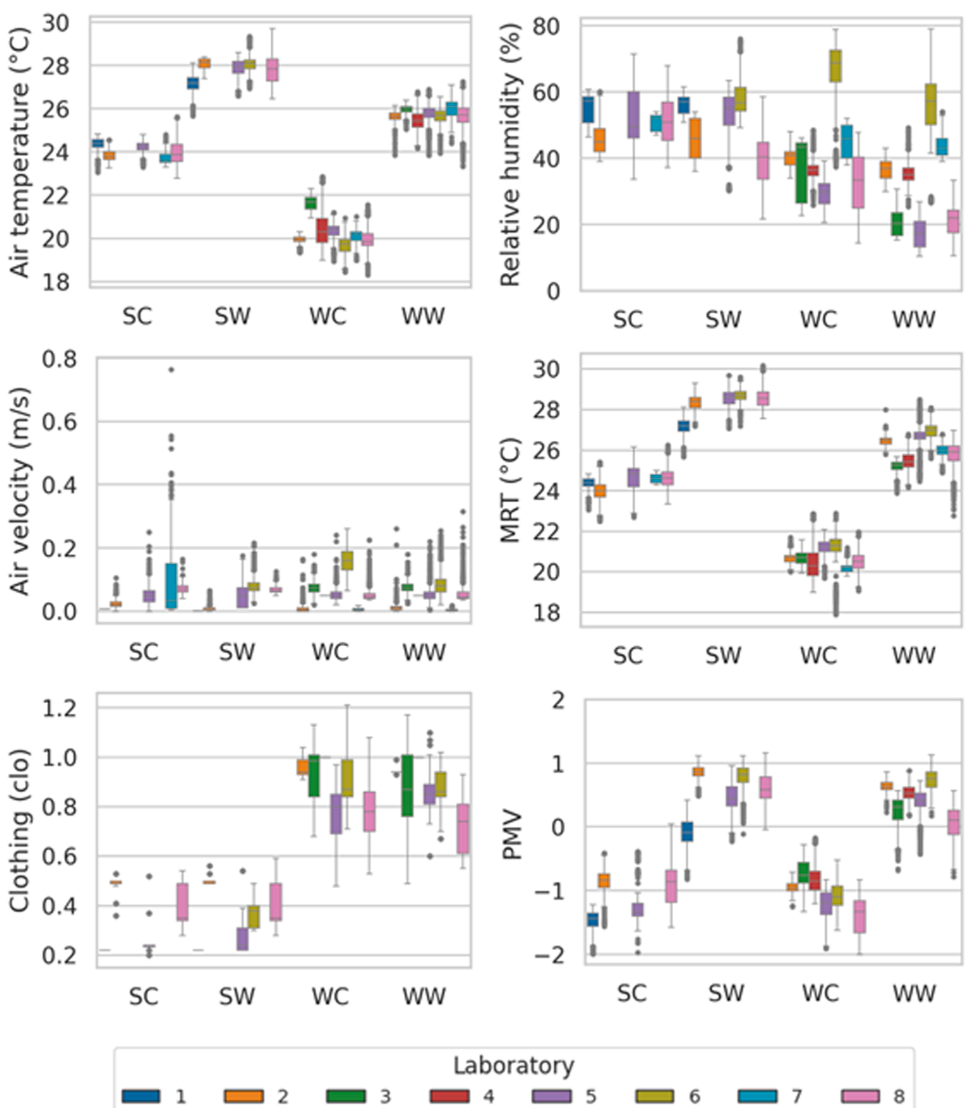

Fig. 3. Characterization of the indoor variables in each laboratory and for each experimental condition[1], i.e., SC, SW, WC, and WW. [1]Thermal experimental conditions: SC: summer–cool; SW: summer–warm; WC: winter–cool; WW: winter–warm.

- Air temperatures followed expected values for each condition: SC: 24 °C; SW: 28 °C; WC: 20 °C; and WW: 26 °C. MRT exhibited a similar trend, with values slightly higher than those of air temperatures across conditions. Slight variations across labs were also observed, representing the variability of conditioning systems used.
- Air velocities remained generally low, consistent with steady-state conditions. A few values exceeded 0.2 m/s, the threshold for low airspeed defined in ASHRAE 55.
- Relative humidity exhibited the greatest variability across laboratories, highlighting the challenge of maintaining consistent conditions in multi-site experiments, particularly in test rooms that lack precise humidification or dehumidification control and are located in diverse climatic conditions.
- Although the protocol specified standardized clothing insulation levels (0.5 clo for summer and 1.0 clo for winter), observed values were slightly different. This suggests that some participants wore clothing more in line with their personal preferences than with the specified standard.
- PMV values also differed slightly across laboratories, but as mentioned above never exceeded the $|\Delta PMV| < 0.5$ threshold.

3.2. Influence of visual conditions on thermal perceptions

Fig. 4 illustrates thermal sensation, thermal comfort, and thermal preference votes reported during each experimental condition and across different laboratory settings. Appendix C synthesizes all the statistical models tested for each instance of thermal perception. The key

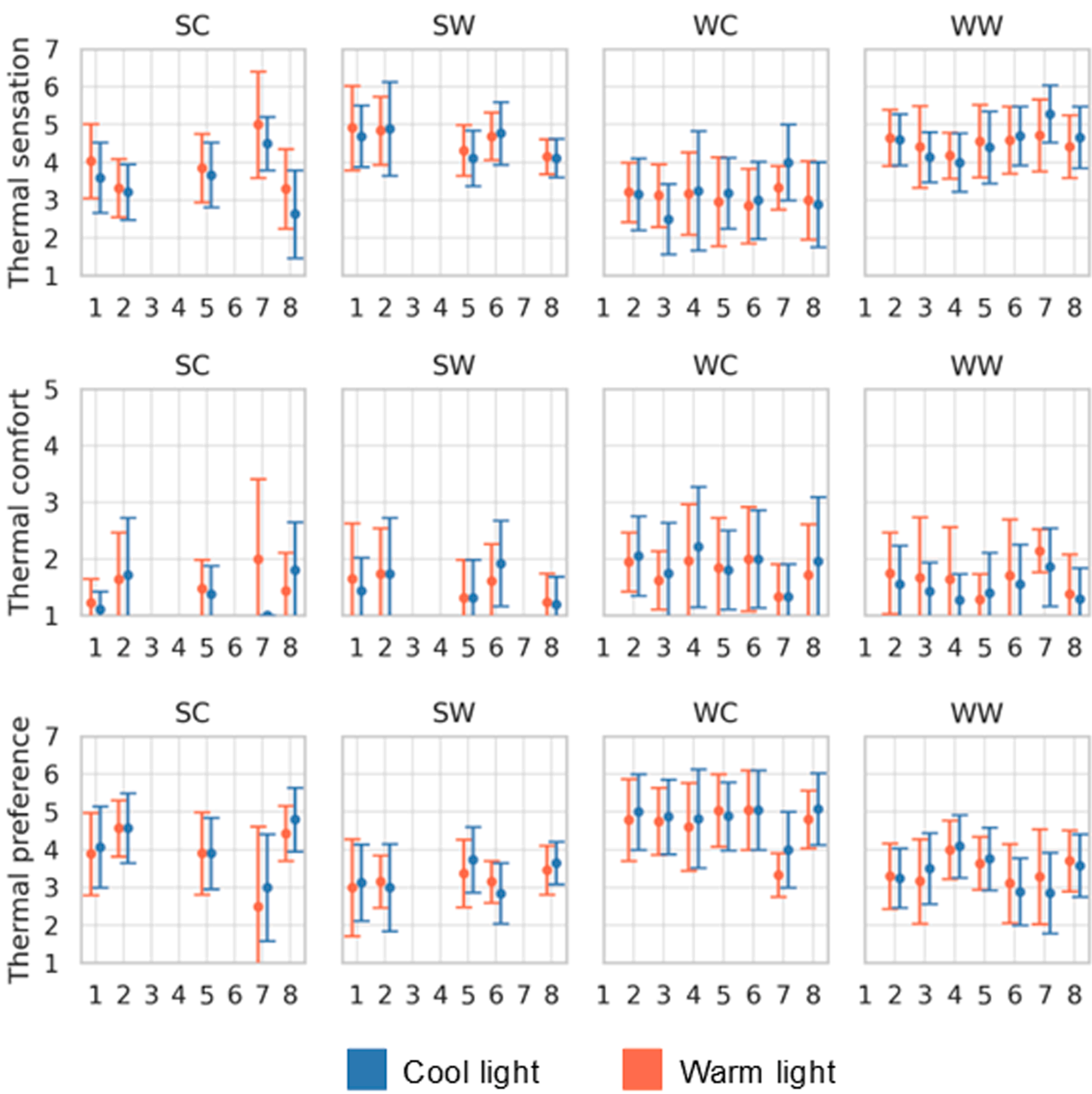

Fig. 4. Thermal sensation (TSV)[1], comfort (TCV)[2], and preference (TPV)[3] votes under different experimental conditions[4] across laboratories. [1]TSV scale: 1 = cold, 2 = cool, 3 = slightly cool, 4 = neutral, 5 = slightly warm, 6 = warm, 7 = hot.; [2]TCV scale: 1 = comfortable, 2 = slightly uncomfortable, 3 = uncomfortable, 4 = very uncomfortable, 5 = extremely uncomfortable; [3]TPV scales: 1 = much cooler, 2 = cooler, 3 = slightly cooler, 4 = without change, 5 = slightly warmer, 6 = warmer, 7 = much warmer. [4]thermal experimental conditions: SC: summer–cool; SW: summer–warm; WC: winter–cool; WW: winter–warm.

findings are as follows:

- TSV: Differences in thermal sensations according to the lighting conditions were minimal within each laboratory. Statistical models found that lighting variables (illuminance and CCT) did not significantly influence thermal sensation. Model 4 (TSV ~ Tair + Gender + Lab) yielded the best fit and reported all the fixed effects as statistically significant: PMV ($p < 0.001$), Gender ($p < 0.001$), and Lab ($p = 0.001$ for lab 1 and 0.046 for lab 5).
- TCV: Although lighting-related variables did not directly affect thermal comfort, our results indicated that certain lighting–thermal interactions did influence TCV ratings. Model 10 (TCV ~ PMV * CCT * Eh + Lab) yielded the best fit, with the following significant effects: PMV ($p < 0.001$), Lab ($p = 0.011$ for lab 2, 0.002 for lab 4, and 0.015 for lab 6), PMV * CCT ($p = 0.002$), PMV * illuminance ($p = 0.004$), and PMV * illuminance * CCT ($p = 0.003$). Importantly, Models 3 and 4, which excluded lighting-related variables, produced slightly higher AIC values; however, the differences were minimal (ΔAIC < 2), indicating that these models cannot be confidently ruled out as inferior to Model 10.
- TPV: Participants consistently displayed a preference for warmer environments in cooler conditions and for cooler environments in warmer conditions across all labs. Model 4 (TPV ~ Tair + Gender + Lab) also reached the best fit, with all the effects deemed as statistically significant: PMV ($p < 0.001$), Gender ($p < 0.001$), and Lab ($p < 0.001$ for lab 1 and 0.021 for lab 4).

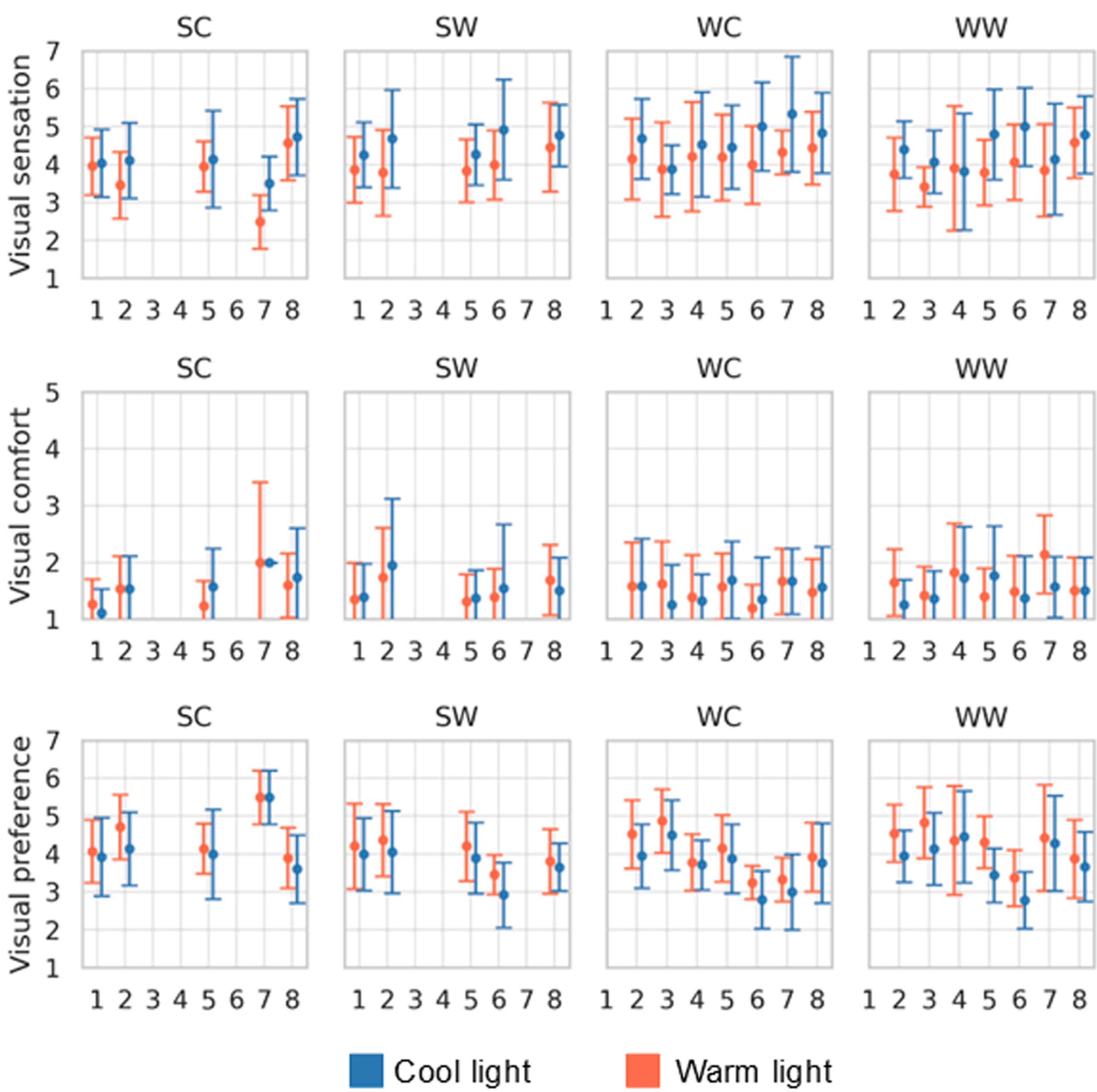

Fig. 5. Visual sensation (VSV)[1], comfort (VCV)[2], and preference (VPV)[3] votes under different experimental conditions[4] across laboratories. [1]VSV scale: 1 = too dark, 2 = dark, 3 = slightly dark, 4 = neutral, 5 = slightly bright, 6 = bright, 7 = too bright; [2]vcv scale: 1 = comfortable, 2 = slightly uncomfortable, 3 = uncomfortable, 4 = very uncomfortable, 5 = extremely uncomfortable; [3]vpv scales: 1 = much darker, 2 = darker, 3 = slightly darker, 4 = without change, 5 = slightly brighter, 6 = brighter, 7 = much brighter. [4]thermal experimental conditions: SC: summer–cool, SW: summer–warm, WC: winter–cool, WW: winter–warm.

3.3. Influence of thermal conditions on visual perceptions

Fig. 5 presents visual sensation, visual comfort, and visual preference votes reported during each experimental condition across different laboratory settings. Appendix D synthesizes all the statistical models tested for each instance of visual perception. The key findings are as follows:

- VSV: Differences in visual sensation votes were influenced by lighting and contextual variables, with no apparent effect from thermal conditions. Model 4 (VSV ~ Eh + CCT + Lab) yielded the best fit, indicating that thermal-related variables did not contribute meaningfully. Significant predictors included: Illuminance ($p = 0.002$), CCT ($p < 0.001$), and Lab ($p = 0.001$ for lab 1, < 0.001 for lab 2, and 0.020 for lab 4). Although Models 5 and 10 produced comparable AIC values, the additional variables included (gender in Model 5 and PMV in Model 10) were not statistically significant.
- VCV: Consistent responses were observed for VCV across different lighting and thermal conditions. Model 9 (VCV ~ PMV + CCT + Lab) provided the best fit, although only the Lab variable showed statistically significant effects ($p = 0.001$ for lab 1 and 0.023 for lab 6). While other models produced similar AIC values, they either identified no significant effects or mirrored the same significant predictors found in Model 9, disregarding the influence of most variables tested as fixed effects. Although CCT is included in the model, it was not deemed statistically significant ($p = 0.313$).
- VPV: Visual preference votes were primarily influenced by lighting and contextual variables, with no clear effect from thermal factors. Model 5 (VPV ~ Eh + CCT + Gender + Lab) reached the best fit. Significant predictors included: CCT ($p < 0.001$), Gender ($p = 0.007$), and Lab ($p < 0.001$ for lab 2, 0.016 for lab 3, and < 0.001 for lab 6).

3.4. Overall comfort

Fig. 6 presents the overall comfort votes reported under each experimental condition across the different laboratory settings. Appendix E summarizes all statistical models tested. Models 4, 5, 8, 9, and 10 yielded similar AIC values, ranging from 1749.53 to 1751.65. In all cases, Lab was the only significant predictor, with Lab 1 showing a statistically significant effect ($p < 0.02$) in Models 4, 5, 9, and 10.

4. Discussions

Previous literature reviews and meta-analyses of HHH have highlighted the lack of consistency in measurements and experimental conditions across experiments performed worldwide [12,13,27]. Such variability hinders direct comparisons among the results obtained, which is reflected in some pieces of literature reporting no evidence for HHH and others reporting some evidence. To the best of the authors' knowledge, this is the first international, large-scale initiative to test this hypothesis and provide the scientific community with a comprehensive database and hypothesis-testing approach. Broader cross-modal interactions between lighting and thermal stimuli were also assessed. This section discusses our results in the context of the previous literature and provides a comprehensive perspective gained from this original work.

4.1. Thermal perceptions

Regarding the potential influence of CCT on thermal perceptions, our study aligns with previous literature that has found no significant effects of lighting on thermal sensations [28]. Importantly, some previous literature that found significant hue-heat effects was based on actually testing different hues, either by using different wall colors [6], using colored windows to adjust the perceived daylighting color [7], using colored electric lighting [29], relying on very contrasting CCTs levels (e.g., from 1772 to 11,530 K) [30], or using virtual reality besides colored lighting [31]. In our experimental protocol, office-like lights with a white appearance were used, ensuring more ecological validity and consistency with real-world conditions. In addition to the CCT levels, some previous research supporting HHH relied on varying the lighting intensity (e.g., 300, 500 and 750 lx [32]). Although the experimental protocol targeted ~500 lx, incidental variations in illuminance occurred due to differences in the test rooms' characteristics. These variations were incorporated into the statistical models. Another key divergence is the duration of light exposure, since some previous experiments focused on short-term exposures, ranging from seconds [3] to a few minutes [33–35] while we used a longer exposure period. Finally, statistical analyses focusing specifically on each temperature exposure confirmed the HHH under certain temperatures (e.g., at 26 °C) and rejected it in others (e.g., at 21 °C) [10].

Our results suggest that thermal sensations and preferences were not significantly influenced by CCT and illuminance, under real conditions of office lighting exposure. As previously discussed, the literature remains controversial on this topic, with evidence supporting and rejecting such trends [12,13,27], as well as evidence supporting that individuals may respond differently to light exposures [36]. Even when considering the potential effects of CCT on thermal sensations, the synthesis of the literature still supports the fact that, as expected, air temperature is the predominant predictor of thermal sensation [13]. On the contrary, thermal comfort votes resulted in more complex

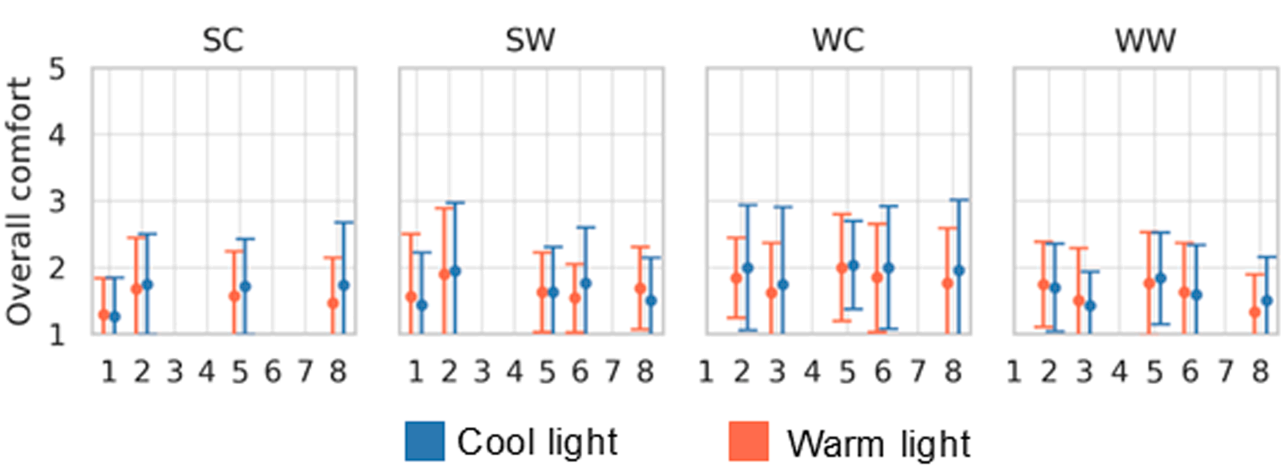

Fig. 6. Overall comfort votes (OCV)[1] under different experimental conditions[2] across laboratories. [1]OCV scale: 1 = comfortable, 2 = slightly uncomfortable, 3 = uncomfortable, 4 = very uncomfortable, 5 = extremely uncomfortable. [2]thermal experimental conditions: SC: summer–cool, SW: summer–warm, WC: winter–cool, WW: winter–warm.

assessments by the participants, which our statistical models confirmed were influenced by interactions between lighting and thermal variables in their perceptions. Such complexity could be a result of the more hedonic origin of occupants' thermal comfort, compared to the more objective nature of thermal sensation [37]. This trend aligns with the complexity of potential multi-domain exposures and stimuli to which office occupants are regularly exposed.

4.2. Visual perceptions

Visual sensations were higher under cool light, and visual preferences followed a similar path, in which participants reported a preference for brighter environments under warm light compared to cool light. Similar to the thermal domain, visual comfort appears to be a complex combination of environmental conditions and individual preferences. Regarding the multi-domain inference, the non-significant influence of temperature on visual perceptions may be attributed to the fact that average thermal sensations were maintained within the neutral range. Previous studies identified that higher visual comfort is observed within thermoneutrality or thermally comfortable conditions compared to non-neutral or uncomfortable perceptions [28,38]. Individual variations on color-temperature associations are also discussed in the literature [39], highlighting the importance of a comprehensive and diverse sample. Such a fact may also be linked to the strength of HHH effects, leading to the possibility of personalizing these aspects according to individual sensitivities.

Our models did not prove the significant influence of lighting and thermal variables on visual comfort votes. Individual preferences for cool or warm light resulted in no clear effect of fixed CCT values on overall visual comfort, considering that lighting conditions deemed as comfortable may significantly vary between individuals [28], and may not be associated with CCT levels [39].

4.3. Challenges and learnings related to the multi-site aspect of this project

This international project demonstrated that interlaboratory research in multi-domain comfort necessitates a thorough consideration of local climate and test room capabilities. Our results showed that different local conditions (e.g., outdoor air humidity) and test-room features (e.g., conditioning systems) directly influenced indoor parameters, such as relative humidity, air velocity, and temperature maintenance, during the test. Consequently, a strict approach to data cleaning, preparation, and statistical modeling was needed to ensure that responses under different lighting scenarios were comparable. However, some degree of variation was accepted in the data cleaning and preparation. For instance, setting very restrictive boundaries on air velocities or air humidities inside the test rooms would have made the international comparison unfeasible and unrealistic. For air velocities, different systems, such as radiant systems versus air-based ones, yielded variable outcomes, particularly regarding airflow effects on local sensation, which were not addressed in this study. For air humidity, cities from different locations were involved in the initiative, with very low mean relative humidity observed, especially in winter. Coastal cities, on the other hand, consistently exhibited high humidity levels throughout the testing periods. Therefore, this project emphasized the challenges regarding harmonizing interlaboratory experimental datasets in multi-domain human comfort.

Another key challenge related to the multi-site experiment is the potential influence of outdoor exposures before the experiments. Since climate zones diverged, typical summer and winter temperatures are expected to have a broad range. Therefore, from a practical perspective regarding experimental setups, it was essential to include a significant acclimation period under neutral lighting conditions before exposure to different CCTs, not disregarding the fact that participants in predominantly hot or cold climates are probably more prone to tolerate certain "extreme" conditions. At the same time, the open-source datasets generated by this project provide an opportunity to evaluate how outdoor weather conditions may shape psychophysiological responses in future analyses. Another aspect related to the outdoor conditions in each location is related to the clothing reported by the participants. Since providing standardized clothing was not possible in most labs, a broad range of clothing levels was observed within the experiments. Variations from the expected levels (0.5 and 1.0 in summer and winter, respectively) may indirectly suggest that standard values are no longer realistic and too general.

Beyond these environmental and procedural challenges, the results also highlight the strong role of contextual differences across laboratories. The influence of visual stimuli on thermal perception was consistently small, in line with the literature, whereas the differences between laboratories were often larger than those observed between lighting conditions. For example, in some cases the variation in TSV between two laboratories under the same condition exceeded one unit in the scale used, while differences between lighting conditions remained below half a unit. This suggests that contextual and cultural factors associated with each laboratory may overshadow the cross-modal effects of lighting. Therefore, future analyses may need to adopt both cross-site and within-site perspectives to disentangle these influences and to better assess the relative contribution of visual stimuli compared with broader contextual determinants.

4.4. Practical implications of the results

Although several studies support the influence of lighting variables on thermal perception, Mayes et al. [12] noted that it remains unclear how much manipulation is needed in the visual environment to achieve such effects. Our multi-site experimental campaign, conducted within commonly adopted boundaries for indoor conditions, emphasized that white-light electric sources, typically found in office-like environments, may be insufficient to manipulate and shift the thermal perceptions of occupants toward different directions. In our study, warm lighting did not significantly increase thermal sensations in cooler environments, nor did cool light reduce sensations in warmer conditions. This finding highlights the importance of ensuring acceptable thermal conditions (within or slightly beyond thermal comfort ranges) before relying on visual or other sensory inputs to influence perception.

An important factor often overlooked in HHH studies is the variability in individual responses to standardized lighting adjustments. While such changes may enhance thermal perception for some occupants, they can induce stress or discomfort in others, potentially compromising both thermal and visual comfort. Such individual variations have been discussed in terms of HHH effects, as previous research has highlighted the potential subjective nature of the hue-heat effect [40]. Additionally, personalized adjustments to CCT have been linked with higher visual comfort responses [41], supporting the idea that personalized environmental control systems (PECS) may be an effective way to tailor lighting conditions and leverage any potential hue-heat effects.

Furthermore, a meta-analysis of previous experiments emphasized that the HHH effects are more perceptible during short-term exposures [13]. Additionally, the use of actual hues (e.g., red or blue lighting) appears to elicit stronger effects, which may limit the real-world applicability of this approach in office settings. From a practical perspective, building designers and operators can benefit from the combination of short-term impacts and the potential use of colored lighting when enhancing the indoor conditions of transitional spaces [7,13].

Considering studies that support the HHH, Wang et al. [27] discussed how the thermal effects of light may be relatively more noticeable in neutral-to-cool environments compared to neutral-to-warm environments. Li et al. [13] suggested that the effect of CCT may be more pronounced in neutral environments. Even if these findings translate into design strategies, the overall energy-saving potential of manipulating lighting remains modest. Indeed, literature reviews did not support the notion that lighting can meaningfully influence thermal perception in non-neutral, especially hot, environments.

Ultimately, the exploration of the HHH has been motivated both by a fundamental interest in cross-modal mechanisms of perception and by potential implications for real-world applications. Current findings, however, remain inconsistent, reflecting a large variety of experimental setups and the different ways in which lighting hue has been operationalized. This calls for further research to better understand why some studies find effects while others do not. From a practical perspective, while manipulating CCT appears to offer limited value for altering thermal sensation, the broader challenge remains to design lighting environments that support comfort, health, and integration with daylight.

5. Conclusion

This international, multi-site investigation revisited the hue-heat hypothesis (HHH) under realistic office-like conditions using standardized protocols across diverse laboratories, while also assessing broader cross-modal interactions between lighting and thermal stimuli. By combining common indoor air temperatures with typical white-light correlated color temperatures (i.e., ~3000 K, ~4000 K, and ~6000 K), the study aimed to assess potential cross-domain effects on thermal and visual perceptions in a way that reflects real-world indoor environments. This distinguishes our study from previous research that relied on extreme or isolated conditions, either in experimental design or statistical analysis.

Across 464 experimental sessions, results suggest that thermal sensation and preference were predominantly influenced by thermal conditions and contextual factors such as gender and laboratory setting, while lighting parameters (CCT and illuminance) showed no significant impact. Although CCT and illuminance had no direct effect on thermal comfort, significant interactions with thermal variables suggest that lighting may affect comfort when combined with certain thermal conditions. In the visual domain, lighting conditions affected participants' responses (cool light was perceived as brighter than warm light), while thermal variables had little to no effect. These findings indicate that lighting within commonly used illuminance and CCT ranges, as found in typical office environments, is unlikely to meaningfully alter thermal perception. Given the inevitable variability between sites and participants, these findings do not a priori rule out the existence of subtle or context-dependent hue-heat effects that may emerge under different conditions.

The international collaboration highlighted both the challenges and benefits of harmonizing controlled experiments across diverse geographic and technical contexts. Differences in climate, building systems, and participant characteristics required careful calibration, data cleaning, and validation to ensure meaningful comparisons. Despite these complexities, the study successfully applied robust statistical models to assess interactions between visual and thermal domains, considering potential hue-heat effects. Our experience with this round-robin approach demonstrates that coordinated, multi-site testing is feasible and valuable, providing a blueprint for future efforts to validate hypotheses in the comfort domain or other multi-domain perceptual studies. By testing the HHH under realistic conditions, this study not only advances the field but also offers the building science community practical insights into both the limits and opportunities for transferring this knowledge to real-world environments.

Beyond these scientific contributions, this project also yielded methodological lessons for the design of future multi-site studies. First, the results underscore the importance of setting realistic harmonization targets across laboratories. Because strict alignment of indoor conditions is often infeasible due to climate and test-room constraints, common protocols with clearly defined acceptable ranges may be more effective. However, excessive divergence between datasets reduces analytical comparability, underscoring the need to carefully balance protocol consistency with local feasibility. Achieving this balance depends critically on the active involvement of local researchers in implementing and monitoring the expected experimental procedures. Second, given that participants arrive with different outdoor thermal histories, a dedicated acclimation period under neutral conditions is essential to reduce initial variability that may bias the outcomes. Third, differences in demographic composition and cultural context across laboratories can exceed the effects of the experimental manipulation itself, suggesting that coordinated studies should balance sampling across sites and explicitly consider both within-site and cross-site perspectives. These methodological practices may increase comparability and reproducibility in future multi-domain perception research, while providing rich open-source datasets to advance the body of knowledge on human comfort.

Data availability

The data used is publicly availabe at: doi:10.1038/s41597-025-05962-1.

CRediT authorship contribution statement

Mateus Bavaresco: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Roberta Jacoby Cureau:** Writing – review & editing, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ilaria Pigliautile:** Writing – review & editing, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Marcel Schweiker:** Writing – review & editing, Supervision, Methodology, Investigation, Data curation, Conceptualization. **Veronica Martins Gnecco:** Writing – review & editing, Methodology, Investigation, Data curation. **Giorgia Chinazzo:** Writing – review & editing, Methodology, Conceptualization. **Edit Barna:** Writing – review & editing, Investigation, Data curation. **Zsofia Deme Belafi:** Writing – review & editing, Investigation, Data curation. **Lorenzo Belussi:** Writing – review & editing, Investigation, Data curation. **Agnese Chiucchiù:** Writing – review & editing, Investigation, Data curation. **Ludovico Danza:** Writing – review & editing, Investigation, Data curation. **Zhipeng Deng:** Writing – review & editing, Investigation, Data curation. **Bing Dong:** Writing – review & editing, Investigation, Data curation. **Natasha Hansen Gapski:** Writing – review & editing, Investigation, Data curation. **Liége Garlet:** Writing – review & editing, Investigation, Data curation. **Xingtong Guo:** Writing – review & editing, Investigation, Data curation. **Peiman Pilehchi Ha:** Writing – review & editing, Investigation, Data curation. **Hamidreza Karimian:** Writing – review & editing, Investigation, Data curation. **Roberto Lamberts:** Writing – review & editing, Investigation, Data curation. **Shichao Liu:** Writing – review & editing, Investigation, Data curation. **Brenda da Costa Loeser:** Writing – review & editing, Investigation, Data curation. **Camilla Massucci:** Writing – review & editing, Investigation, Data curation. **Ana Paula Melo:** Writing – review & editing, Investigation, Data curation. **Balázs Vince Nagy:** Writing – review & editing, Investigation, Data curation. **Mohamed M. Ouf:** Writing – review & editing, Investigation, Data curation. **Francesco Salamone:** Writing – review & editing, Investigation, Data curation. **Anna Laura Pisello:** Writing – review & editing, Supervision, Project administration, Investigation, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

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Appendix A: Overview of the lights used

Table A.1

Table A.1
Test rooms and cool-light condition[1] in laboratories 2, 3, 6, 7, and 8[2].

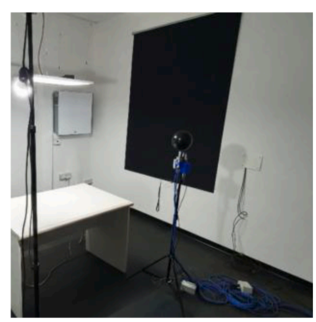
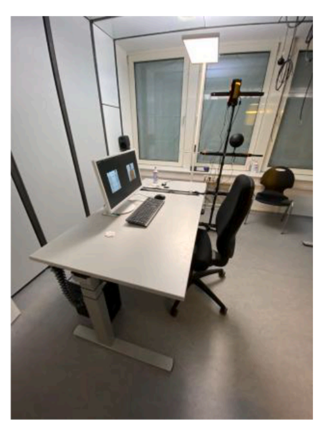
Test Room	Cool light (~6000K)
TR 2 ITC: San Giuliano Milanese (Milan), Italy	
TR 3 RWTH: Aachen, Germany	

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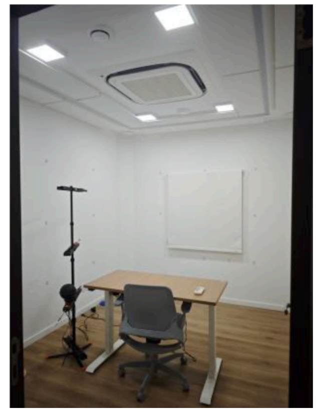
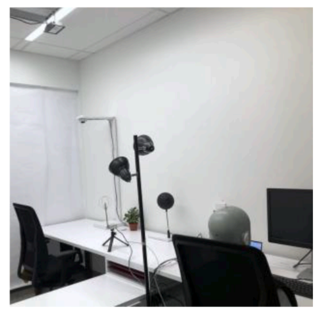
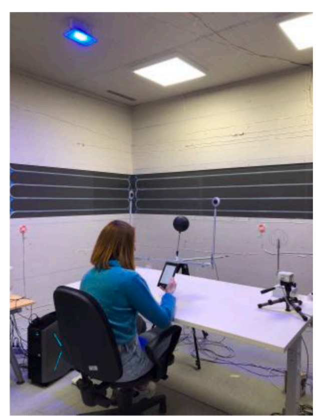
Table A.1 (*continued*)

Test Room	Cool light (~6000K)
TR 6 UFSC: Florianópolis, Brazil	
TR 7 Concordia: Montreal, Canada	
TR 8 UNIPG: Perugia, Italy	

[1] Only the cool-light condition is shown, as automatic camera white-balance and exposure adjustments preclude reliable visual comparison of correlated color temperature across conditions.

[2] Photographs are not available for all laboratories; some experimental setups were dismantled after completion of the tests. However, readers can refer to the corresponding technical sheets available in [17].

Appendix B: Gender and age distribution of participants in each laboratory

Table B.1,Table B.2

Table B.1
Gender distribution of participants involved in experiments in each laboratory.

Laboratory	Male	Female	Do not want to disclose
1	66 %	30 %	4 %
2	51 %	49 %	0 %
3	65 %	35 %	0 %
4	49 %	51 %	0 %

(*continued on next page*)

Table B.1 (*continued*)

Laboratory	Male	Female	Do not want to disclose
5	60 %	40 %	0 %
6	48 %	52 %	0 %
7	33 %	67 %	0 %
8	50 %	50 %	0 %

Table B.1
Age distribution of participants involved in experiments in each laboratory.

Laboratory	Under 21 years old	21 – 25 years old	26 – 35 years old	36 – 40 years old	40 – 55 years old	Over 55 years old
1	34 %	40 %	26 %	0 %	0 %	0 %
2	0 %	21 %	50 %	24 %	5 %	0 %
3	0 %	45 %	45 %	10 %	0 %	0 %
4	15 %	23 %	54 %	8 %	0 %	0 %
5	4 %	86 %	8 %	0 %	2 %	0 %
6	3 %	32 %	63 %	2 %	0 %	0 %
7	0 %	0 %	100 %	0 %	0 %	0 %
8	5 %	34 %	59 %	2 %	0 %	0 %

Appendix C: Synthesis of the mixed-effect models for thermal perceptions

Table C.1, Table C.2, Table C.3

Table C.1
Comparison of mixed-effect models for thermal sensation votes (TSV).

Model	Fixed effects	Akaike Information Criterion (AIC)	Log-likelihood	Significant variables ($p < 0.05$)
M1	TSV ~ PMV	2326.78	−1159.39	PMV
M2	TSV ~ PMV + Gender	2303.70	−1146.85	PMV and gender
M3	TSV ~ PMV + Lab	2288.26	−1134.13	PMV and labs 1 and 5
M4	TSV ~ PMV + Gender + Lab	2268.04	−1123.02	PMV, gender, and labs 1 and 5
M5	TSV ~ PMV + CCT_h	2324.57	−1157.29	PMV and CCT_h
M6	TSV ~ PMV * CCT_h	2325.42	−1156.71	PMV
M7	TSV ~ PMV + E_h	2318.20	−1154.10	PMV and E_h
M8	TSV ~ PMV + CCT_h + Lab	2286.12	−1132.06	PMV, CCT_h and labs 1 and 5
M9	TSV ~ PMV + CCT_h + Lab + E_h	2284.14	−1130.07	PMV, labs 1 and 5, and E_h
M10	TSV ~ PMV * CCT_h * E_h + Lab	2288.67	−1128.34	PMV, lab 1, and E_h

Table C.2
Comparison of mixed-effect models for thermal comfort votes (TCV).

Model	Fixed effects	Akaike Information Criterion (AIC)	Log-likelihood	Significant variables ($p < 0.05$)
M1	TCV ~ PMV	2011.62	−1001.81	PMV
M2	TCV ~ PMV + Gender	2010.886	−1000.43	PMV
M3	TCV ~ PMV + Lab	1986.35	−983.18	PMV and labs 1, 2, 4, and 6
M4	TCV ~ PMV + Gender + Lab	1986.95	−982.47	PMV and labs 1, 2, 4, and 6
M5	TCV ~ PMV + CCT_h	2013.47	−1001.74	PMV
M6	TCV ~ PMV * CCT_h	2013.02	−1000.51	PMV
M7	TCV ~ PMV + E_h	2009.44	−999.72	PMV and E_h
M8	TCV ~ PMV + CCT_h + Lab	1988.21	−983.10	PMV and labs 1, 2, 4, and 6
M9	TCV ~ PMV + CCT_h + Lab + E_h	1988.78	−982.39	PMV, and labs 1, 2, 4, and 6
M10	TCV ~ PMV * CCT_h * E_h + Lab	1985.37	−976.68	PMV, labs 2, 4, and 6, the interactions between PMV-CCT_h, PMV-E_h, and PMV-E_h-CCT_h

Table C.3
Comparison of mixed-effect models for thermal preference votes (TPV).

Model	Fixed effects	Akaike Information Criterion (AIC)	Log-likelihood	Significant variables ($p < 0.05$)
M1	TPV ~ PMV	2246.10	−1119.05	PMV
M2	TPV ~ PMV + Gender	2218.90	−1104.45	PMV and gender
M3	TPV ~ PMV + Lab	2207.01	−1093.51	PMV and labs 1 and 4
M4	TPV ~ PMV + Gender + Lab	2183.08	−1080.54	PMV, gender, and labs 1 and 4
M5	TPV ~ PMV + CCT_h	2244.90	−1117.45	PMV
M6	TPV ~ PMV * CCT_h	2244.41	−1116.20	PMV
M7	TPV ~ PMV + E_h	2238.36	−1114.18	PMV and E_h
M8	TPV ~ PMV + CCT_h + Lab	2205.82	−1091.91	PMV and labs 1 and 4
M9	TPV ~ PMV + CCT_h + Lab + E_h	2201.33	−1088.66	PMV, lab 1, and E_h
M10	TPV ~ PMV * CCT_h * E_h + Lab	2197.96	−1082.98	PMV, E_h, labs 1 and 4, and the interaction between PMV-CCT_h-E_h

Appendix D: Synthesis of the mixed-effect models for visual perceptions

Table D.1, Table D.2, Table D.3

Table D.1
Comparison of mixed-effect models for visual sensation votes (VSV).

Model	Fixed effects	Akaike Information Criterion (AIC)	Log-likelihood	Significant variables ($p < 0.05$)
M1	VSV ~ E_h	2474.89	−1233.44	–
M2	VSV ~ CCT_h	2406.22	−1199.11	CCT_h
M3	VSV ~ E_h + CCT_h + Gender	2396.84	−1192.42	Illuminance and CCT_h
M4	VSV ~ E_h + CCT_h + Lab	2383.92	−1180.96	E_h, CCT_h, and labs 1, 2, and 4
M5	VSV ~ E_h + CCT_h + Gender + Lab	2385.59	−1180.79	E_h, CCT_h, and labs 1, 2, and 4
M6	VSV ~ PMV + CCT_h	2408.20	−1199.10	CCT_h
M7	VSV ~ PMV * CCT_h	2402.74	−1195.37	PMV and the interaction between PMV-CCT_h
M8	VSV ~ PMV + E_h	2476.84	−1233.42	–
M9	VSV ~ PMV + CCT_h + Lab	2393.50	−1185.75	CCT and labs 1, 2, 3, and 4
M10	VSV ~ PMV + CCT_h + E_h + Lab	2385.92	−1180.96	CCT, illuminance, and labs 1, 2, and 4
M11	VSV ~ PMV * CCT_h * E_h + Lab	2388.15	−1178.08	CCT_h and labs 1, 2, and 4

Table D.2
Comparison of mixed-effect models for visual comfort votes (VCV).

Model	Fixed effects	Akaike Information Criterion (AIC)	Log-likelihood	Significant variables ($p < 0.05$)
M1	VCV ~ E_h	1711.50	−851.75	–
M2	VCV ~ CCT_h	1711.56	−851.78	–
M3	VCV ~ E_h + CCT_h + Gender	1713.39	−850.69	–
M4	VCV ~ E_h + CCT_h + Lab	1710.42	−844.21	Labs 1 and 6
M5	VCV ~ E_h + CCT_h + Gender + Lab	1711.23	−843.62	Labs 1 and 6
M6	VCV ~ PMV + CCT_h	1710.65	−850.32	–
M7	VCV ~ PMV * CCT_h	1712.20	−850.10	–
M8	VCV ~ PMV + E_h	1710.49	−850.24	–
M9	VCV ~ PMV + CCT_h + Lab	1707.90	−842.95	Labs 1 and 6
M10	VCV ~ PMV + CCT_h + E_h + Lab	1709.89	−842.95	Labs 1 and 6
M11	VCV ~ PMV * CCT_h * E_h + Lab	1715.58	−841.80	Labs 1 and 6

Table D.3
Comparison of mixed-effect models for visual preference votes (VPV).

Model	Fixed effects	Akaike Information Criterion (AIC)	Log-likelihood	Significant variables ($p < 0.05$)
M1	VPV ~ E_h	2193.86	−1092.93	–
M2	VPV ~ CCT_h	2132.43	−1062.22	CCT_h
M3	VPV ~ E_h + CCT_h + Gender	2125.49	−1056.75	CCT_h and gender
M4	VPV ~ E_h + CCT_h + Lab	2067.00	−1022.50	CCT_h and labs 2, 3, and 6
M5	VPV ~ E_h + CCT_h + Gender + Lab	2061.72	−1018.86	CCT_h, gender, and labs 2, 3, and 6
M6	VPV ~ PMV + CCT_h	2134.40	−1062.20	CCT_h
M7	VPV ~ PMV * CCT_h	2133.53	−1060.77	CCT_h
M8	VPV ~ PMV + E_h	2195.85	−1092.92	–
M9	VPV ~ PMV + CCT_h + Lab	2068.72	−1023.36	CCT_h and labs 2, 3, and 6

(continued on next page)

Table D.3 (*continued*)

Model	Fixed effects	Akaike Information Criterion (AIC)	Log-likelihood	Significant variables ($p < 0.05$)
M10	VPV ~ PMV + CCT_h + E_h + Lab	2068.19	−1022.09	CCT_h and labs 2, 3, and 6
M11	VPV ~ PMV * CCT_h * E_h + Lab	2070.27	−1019.14	CCT_h, labs 2, 3, and 6, and the interaction between CCT_h-PMV

Appendix E: Synthesis of the mixed-effect models for overall comfort

Table E.1

Table E.1
Comparison of mixed-effect models for overall comfort votes (OCV).

Model	Fixed effects	Akaike Information Criterion (AIC)	Log-likelihood	Significant variables ($p < 0.05$)
M1	OCV ~ PMV	1758.58	−875.29	–
M2	OCV ~ E_h + CCT_h	1759.55	−874.78	–
M3	OCV ~ PMV + Gender	1759.95	−874.97	–
M4	OCV ~ PMV + Lab	1749.69	−865.85	Lab 1
M5	OCV ~ PMV + Gender + Lab	1751.49	−865.74	Lab 1
M6	OCV ~ PMV + CCT_h	1758.75	−874.38	–
M7	OCV ~ PMV * CCT_h	1759.28	−873.64	–
M8	OCV ~ PMV + E_h	1749.53	−864.77	–
M9	OCV ~ PMV + CCT_h + Lab	1749.86	−864.93	Lab 1
M10	OCV ~ PMV + CCT_h + E_h + Lab	1751.65	−864.83	Lab 1
M11	OCV ~ PMV * CCT_h * E_h + Lab	1753.72	−861.86	PMV and the interaction between PMV-E_h

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