Energy & Buildings 370 (2026) 118099

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enb

When the sun is in occupants' field of view: assessing discomfort glare, thermal comfort, and overall comfort

Abel Sepúlveda [a,*], Caroline Karmann [b]

[a] Laboratory of Architecture and Intelligent Living (AIL), Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany
[b] Institut TRANSFORM, Haute école d'ingénierie et d'architecture de Fribourg, HES-SO University of Applied Sciences and Arts Western Switzerland, Switzerland

ARTICLE INFO

Keywords:
Visual comfort
Thermal comfort
Discomfort glare
Physiological responses
Controlled-lab experiments
Sun in the field of view (FOV)

ABSTRACT

This study investigates the cross-effects between thermal comfort and discomfort glare in office environments where the sun is in the field of view (FOV). While thermal and visual comfort have been extensively studied independently, their combined effects under real sunlit conditions remain unclear. A 2 × 2 within-subject experiment was conducted in a controlled test facility located in Germany, exposing 36 participants to two thermal conditions (lower temperature: $-1 < PMV < 0$ and higher temperature: $0 < PMV < +1$) and two perceived glare levels (imperceptible and noticeable) under clear and stable sky conditions. Subjective comfort responses and physiological parameters (skin temperature and heart rate variability) were collected alongside environmental data. Results under these stimulus conditions showed no significant effect of temperature on glare discomfort, nor of glare discomfort on thermal perception, suggesting that thermal and visual sensations may not strongly interact under the tested conditions. However, glare discomfort showed a negative effect on overall comfort, while thermal variables (acceptability and sensation) showed weaker but still significant positive associations with overall comfort. Physiological analyses revealed that neither skin temperature nor its spatial variability were significantly associated with glare discomfort or thermal acceptability. However, glare discomfort showed a significant yet non-intuitive negative association with cardiovascular activation. Taken together, these findings suggest that discomfort glare due to the sun in the field of view may play a more prominent role in overall comfort perception than the thermal variations investigated in this study, while emphasizing the value of effective shading to improve occupants' well-being in office spaces.

1. Introduction

The quality of the indoor environment in buildings has a significant impact on the health, comfort, satisfaction, and cognitive performance of building occupant [1–3] s. Scientists have identified four key factors that influence indoor environmental quality (IEQ): air quality, thermal comfort, visual comfort, and acoustic comfort. It is, therefore, important to consider these factors during the early design stages to ensure the well-being and performance of building occupants [1]. Recent work has emphasized the need for integrated comfort indicators that consider time-based and spatial uniformity across thermal and visual domains [4]. Nevertheless, current standards may not fully ensure occupants' comfort and health, since gaps remain between design recommendations and occupants' actual needs and preferences [2]. In fact, our sensory system responds to several environmental factors simultaneously at all active times [5], making multi-domain investigation challenging but necessary. Cross-domain interactions between comfort domains were found in previous investigations supporting the idea that comfort cannot be cleanly partitioned in practice into separate domains [3]. Specifically, thermal, visual, and acoustic comfort tend to dominate occupant satisfaction and performance metrics [6–8]. The European Standard EN 17037:2018 assesses visual comfort from daylight based on four components: daylight provision, glare protection, view out, and sunlight exposure [9]. Yet, as soon as direct sunlight enters one's field of view, not only glare comes into play but also the effect of direct shortwave radiation on thermal comfort. Previous studies suggest that thermal perception may influence glare appraisal under specific daylight exposure conditions. Nevertheless, they have rarely been studied together.

* Corresponding author at: Laboratory of Architecture and Intelligent Living (AIL), Institute for Building Design and Technology (IEB), Karlsruhe Institute of Technology (KIT), Englerstr. 7, Building 20.40, Room 108, Karlsruhe 76131, Germany.
E-mail address: gd0796@partner.kit.edu (A. Sepúlveda).

https://doi.org/10.1016/j.enbuild.2026.118099
Received 21 May 2026; Received in revised form 6 August 2026; Accepted 12 August 2026
Available online 13 August 2026

1.1. Daylight glare discomfort and the role of the sun in the field of view (FOV)

Daylight is the most preferred light source by building occupants [10]. In fact, daylight has significant psychological and physiological advantages compared to electric lighting [11]. Exposure to daylight strongly supports human circadian rhythms, improves sleep quality/mood/alertness, and also enhances visual comfort, cognitive performance, and overall well-being [12]. However, excessive daylight exposure may lead to discomfort glare and reduced subjective visual comfort, particularly when occupants are exposed to direct sunlight within their field of view, especially in buildings where occupants have no flexibility to adapt their viewing direction while conducting their indoor activities [13]. Field evaluations have confirmed that daylight and glare control strategies influence occupant satisfaction and productivity, underlining the need to balance glare protection and daylight access [14].

Due to the large number of factors influencing glare (e.g. viewing direction, reflections, colors, personal sensitivity, view position, glazing system, etc.) [15] the development of reliable glare metrics has been challenging, in particular, glare indices developed for electric lighting conditions appeared as not reliable to assess glare from daylight [16]. The Daylight Glare Probability (DGP) was proved to be the most robust glare metric for daylight situations in buildings [17,18]. This metric includes two effects that influence the glare phenomenon: the saturation effect (defined by the vertical illuminance at eye level) and the contrast effect (defined by the luminance of the glare sources and their position in the field of view). However, there is no universal glare metric or illuminance threshold applicable to all contexts [19]. Pierson et al. found that current glare metrics may underestimate perceived glare in real offices since cut-off values derived from field study data were systematically lower than those derived from laboratory data [20]**.** In addition, when using electrochromic glazing DGP tends to overestimate discomfort glare when large glare sources are in the field of view (FOV) [21,22]. Another study from Konstantzos et al. proposed a modified DGP equation more reliable to predict glare discomfort when using window shades and with the sun in the FOV [23]. Moreover, when sunlight patches are in the FOV, DGP metric does not perform reliably since the perceived temperature significantly affects glare predictions. Therefore, Garretón et al. concluded that DGP should be used only when the building occupant is in thermal comfort and recommended the inclusion of perceived temperature into glare (due to sun patches on the desk) models for more accurate predictions [24]. The multi-domain nature of occupants' perceived comfort in buildings, combined with the complexity of glare, makes studying its interaction with other comfort domains more challenging, but necessary.

1.2. Thermal comfort and the role of direct shortwave radiation

The quantification of thermal comfort through metrics is also challenging. Although the Predicted Mean Vote (PMV) model [25] has shown certain limitations, as reported in the literature using large-scale field data [26], it appeared to be the most suitable model for the purposes of this investigation, in which environmental parameters were precisely controlled and participants were located in a laboratory setting without the ability to control their own environment. Apart from subjective ratings, thermal comfort can be informed by physiological responses of the skin temperature, electrocardiograph (ECG), and electroencephalogram (EEG) [27]. One of the most impactful factors **on** humans' perceived thermal comfort is sun exposure. Ioannou et al. demonstrated that working under the sun significantly increased skin temperature, physiological strain, and symptoms such as dizziness and weakness, even when overall thermal stress was the same as in shaded environment. Additionally, cognitive performance declined sharply under direct sun exposure [28]. Thanks to the existence of the facade of buildings, these negative effects on human health might not be such extreme but still, the presence of shortwave radiation in buildings is also important not only for thermal comfort, but energy performance, and visual comfort [29]. Shortwave radiation due to the sun exposure on the facade has not been included in the PMV formula for decades until Arens et al. proposed the SolarCal model in 2015 [30]. SolarCal model is based on the effective radiant field (ERF), which measures the net radiant energy flux to or from the human body. This model converts shortwave gains — direct, diffuse, and indoor-reflected — into an equivalent increase in mean radiant temperature (MRT). This increase in MRT is used to correct the PMV metric [30]. Although this model cannot differentiate between local body parts or between clothed and unclothed body areas, SolarCal provides reasonable predictions of solar effects on MRT and comfort expressed as PMV. Standards like the ASHRAE Standard 55–2017 require consideration of direct solar radiation in thermal comfort evaluation through the SolarCal model. This consideration promotes better facade and shading design decisions, improves occupant well-being and ensures consistent comfort across both sunlit and shaded zones in indoor spaces [31]. Near window zones, solar radiation can have a significant effect on MRT and thermal comfort depending on the area and type of glazing used. Hence, a proper selection of low SHGC glazing can decrease overheating risk and improve thermal comfort [32]. Recent simulation-based work has quantified long-term solar radiation effects on indoor thermal comfort across multiple climates, showing that facades with low SHGC glazing can reduce discomfort hours by over 80% [33]. In cases where the glazing system is very spectrally selective (i.e., light transmission for certain wavelengths is much higher than others), the spectrally solved model like the one of Wang et al. appear the more reliable to use [34].

1.3. Cross-modal interactions between visual and thermal domains

The study of cross-modal interactions between visual and thermal comfort has been widely studied in the past decades. In 2000, Laurentin et al. exposed 20 participants to two thermal conditions (20.5 °C and 27 °C) and three lighting types (daylight, electric light, and mixed) and found that thermal conditions had no systematic influence on visual comfort appraisal [35]. Chinazzo et al. investigated the combined effect of indoor temperature and daylight illuminance on visual perception and showed significant cross-modal effects of indoor temperature on visual perception: high illuminance (1440 lx) was more pleasant than low illuminance (140 lx) under neutral thermal conditions (23 °C). However, at 27 °C, all illuminance were rated equally pleasant, meaning that low illuminance becomes more acceptable under warm thermal conditions [36]. The same experiment showed that daylight significantly affects subjective thermal perception but not physiological responses, supporting the need for integrating daylight as a factor in thermal comfort models (i.e. PMV) [7].

Specifically, the majority of investigations related to cross-modal effects between visual and thermal domains are those that include thermal comfort and color light temperature [7,29,36–41]. te Kulve et al. found through a review study that light color tones influence environmental perception, with reddish tones perceived as warmer compared to bluish tones, hence, lighting conditions should be considered in chronophysiological research and indoor climate design [40]. Two years later, te Kulve et al. confirmed that visual and thermal perception affect each other for young female participants in a respiration/climate chamber [41]. A recent lab-controlled study (2 illuminance levels, 2 temperature levels, and 3 color light temperature levels) indicated that temperature significantly influenced visual perception, while illuminance and CCT weakly influenced thermal perception. In addition, the interaction between temperature and CCT significantly affected both visual and thermal perception, highlighting that outside comfort zones, thermal and light factors interact in complex ways and therefore the consideration of both factors is crucial when designing indoor environments [29]. Chinazzo et al. confirmed that symmetrical cross-modal effects take place between daylight color and temperature [37]. Even using Virtual Reality (VR) environments, cross-modal effects were found between daylight color and temperature on visual and thermal perception [38,39].

A central precursor to the present investigation is the laboratory study by Garretón et al., which is the only existing work that directly examined the interaction between thermal sensation and daylight glare perception. Their experiment exposed participants to identical photometric conditions (sun patches on the desk, constant vertical illuminance at the eye, and controlled luminance ratios) while varying only the perceived indoor temperature. They demonstrated that perceived temperature significantly alters glare sensation and that glare prediction models such as DGP lose reliability when occupants are outside thermal comfort. Consequently, they argued that glare models should incorporate perceived temperature and that DGP should only be applied when occupants are thermally comfortable. This seminal finding highlights that thermal and visual comfort are cross-modal and cannot be treated as independent in daylight environments [24].

1.4. Research gap and objectives of this present study

As can be seen in Table 1, the majority of previous controlled-lab studies that focused on visual-thermal cross-modal effects considered daylight color and thermal comfort as independent variables [7,29,35–38]. Although Garretón et al. were the only one to consider thermal comfort and glare discomfort in controlled-lab experiments, important questions remain unresolved: Garretón et al.'s study did not include physiological responses and examined glare caused only by sun patches rather than direct sunlight on participants. The resulting gaps underscore the need for a more comprehensive investigation of cross-modal interactions under realistic sunlit office conditions, which the present study addresses by systematically manipulating both temperature and glare level (with the sun in the FOV) and by incorporating physiological, visual, thermal, and overall comfort responses [24].

As mentioned in previous sections, when the sun is in the field of view (presence of short-wave radiation), most common assessment metrics are not reliable enough. The presence of the sun could lead to a different sensitivity of occupants to experience glare discomfort. The overall comfort could be influenced by glare/thermal discomfort. Despite the importance of this matter, there are no studies focused on these comfort domains in the presence of direct sunlight in office rooms.

This study investigates the cross-modal effects between thermal, visual, and overall comfort in office spaces with the sun in the field of view and aims to address these gaps through the following research questions

- RQ1: What is the impact of temperature levels on visual comfort perception?
- RQ2: What is the impact of discomfort glare due to sunlight in the field of view on thermal responses?
- RQ3: What is the combined effect of sunlight discomfort glare and thermal comfort on overall comfort perception?
- RQ4: What is the combined impact of sunlight discomfort glare and thermal comfort on human physiological responses?

By addressing these questions, this research advances the understanding of **cross-modal comfort interactions** and informs strategies for IEQ control that better support occupant well-being. The findings also provide a basis for refining predictive comfort models and for guiding architectural and operational decisions in daylit office spaces where occupants are regularly exposed to direct solar gains.

2. Methodology

We used a quantitative, psychophysical methodology to answer these research questions. To design the experiments, we conducted daylight and thermal comfort simulations. We conducted the experiments in controlled-environment test facility LOBSTER (Laboratory for Occupant Behavior, Satisfaction, Thermal Comfort and Environment Research) located in Karlsruhe, Germany (49°01′24.0"N, 8°22′02.8″E) [43]. During the experiments we gathered subjective-related data from participants through on-site questionnaires. In parallel, we measured environmental (indoors and outdoors) and physiological variables to validate the experimental conditions and to have a better understanding of the subjective-related data. The experimental procedure was approved by the ethical commission at the Karlsruhe Institute of

Table 1
Summary of the existing controlled lab experiments that include visual-thermal domain.

Authors / Reference	Laurentin et al. [35]	te Kulve et al. [41]	Garretón et al. [24]	Chinazzo et al. (2018) [42]	Chinazzo et al. (2019) [7] & Chinazzo et al. (2020) [36]	Wang et al. [29]
Sample size	20	20	19	75	84	**36**
Thermal adaptation time	60 min	60 min	15 min	45 min	45 min	**25 min**
Visual stimulus	Daylight Electric, Combined (300 lx)	Not reported	Constant Ev (2000–3000 lx) and luminance ratio (19.70–25.82)	Daylight through blue, orange, neutral glazing (~300–600 lx)	Daylight illuminance levels: ~130, ~600, ~1400 lx	**300, 750 lx × 2700, 4000, 7800 K (daylight)**
Thermal conditions (°C)	20.5, 27	21, 24, 26 29	Winter 13 Winter 20 Summer 28	19, 22, 26	19, 23, 27	23, 29
Visual comfort rating	Illuminance sensation, preference, pleasantness	None	Glare sensation vote (GSV)	Overall comfort + visual discomfort (no direct glare scale)	Visual sensation, comfort, pref., overall visual environment comfort, lighting cold-warm assoc., comfort, pleas., evaluation, raking	Lighting sensation, comfort, preference
Thermal ratings	Thermal sensation, preference, pleasantness	Thermal sensation	Thermal sensation vote (TSV)	Sensation, comfort, preference, acceptability, local body sensation	Thermal sensation, comfort, preference, hands, trunk and feet, acceptability	Thermal sensation, comfort, preference, tolerance
Physiological measurements	None	Skin temperature (16) & brain signals	None	Skin temperature, heart rate, skin conductance	Skin temperature (4)	None
Other ratings	Environment sensation, preference, pleasantness	None	None	Overall comfort + discomfort sources	Overall comfort, discomfort reasons	Color sensation, comfort, preference
Sunlight glare	None	None	Glare from sun patches on the screen and desk	None (North facade)	None (North facade)	None

Technology (Project ID: A2023–071).

2.1. Experiment design

We chose a 2 × 2 experimental design to answer the research questions presented in section 1.4: we considered 2 levels of glare discomfort and 2 levels of thermal comfort. We wanted to expose our participants to non-perceptible glare and disturbing-intolerant glare conditions. Thus, in terms of the DGP metric, the low glare condition is associated to a DGP < 0.35 and high glare condition to a DGP ∼ 0.40–0.45 [16]. We used Radiance simulations to determine which combination of window filters would achieve these two glare discomfort levels when the sun is within the FOV. As highlighted in the previous literature [7,40], the color of the light can influence thermal responses, the window filter should ensure the color neutrality of the daylight entering the test rooms. Taking into consideration these two glare discomfort levels (under full clear sky), we conducted a simulation study to calculate the optimal orientation for the test rooms (i.e. minimizing the external obstructions and maximizing the direct sun exposure time resulting in an east-facing orientation) and the sitting position of the participant (we set them 1.5 m from the window side, in the middle of the room) within the test room as well as the visible transmittance (VT) of the combination between the existing window glazing (VT = 70%) and window filter(s). We concluded that the visible transmittance of the whole fenestration system should be around 0.4%. To ensure color neutrality, we had to conduct an experimental study in which we could calculate the visible transmittance of 19 window filters and their colorimetric properties [43]. We selected a specific combination of window filters mounted on a Plexiglas pane (Fig. 1) to achieve the target glare discomfort levels while preserving sufficient daylight on the desk, since low daylight levels can bias participants' subjective ratings [29,41,44]. The central window pane was covered by two clear Plexiglass panes (Tvis = 90%) with a double layer (one layer per side) of the window filter ScenicView SV10 from Johnson (Tvis = 8%). For the side windows, we selected a SolarScreen window filter (Spectra 15C, Tvis = 89%) stuck in a single layer of the same Plexiglas material.

The selection of these window filters ensures the color neutrality of the daylight entering the test room and protects against glare discomfort enough to achieve a low glare level (DGP < 0.35) when the participant's viewing direction is 45° with the window side (Fig. 1d) and high glare level (DGP ∼ 0.40–0.45) when the participant is facing towards the window side (Fig. 1c). In addition, the neutral-colored Spectra 15C filter on the window sides ensures that at least 300 lx of horizontal illuminance is met in the middle of the table desk.

This combination of window filters and Plexiglas allowed us to calculate the possible thermal comfort levels under direct solar radiation (visible sun hours ranged from 7 to 10 am, April–May 2025). We considered the lowest operational indoor air temperature in the test chamber (18 °C) and an intermediate air temperature (22 °C) in order to achieve comparatively lower and higher thermal conditions within the tested comfort range, respectively, according to the SolarCal model, which includes the increase in the Mean Radiant Temperature (ΔMRT) due to the presence of direct shortwave radiation [30,31]. The details about the method we used in the calculations can be seen in Table 2 [43].

The experiment is single blind and the exposure to the thermal conditions was randomized. Regarding glare stimuli, the exposure sequence in our experiment represents a realistic scenario when the office user adapts his/her desk orientation (when possible) when they detect disturbing or intolerable glare discomfort [45]. In line with this behavior, we exposed each participant to the high glare discomfort level before the low glare stimuli in each session (Fig. 2). The implications of this methodological decision are explained in section 5. The experimental protocol can be seen in Fig. 2. By running the two experiments in parallel, we were able to make better use of the limited direct sun hours and fully take advantage of the LOBSTER facility. The participants were told the night before (at 9 pm) to come in the morning if the cloud cover forecast was partial or null.

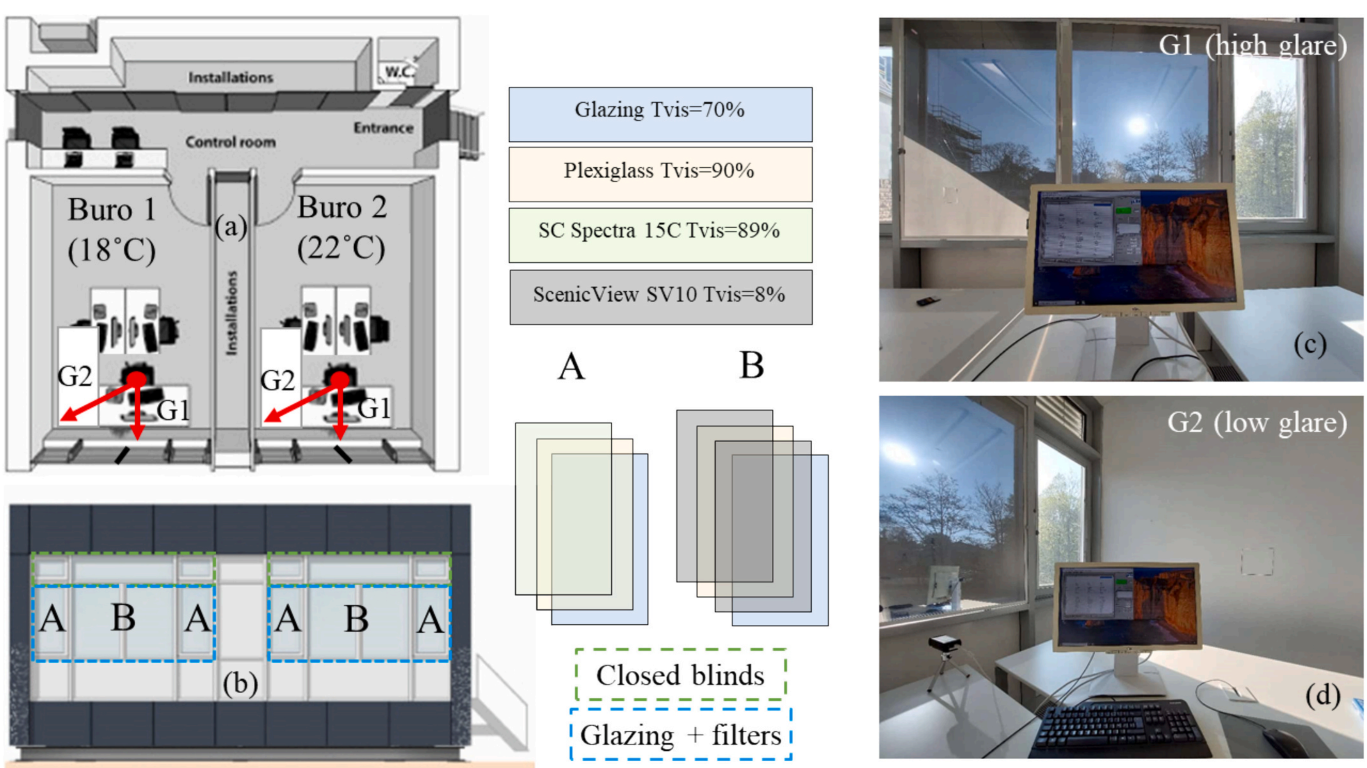

Fig. 1. Top view of the LOBSTER test facility, showing glare discomfort levels (G1, G2) and temperature set points for each test room (22.48 m^2 ach) (a); façade scenario and window filter combination (b); and participant's point of view during high-glare (c) and low-glare (d) conditions.

Table 2
Simulation settings used in the SolarCal model in Grasshopper for the experiment design.

Parameter	Value
Average body shortwave absorptivity	0.5
Average body longwave Emissivity	0.95
Posture	Seated
Ground reflectance	0.25
Solar transmittance	Calculated with "HB Window Construction" considering A and B fenestration systems shown in Fig. 1
Relative humidity	50%
Air speed	0.1 m/s
Metabolic rate	1.15 MET
Clothing level	0.57 clo

Once arrived, the researcher gave the initial instructions to the participants related to: using phones and leaving of the test room once inside were forbidden. The researcher helped the participants to put the skin temperature and heart rate sensors after they read and signed the consent form.

Perceived thermal comfort is highly influenced by the direct exposure to shortwave radiation; therefore, the selection of a neutral color and material was important in our experiment [34]. We tried to homogenize the effect of the clothing level between participants by asking them to bring jeans and providing them with a gray long-sleeve cotton shirt. The wearable sensors were fitted on each participant in each room so as to take advantage of this exposure and allow more time flexibility for the rest of the experiment.

During the thermal adaptation phase (at least 20 min), the Venetian blinds were kept down so that glare was not part of the exposure. Session 1 included a background questionnaire followed by a 10-min familiarization period with the cognitive performance tasks also performed during the exposure periods [46]. Before the first glare stimuli, the researcher put each participant in "resting phase" (white noise in the headphones and blind folded to rest the eyes and ears) for at least 5 min (depending on the sun's visibility in the participant's FOV). Glare exposure began with 10 min of cognitive performance games, after which participants completed an on-screen survey providing subjective ratings of environmental factors. Once the survey was completed, the researcher put the participants in the resting phase and conducted one single capture of the luminance map manually. The researcher changed the position of the desk to expose the participant to the second exposure, which followed the same procedure and measurement procedure as the first exposure.

Session 2 was mapped exactly after session 1, with the exception that participants had a 5-min break at the beginning of that session. They completed the second part of the background questionnaire before 5 min resting phase prior to the glare exposures. The glare exposures of session 2 were exactly mapped after the glare exposure of session 1). After the measurements, the participant removed the wearable sensors and shirt and provided their details to receive the compensation (40€).

2.2. Survey design

There were two types of questionnaires during the experiments for the participants to answer. The background questionnaires and the exposure questionnaire. In the background questionnaire, participants gave demographic information, mood, situational information, which can help us to understand possible patterns in the answers of the exposure questionnaire. The weight of each participant was measured at the end of the experiment by the researcher.

The exposure questionnaire contains questions about discomfort elements of the environment and others about visual comfort, thermal comfort perception, and overall comfort perception (Table 3). The definition of "glare" as "the sensation of visual discomfort caused by differences between light and dark areas or excessive brightness in your field of view" was embedded in the questionnaire to avoid misconceptions about this phenomenon. Each participant answered this questionnaire during each of the 4 experimental conditions. The questions were related to discomfort reasons, overall visual comfort, visual sensation, lighting pleasantness, visual preference, glare discomfort level, overall thermal acceptability, thermal sensation, thermal preference, thermal sensation of body parts, overall acoustic comfort, and overall air quality (Table 3).

2.3. Measurement of physiological and environmental variables

During the experiments, we measured environmental (outdoor and indoor) variables and physiological variables. The main outdoor environmental variable in our experiments was the solar radiation measured by an SPN1 Sunshine Pyranometer [47]. This pyranometer measured the global and diffuse irradiance in W/m^2 each second. Regarding indoor environmental factors, we measured the following: CO2 levels (by inbuilt sensor CO2sen in LOBSTER), illuminance levels, air temperature, relative humidity, air velocity, noise levels, and spectral irradiance. To have better consciousness about the influence of the direct shortwave radiation in the room, air temperature, relative humidity and air velocity were measured next to the participants and in the middle of the test rooms. The noise levels were recorded with a sound meter PCE-430 in the middle of the test rooms [48]. However, the illuminance measurements were taken in the middle of the table desk (horizontal illuminance) and from the back side of the screen monitor (vertical illuminance). Along illuminance measurements, air/globe temperature, relative humidity, and air velocity were measured by Ahlborn station on

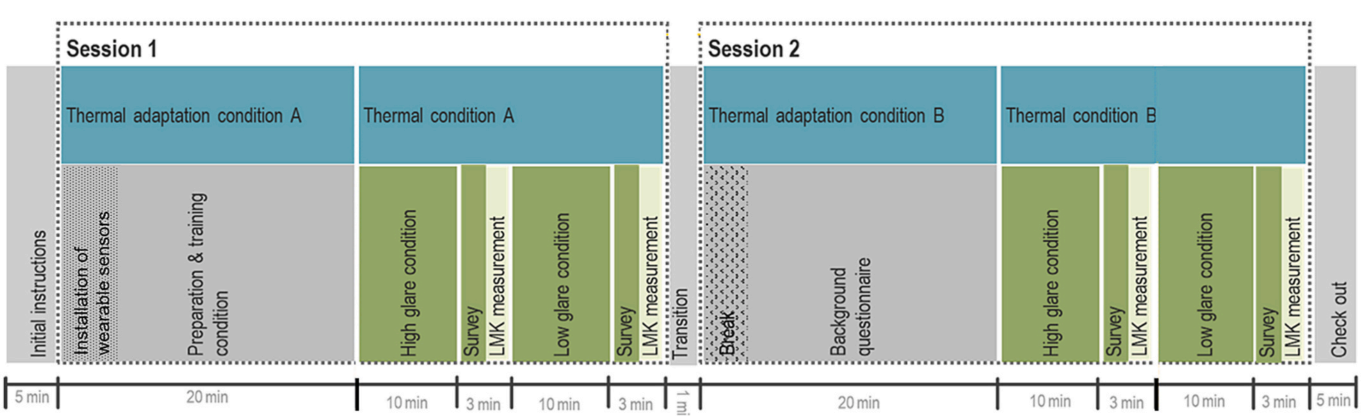

Fig. 2. Experiment protocol.

Table 3
Exposure questionnaire. Ordinal responses were numerically coded for statistical analyses.

ID	Question	Answer type	Answer option
Q3	Is there anything about the physical environment that disturbs you in this moment?	Text field	[Free text field]
Q4	In general, how comfortable do you feel at the moment?	Likert scale	Very uncomfortable (−4) – Just uncomfortable (−1) – Just comfortable (+1) - Very comfortable (+4)
Q5	**Discomfort reasons**: You have said that you are not comfortable with the global indoor environment. Which of the following has contributed to your discomfort?	Multiple choice	Visual conditions – Thermal conditions – Noise from the inside or outside the room - Presence of other people in the room – Poor air quality - Lack of personal control - Other [Text]
Q6	**Overall visual comfort**: In general, how do you find your visual environment?	4 pt-Likert scale	Very uncomfortable (−4) – Just uncomfortable (−1) – Just comfortable (+1) - Very comfortable (+4)
Q7	**Visual sensation**: How do you perceive the quantity of light on your desk?	5-pt Likert scale	Very low (+1) – Low (+2) – Just right (+3) – High (+4) - Very high (+5)
Q8	**Lighting pleasantness**: Please specify how do you perceive the appearance of the indoor light environment at this moment:	5 pt-Likert scale	Very unpleasant (1) – Unpleasant (2) - Slightly unpleasant (3) - Pleasant (4) - Very pleasant (5)
Q9	**Visual preference**: In this moment, would you like to have a light on your desk?	3 pt-Likert scale	Brighter (+1) – No change (+2) - Dimmer (+3)
Q10	At the moment, do you feel any **discomfort due to glare**?	Binary	Yes - No
Q11	At the moment, how would you describe the **level of glare** in your field of view?	Osterhaus-Bailey scale	Imperceptible – Noticeable – Disturbing - Intolerable
Q12	**Overall thermal acceptability**: In general, how do you find your thermal environment?	Likert scale	Unacceptable (+1) – Just unacceptable (+2) – Just acceptable (+3) – Acceptable (+4)
Q13	**Thermal sensation**: How do you feel in this precise moment? I feel…	7 pt-Likert scale	Cold (−3) – Cool (−2) - slightly cool (−1) - Neutral (0) - Slightly warm (+1) - Warm (+2) - Hot (+3)
Q14	**Thermal preference**: In this moment, you would prefer to feel:	3 pt-Likert scale	Cooler (+1) – No change (+2) – Warmer (+3)
Q15	**Thermal sensation (body parts)**: How do you perceive the following parts of your body (head, hands, trunk and feet) (separated subquestions)	5 pt-Likert scale	Very cold (+1) – Cold (+2) - Neutral (+3) - Warm (+4) - Very warm (+5)
Q16	**Overall acoustic comfort**: In general, how comfortable do you feel with the noise around you?	4 pt-Likert scale	Very uncomfortable (−2) – Just uncomfortable (−1) – Just comfortable (+1) – Very comfortable (+4)
Q17	**Overall air quality comfort**: In general, how comfortable do you feel with the air quality around you?	4 pt-Likert scale	Very uncomfortable (−2) – Just uncomfortable (−1) – Just comfortable (+1) – Very comfortable (+2)

the left side of the participant chair position [49]. Detailed equipment specifications can be seen in Table 4. In addition, the spectral distribution of the incoming light through the windows and filters was recorded by a spectrometer JETI located on the table desk directly facing the central window pane [50]. This spectrometer also measured the CCT values that we needed to verify the color neutrality of the indoor light during the experiments.

Regarding physiological variables, skin temperature (Tskin) was recorded (each 20 s) with iButton® DS1922L loggers located in different body parts: back of the neck, back, left wrist, and left leg shin [51]. The heart rate variability was recorded with MOVISENS sensors, which were located with an adjustable strap under the chest level [52].

2.4. Verification of clear sky conditions

In order to ensure that the only glare source of the sky was the solar disk itself, we have to verify that the global horizontal irradiance (GHI) variation (dGHI) (Eq. 1) for the 4 exposure phases for each participant was below 25%. Nevertheless, we also accepted exposure periods when dGHI was higher than 25% for a short period of time caused by the pass of birds (7 exposure periods were found related to this phenomenon).

$$dGHI = (GHI_{max} - GHI_{min})/GHI_{mean} \ (-) \tag{1}$$

where GHI_{max}, GHI_{min}, and GHI_{mean} is the maximum, min, and mean GHI value of the exposure period, respectively.

GHI was calculated in Python using eq. (2):

$$GHI = DHI + DNI \bullet \cos(\theta_z) \ \left(\mathrm{W/m^2}\right) \tag{2}$$

where DHI is the diffuse horizontal irradiance, DNI is the direct normal irradiance, and $\theta_z$is the solar zenith angle. Thus, DNI was calculated from the pyranometer readings each experiment day, the exposure periods were defined with the noted timings for each participant, and θ_z was calculated with the function *solarposition* within the library *pvlib*.

2.5. Calculation of metrics from physiological variables

We analyze in the results section the combined effects of glare discomfort level and thermal acceptability on average skin temperature ($Tskin_{avg}$), standard deviation of skin temperature ($Tskin_{SD}$), and bpm relative deviation (Δbpm) (Eq. 3). The mean skin temperature ($Tskin_{avg}$) was calculated as a weighted average of all skin sites following the well-known method used in thermal comfort research proposed by Ramanathan [53] (Eq. 4), while the standard deviation of skin temperature ($Tskin_{SD}$) was computed unweighted to represent spatial nonuniformity in skin temperature distribution (Eq. 5) [54,55].

$$\Delta \mathrm{bpm}_t = 100 \frac{(\overline{bpm_t} - \overline{bpm_{rest}})}{\overline{bpm_{rest}}} \ (\%) \tag{3}$$

$$\mathrm{Tskin}_{avg} = 0.3(T_{neck} + T_{back}) + 0.2\left(T_{wrist} + T_{leg}\right) \ (^\circ C) \tag{4}$$

$$\mathrm{Tskin}_{SD} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{4}(T_i - \overline{T}_{skin})^2} \ (^\circ C) \tag{5}$$

where $T_{neck} = T1$, $T_{back} = T_2$, $T_{wrist} = T_3$, and $T_{leg} = T_4$ are the skin temperature measurements of the neck, back, wrist, and left shin, respectively, Δbpm_t is the bpm relative deviation of the exposure period t, $\overline{bpm_t}$ is the average bpm value related to the exposure period, and $\overline{bpm_{rest}}$ is the average bpm value during the resting phase of the related session. To answer RQ4, we analyze the results of three linear mixed-effect models with the same independent variables (glare discomfort level and thermal acceptability).

Table 4
Equipment technical data.

Parameter	Manufacturer	Model	Sensor type	Principle	Measurement range	Resolution	Accuracy
Noise level	PCE Instruments	PCE-430	Class 1 SPL meter	Condenser mic +24-bit ADC; freq. Weighting; octave analysis	22–136 dB(A)	0.1 dB	±1 dB (Class 1)
Color temperature	AHLBORN (ALMEMO®)	FLAD23CCT	Color temp. Sensor	RGB *TrueColor* chip → CCT	54–30,000 K	Δx,y < 0.005	< 10% (1600–17,000 K)
Illuminance	AHLBORN (ALMEMO®)	FLAD23CCT	Illuminance sensor	V(λ) with cosine diffuser	10–65,000 lx (opt. 170 klx)	–	< 10% (120–170 klx)
Illuminance	AHLBORN (ALMEMO®)	FLAD03VL1	Illuminance (V-λ)	Photodiode + filter + PTFE	1–200 klx	0.02 lx	< 5% abs.; lin. < 1%
Spectroradiometer	JETI Technische Instrumente GmbH	Jeti Specbos 1201	Spectroradiometer (VIS)	Diffraction grating + photodiode array	Luminance 0.2–150,000 cd/m^2; Illuminance 1–1,800,000 lx	1 nm step; 5 nm FWHM	Photometric ±5%; chromaticity ±0.002; CCT ±20 K
Air temperature	AHLBORN (ALMEMO®)	FHAD46C41A	Digital temp. Sensor	Pt100 element	−40 to +85 °C	0.01 °C	±0.1–0.2°C
Globe temperature	AHLBORN (ALMEMO®)	FHAD46C41A	Digital temp. Sensor	Black globe (Pt100)	−20 to +120 °C	0.1 °C	±0.5 °C
Relative humidity	AHLBORN (ALMEMO®)	FHAD46C41A	Capacitive RH sensor	Capacitive element	0–100% RH	0.1% RH	±2% RH (10–90%)
Air velocity	AHLBORN (ALMEMO®)	FVAD05TOK300	Thermo-anemometer (omnidirectional)	Thermal anemometry	0.05–1.0 m/s	0.01 m/s	±0.05 m/s
Skin temperature	iButton Temperature Loggers	DS1922L	Skin temperature sensor	Semiconductor-based thermal sensing	−40 °C to +85 °C	0.5 °C (8-bit) or 0.0625 °C (11-bit)	±0.5 °C
Heart rate variability	Movisens sensor	Movisens EcgMove 4 – ECG and Activity Sensor	Heart rate variability (HRV)	ECG measured via biopotential electrodes	–	12-bit ECG, 1024 Hz sampling	–

2.6. Statistical methods

A priori statistical power analysis was conducted using G*Power 3.1.9.7 to estimate the minimum sample size required for the repeated-measures experimental design. Assuming a medium effect size ($f = 0.25$), significance level $\alpha = 0.05$, statistical power of 0.80, four repeated measurements (2 × 2 within-subjects design), correlation among repeated measures of 0.5, and nonsphericity correction $\varepsilon = 1$, the required sample size was estimated at 24 participants. Because the experiments depended on stable clear-sky conditions and several exposure sessions were expected to be excluded during the validation process (Section 3.1.1), additional participants were recruited to compensate for potential data loss and ensure sufficient statistical power after exclusions. A total of 45 participants completed the experimental protocol; however, after applying the sky-stability validation criteria 36 participants remained. However, as can be seen in the next sections, the number of observations and participants considered in the statistical analyses were lower than 36: between 22 and 26 participants. This is due to the filtering process of gathered measured and subjective data. We only considered in the statistical analyses subjective answers related to exposure periods which were correctly characterized: when sensors, luminance camera, and survey/data management system were working/operated successfully.

All analyses were performed in Python 3.11.11 through Spyder IDE 6.0.5 using standard libraries including *statsmodels* for regression and hypothesis testing. Analyses were conducted on condition-level averages per participant. Missing data points were removed listwise (e.g., using `dropna()` in Python). For subjective scales, both mean and median values were inspected; medians were emphasized in descriptive summaries to respect the ordinal nature of the data.

Firstly, we tested the normality by running Shapiro-Wilk tests of our data separated by experimental condition (4 different groups). As our data showed behavior of non-normal distributions, for between-condition comparisons (e.g., high vs. low glare at a given temperature level), paired-sample Wilcoxon-tests were performed when the same participants contributed data to both conditions. Specifically, three parameters were reported: W-Wilcoxon, p-Wilcoxon value, and effect size Wilcoxon's r value for each comparison [56–58]. Thus, effect size was calculated as $r = |z / \sqrt{n}|$, where z is the standardized Wilcoxon statistic and n is the number of non-zero paired observations included in the test after excluding tied pairs. Because the presence of many tied responses can substantially reduce n, large effect-size estimates may occasionally occur together with non-significant p-values and should be interpreted with caution. Effect sizes (Wilcoxon r) were interpreted according to Ferguson's thresholds, which define $r \geq 0.20$ as the minimum practically meaningful effect, $\boldsymbol{r \geq 0.50}$ a moderate effect, and $\boldsymbol{r \geq 0.80}$ a strong effect [59].

To account for the repeated-measure structure of the experiment, linear mixed-effect models were fitted using the Python *statsmodels* package [60]. Overall comfort was treated as the dependent variable, while glare condition, thermal condition, and their interaction were included as fixed effects. Participant identity was included as a random intercept to account for within-subject dependence. Although comfort ratings were collected on ordinal scales, we used linear mixed-effects models for the multivariable analyses. This is common practice in comfort research: Likert scales with four or more categories can reasonably be treated as continuous when estimating average effects in balanced repeated-measures designs [61–63]. In addition, simulation studies have shown that treating ordinal variables as continuous often yields conclusions comparable to ordinal modeling approaches under many practical conditions, particularly when the number of response categories is four or more and the distributions are not highly skewed [64]. To evaluate the robustness of this assumption, an ordinal mixed-effects sensitivity analysis (through *OrderedModel* function) was additionally performed for the primary outcome (overall comfort), and the qualitative direction and interpretation of the estimated effects were compared with those obtained from the linear mixed-effects models.

The analyses addressing the primary research questions related to overall visual comfort, thermal comfort, and overall comfort perception were considered confirmatory. Analyses involving local body-part thermal sensations and physiological outcomes were considered exploratory and were intended to identify potential patterns for future investigation. Because a relatively large number of statistical tests were performed, *p*-values close to the conventional significance threshold ($0.05 < p < 0.10$ and isolated p-values near 0.05) were interpreted cautiously and not considered definitive evidence on their own.

3. Results

In this section, we present, analyze, and interpret the results of our investigation. We first validate the experimental conditions in section 3.1 as designed in section 2.1, then show general descriptive statistical analysis of the participants whose experiment sessions were validated in section 3.1. Further, we analyze the impact of temperature on visual responses and glare stimuli on thermal responses in sections 3.2. and 3.3, respectively. We dedicate section 3.4 to the analyses of combined effects between visual and thermal responses. Finally, we study in section 3.5 the combined effect of sunlight glare discomfort and thermal comfort on physiological responses (skin temperature and relative change in HRV).

3.1. Validation of experimental conditions

3.1.1. Variation in global horizontal irradiance (GHI)

To consider subjective ratings from participants valid, we needed to ensure four conditions: stable sky conditions during the exposure times (i.e. high/low glare with high/low temperature levels), color neutrality of indoor lighting, glare stimuli and thermal stimuli. There is one exposure period per experimental condition: high glare and low temperature (h_b1), high glare and high temperature (h_b2), low glare and low temperature (l_b1), and low glare and high temperature (l_b2). The total number of participants of the study was 45. The start time of the experiment varied between 06:45 and 08:00 in the morning, depending on the day and month (19 April – 26 May 2025). From a total of 180 exposure periods (45 participants × 4 exposure periods per participant), during 121 of them, the sky was stable enough to consider the data points we consider in all further analyses. Thus, we have 27, 36, 29, and 29 exposure periods with stable sky conditions (S1_h, S1_l, S2_h, and S2_l, respectively).

Regarding the CCT of the incoming light to the test rooms, most of the exposure periods were exposed to CCT between 5000 K and 6500 K. This CCT range is considered as color neutral by the CIE standard CIE / ISO 11664-2:2022 “Colorimetry — Part 2: CIE Standard Illuminants” [65].

3.1.2. Demographics

Out of all valid laboratory conditions (i.e., under stable sky conditions), 36 participants were included in the analysis, comprising 19 males (56.5%) and 17 females (43.5%) (Table 5). Participants were from 15 different countries, with Spain (19.4%), India (16.7%), and Iran (16.7%) as the most common ones. Participants from Colombia, Germany, and Mexico represent 8.3% each. The age of the participants ranges between 19 and 36 years old, with an average age of 27.7 and 26.9 for males and females, respectively. The body mass index (BMI) values are between 16.3 and 32.9 kg/m^2, with an average BMI of 24.6 and 21.6 for males and females, respectively. Thus, according to the World Health Organization, our participants in average have normal weight. Regarding lens, 61.5% of males and 55% of females used them during the experiment. None of the participants was colorblind.

Table 5
General statistics related to age, weight, and height of the participants.

Variable	Gender	Min	Max	Avg	Median	Std. Dev.	N
Age	Male	20	36	27.7	28	4.0	19
	Female	19	36	26.9	27	4.7	17
BMI (kg/m^2)	Male	20.6	32.9	24.6	23.6	3.3	19
	Female	16.3	27.9	21.6	22	2.8	17

3.1.3. Glare levels (DGP)

Measurements of the luminance maps were made at the end of each exposure period (~12 min each). After the capture of the luminance maps with the LMK 6 camera, we converted the .pf files to HDR format using the Radiance function *pftopic2* and *evalglare* to calculate the DGP value [66]. As can be seen in Fig. 3, considering valid DGP values those associated to exposure periods with valid LMK measurements and stable sky conditions, we have 27, 34, 27, and 28 valid DGP values for S1_h, S1_l, S2_h, and S2_l, respectively. The median DGP values for high glare stimuli are around 0.44 (between disturbing and intolerant glare discomfort categories) and 0.30 for low glare stimuli (non-perceptible glare discomfort category). The difference between these two glare discomfort levels for the same thermal level (same session) is statistically significant ($p < 0.05$) as can be seen in Fig. 3. Therefore, we can validate the glare stimulus levels in our experiments. It should be noted that these DGP values reflect the *designed* glare conditions rather than participants' *subjectively perceived* glare level. As shown in Section 3.2, the median subjective glare rating under the high-glare (DGP-disturbing) condition was ‘noticeable’ rather than ‘disturbing,’ indicating a divergence between the DGP-based glare category and participants' subjective glare experience under these conditions.

3.1.4. Thermal conditions

We show in Fig. 4 the Predicted Mean Value (PMV) near the participant in each test room. ‘Buro 1’ was the cold room and ‘Buro 2’ the warm one. We adjusted the set point of the HVAC system (temperature sensor is located in the interior wall, 6.5 m away from the external facade) in the LOBSTER test facility depending on the actual temperature sensor readings next to the participant. The standard deviation ranges between 0.41 °C and 1.96 °C for any experiment day. The PMV levels between test rooms are statistically significant ($p < 0.05$) as can be seen in Fig. 4.

The average temperature was 21.6 °C in the colder room ($N = 1942$) and 26 °C in the warmer room ($N = 1681$), corresponding to lower and higher PMV ranges (−1 to 0 and 0 to +1, respectively). PMV was calculated with the Python library pythermalcomfort 3.9.1 [67,68] integrating the Mean Radiant Temperature (MRT) derived from globe temperature measurements taken 30 cm from the participant. For each time step, we calculated the MRT value with the *mean_radiant_tmp* function, based on the measured globe temperature (tg), measured dry bulb temperature (tdb), measured air velocity (v), seated posture (d = 0.15), and emissivity (0.95). Once MRT was obtained, we used the *pmv_ppd_iso* function to compute the PMV, which required tdb, MRT, and v, along with the measured relative humidity (rh), metabolic rate (MET = 1.15), and clothing level (clo = 0.57). The actual indoor temperature values were higher than the HVAC set points (18 °C and 22 °C) because of the presence of the short-wave radiation.

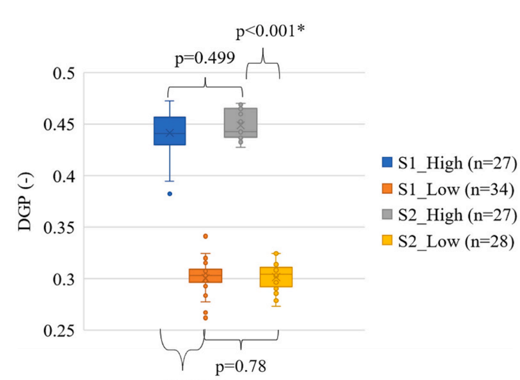

Fig. 3. DGP values of the exposure periods with valid skies and valid LMK measurements. *P*-values (*$p < 0.05$ = statistically significant) were calculated from Mann-Whitney and r *t*-tests, depending on data normality.

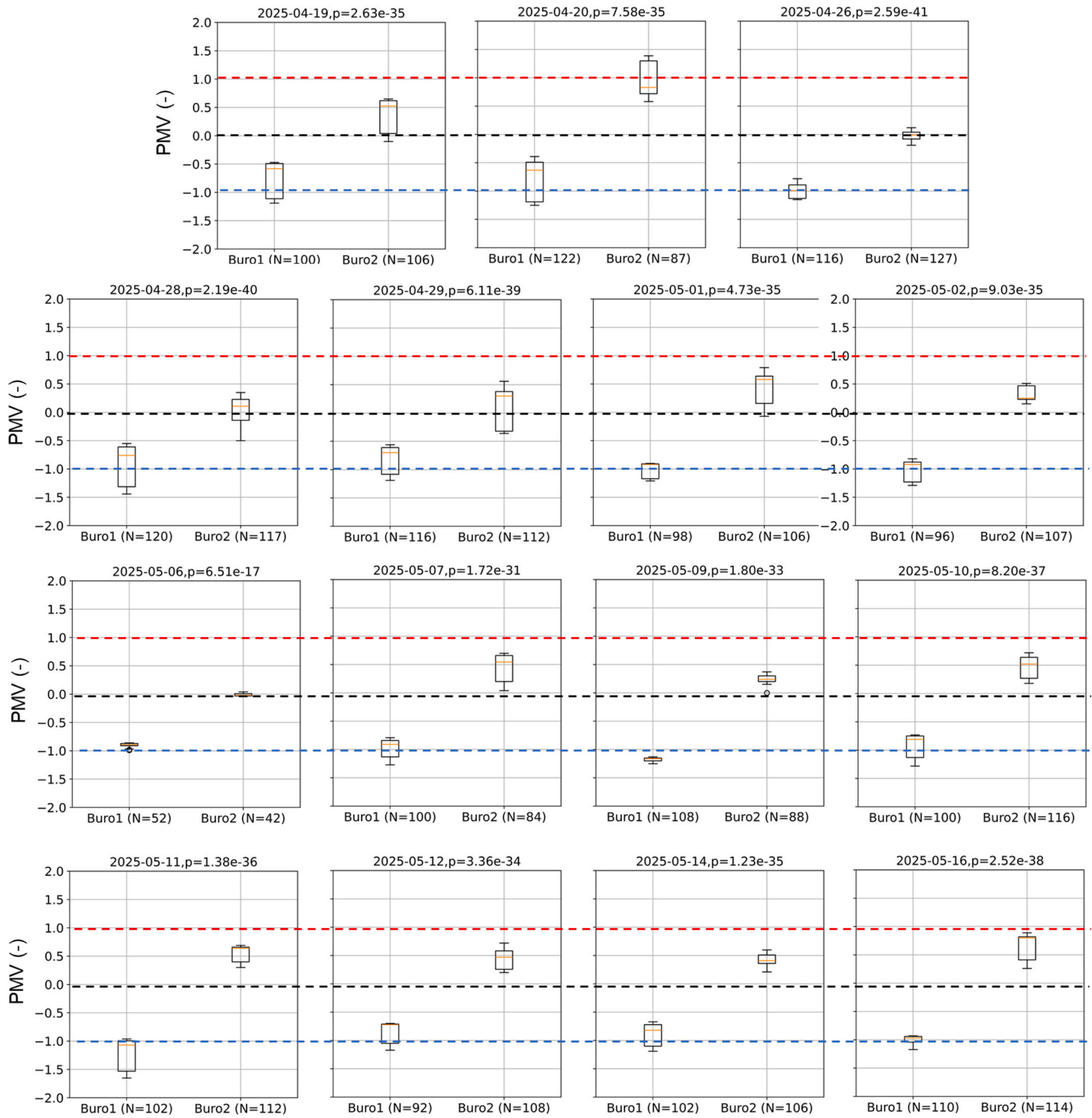

Fig. 4. Predicted Mean Vote (PMV) including short-wave radiation effects via globe temperature measured next to participants, for both test rooms across experiment days. *P*-values were calculated using Mann-Whitney or *t*-tests, depending on data normality.

3.1.5. *Other indoor variables*

Regarding perceived acoustic comfort and air quality levels (Fig. 5), participants perceived these environmental variables mostly between "Just comfortable (1)" and "Very comfortable (4)" categories (average scores between 0.83 and 2.29).

3.2. *Impact of temperature on visual comfort responses*

The aim of this section is to answer RQ1: What is the impact of temperature levels on visual comfort perception? Firstly, we show participants' ratings on visual comfort variables considered in the exposure questionnaires.

As can be seen in Fig. 6, the median value of each visual comfort response does not depend on experimental conditions. The median category reported by participants under any experimental condition was noticeable glare. In Table 6, we can see that there is no statistically significant effect (p-Wilcoxon values >0.05) of temperature levels on glare discomfort levels, overall visual environment, visual sensation, light pleasantness, and visual preference.

No statistically significant differences were found between temperature conditions for any visual comfort variable (all $p > 0.05$). Although some comparisons yielded relatively large effect size estimates ($|r| = 0.51–0.67$), these results should be interpreted cautiously because the Wilcoxon effect size was influenced by a limited number of non-zero

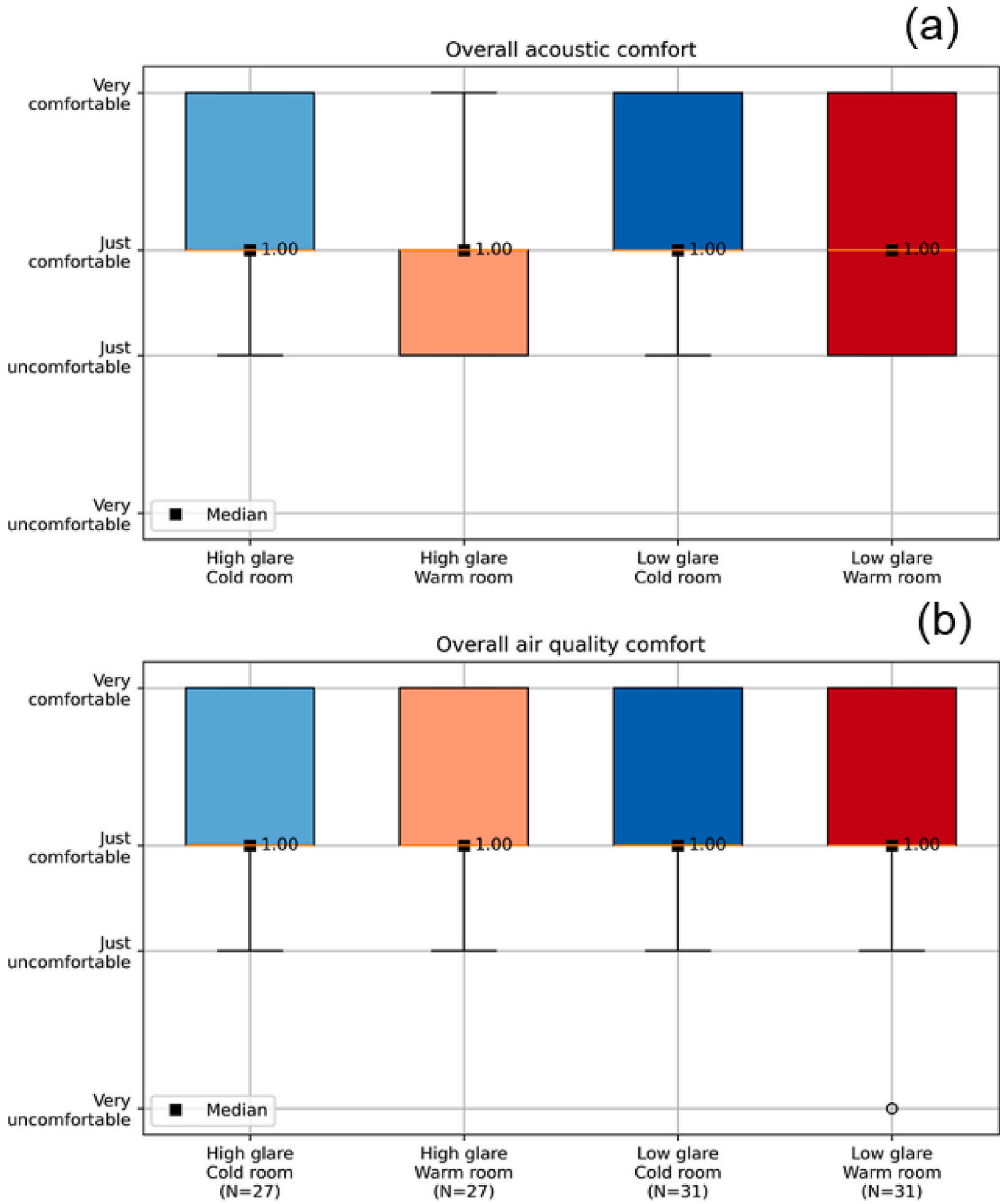

Fig. 5. Subjective ratings for overall acoustic (a) and overall air quality (b) comfort.

paired observations and a substantial number of tied responses.

3.3. Impact of sunlight discomfort glare on thermal responses

The aim of this section is to answer RQ2: What is the impact of discomfort glare due to sunlight in the field of view on thermal responses? We show participants' ratings on thermal comfort variables considered in the exposure questionnaires. Median overall thermal acceptability ratings are between "Just acceptable" and "Acceptable" for any combination of thermal and glare stimuli (Fig. 7a). Thermal sensation in the cold test room (b1) was rated by most of the participants between cool and neutral, whereas in the warm test room (b2), it was rated from neutral to slightly warm (Fig. 7b). In fact, most of participants wished for a warmer temperature while they were in b1 and almost no change for b2 (Fig. 7c).

As shown in Table 7, several exploratory comparisons yielded p-values near the conventional significance threshold, including overall thermal sensation ($W = 3.5$, $p = 0.071$), thermal sensation of the neck ($W = 15$, $p = 0.053$), and thermal sensation of the arm ($W = 9$, $p = 0.052$). However, none of these comparisons reached statistical significance and therefore should not be interpreted as evidence of glare-related effects on thermal perception.

Moderate-to-strong effect sizes were observed for thermal sensation ($r = 0.750$), thermal preference ($r = 1.000$–0.600), and body-part sensation at the head ($r = 0.667$), neck ($r = 0.615$), chest ($r = 0.545$), and arm ($r = 0.673$–1.000). However, none of the differences reached statistical significance (all $p > 0.05$). Given the substantial number of tied responses and the resulting small number of non-zero paired observations in several comparisons, these effect-size estimates should be considered exploratory and should not be interpreted as evidence of meaningful effects.

Overall, the Wilcoxon analyses provide no statistically significant evidence that glare discomfort from sunlight influenced participants' thermal comfort perceptions under the tested thermal conditions. The

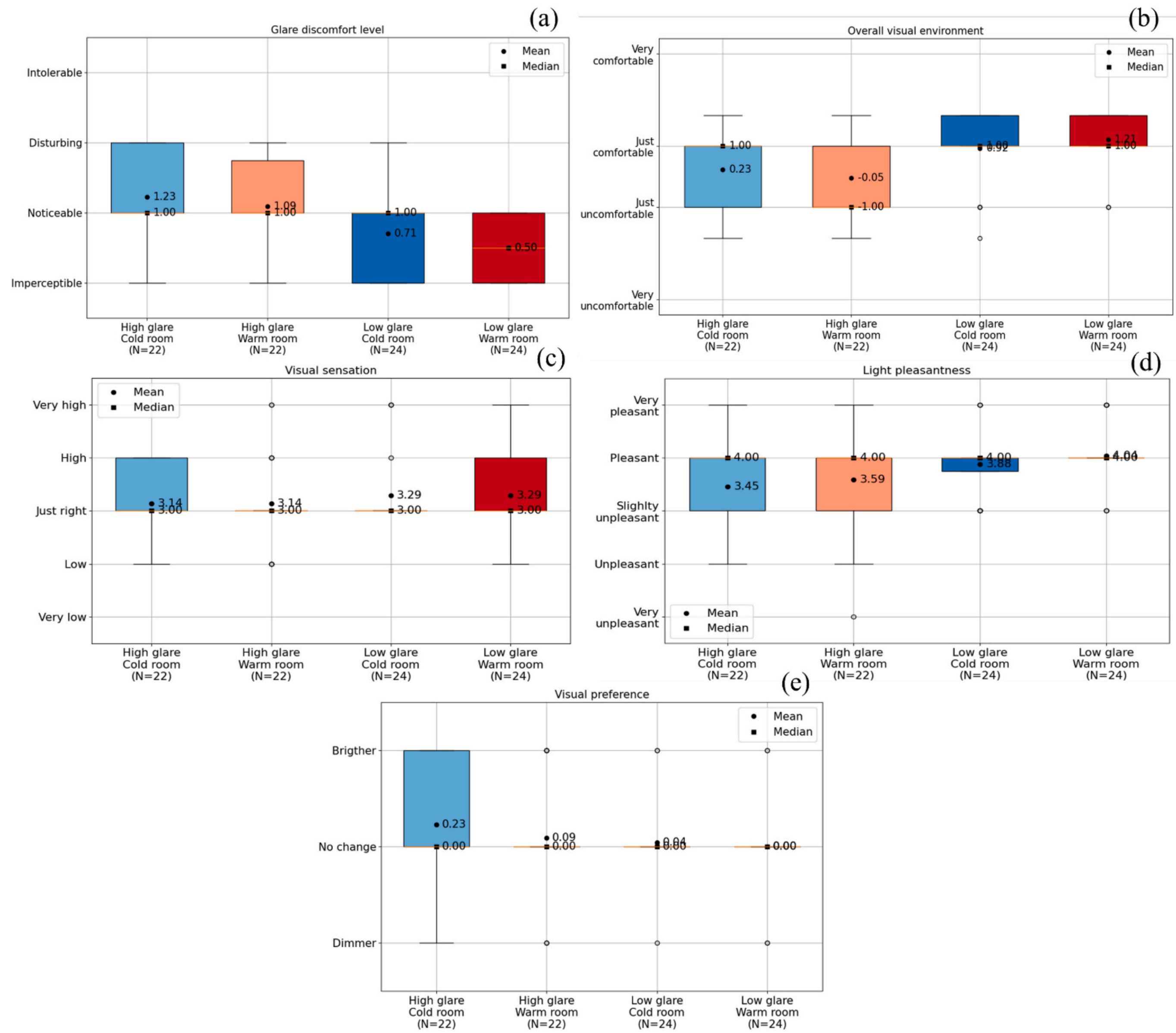

Fig. 6. Ratings of the visual indoor variables for the different exposure conditions.

comparatively larger effects observed for arm thermal sensation may be explained by this body part being directly exposed to solar irradiation.

3.4. Combined effect of sunlight glare discomfort and thermal comfort on overall comfort

The aim of this section is to answer RQ3: What is the combined effect of sunlight discomfort glare and thermal comfort on overall comfort perception? To answer that, we analyze the results of Linear mixed-effect test considering two models: A1 includes glare discomfort level and thermal sensation as independent variables, and A2 includes overall thermal acceptability instead of thermal sensation along with glare discomfort level. The dependent variable is the overall comfort, which is the same for both models. We show the Linear mixed-effect model predictors and model fit statistics in Tables 8 and 9, respectively.

Both models followed the general form (Eq. 6):

$$Overall\ comfort = \beta_0 + \beta_1(Glare\ discomfort\ level) + \beta_2(Thermal\ variable) + \beta_3(Interaction) + u_p + \varepsilon \quad (6)$$

Where u_p represents the participant-specific random intercept. Model A1 showed that both glare discomfort level and thermal sensation were significant predictors of overall comfort. Glare discomfort level was negatively associated with overall comfort ($\beta = -0.449$, $p = 0.003$), indicating that increased glare discomfort significantly reduced perceived comfort. Thermal sensation was positively associated with overall comfort ($\beta = 0.278$, $p = 0.020$), suggesting that warmer thermal sensations within the tested range were associated with improved comfort perception. However, the interaction between glare discomfort level and thermal sensation was not statistically significant ($p = 0.543$), indicating that the effect of glare discomfort on overall comfort did not substantially depend on thermal sensation.

Model A2 showed that overall thermal acceptability was significantly associated with overall comfort ($\beta = 0.425$, $p = 0.046$), whereas glare discomfort level showed a negative but non-significant association with overall comfort after accounting for repeated measurements ($\beta = -0.697$, $p = 0.108$). The interaction between glare discomfort level and overall thermal acceptability was also not statistically significant ($p = 0.531$). These results indicate that higher thermal acceptability was associated with improved overall comfort, while the interaction

Table 6
Statistical analysis of visual comfort ratings. High glare stimuli = h, low glare stimuli = l, high temperature level = b2, and low temperature level = b1. Statistically significant (*p*-value<0.05) = *. Effect sizes according to Ferguson's thresholds: minimum practically meaningful ($r \geq 0.20$), moderate ($r \geq 0.50$), and strong ($r \geq 0.80$).

Target variable	Condition X	Condition Y	Wilcoxon W	Wilcoxon p-value	Effect size ($r = \lvert z / \sqrt{n} \rvert$)
Glare discomfort level	h_b1 (*N* = 22)	h_b2 (N = 22)	30	0.464	0.231
	l_b1 (*N* = 24)	l_b2 (N = 24)	10	0.110	0.556
Overall visual environment	h_b1 (N = 22)	h_b2 (*N* = 22)	39	0.408	0.257
	l_b1 (N = 24)	l_b2 (*N* = 24)	13.5	0.158	0.509
Visual sensation	h_b1 (N = 22)	h_b2 (N = 22)	33	1	0
	l_b1 (N = 24)	l_b2 (N = 24)	14	1	0
Light pleasantness	h_b1 (N = 22)	h_b2 (N = 22)	27	0.343	0.308
	l_b1 (N = 24)	l_b2 (N = 24)	2.5	0.203	0.667
Visual preference	h_b1 (N = 22)	h_b2 (N = 22)	8	0.299	0.429
	l_b1 (N = 24)	l_b2 (N = 24)	2	0.773	0.333

between visual and thermal perception variables did not significantly contribute to the prediction of overall comfort.

Overall, the mixed-effect analyses suggest that both visual and thermal perceptions were associated with overall comfort perception, although the evidence for glare discomfort was not consistent across models. Glare discomfort level showed a significant negative association with overall comfort in Model A1, but not in Model A2. In contrast, thermal sensation (A1) and thermal acceptability (A2) were both positively associated with overall comfort. Interaction effects were not statistically significant in either model. Furthermore, the inclusion of participant-specific random intercepts revealed substantial inter-individual variability, supporting the appropriateness of the mixed-effects modeling approach for repeated-measure comfort data.

As a sensitivity analysis, ordinal logistic regression models were fitted using overall comfort as the ordinal outcome. For Model A1, the ordinal analysis confirmed the same qualitative conclusions as the linear mixed-effects model, with glare discomfort showing a significant negative association with overall comfort ($\beta = -1.00, p = 0.001$) and thermal sensation showing a significant positive association ($\beta = 0.47$, $p = 0.008$). Similarly, for Model A2, glare discomfort remained negatively associated with overall comfort ($\beta = -1.08, p = 0.001$), whereas thermal acceptability showed a positive association ($\beta = 1.32$, $p < 0.001$). Although glare discomfort did not reach statistical significance in the linear mixed-effects model for A2 ($p = 0.108$), the direction of the effect was identical across both approaches. Overall, the ordinal analyses supported the robustness of the principal conclusions obtained from the linear mixed-effects models.

3.5. Combined effect of sunlight glare discomfort and thermal comfort on physiological responses

The aim of this section is to answer RQ4: What is the combined impact of sunlight discomfort glare and thermal comfort on human physiological responses? Specifically, we analyze the combined effects of glare discomfort level and thermal acceptability on average skin temperature ($Tskin_{avg}$), standard deviation of skin temperature ($Tskin_{SD}$), and bpm relative deviation (Δbpm) (Eq. 3). We considered Δbpm instead of the standard HRV metric to evaluate the effect of the visual stimuli on the participant's HRV after each resting phase. The dependent variable (i.e. target variable) varies with the model: $Tskin_{avg}$, $Tskin_{SD}$, and Δbpm for models P1, P2, and P3, respectively. We show the linear mixed-effects model predictors and model fit statistics in Tables 10 and 11, respectively. Thus, the three models followed the general form (Eq. 7):

$$Target\ variable = \beta_0 + \beta_1(Glare\ discomfort\ level) + \beta_2(Thermal\ acceptability) + \beta_3(Interaction) + u_p + \varepsilon \tag{7}$$

Tables 10 and 11 summarize the results of the three linear mixed-effects models P1, P2, and P3. Overall, the models revealed limited evidence that glare discomfort and thermal acceptability were associated with physiological outcomes. Specifically, in the exploratory physiological analyses, glare discomfort level was negatively associated with heart rate change ($\beta = -9.882$, $p = 0.049$). Given the large number of statistical comparisons performed and the proximity of the *p*-value to the significance threshold, this finding should be interpreted cautiously and requires confirmation in future studies. Despite this statistical significance, the physiological meaning of this finding is not intuitive. Therefore, additional research is needed to confirm this finding. The interaction term in this model ($p = 0.092$) was not statistically significant, although it remained close to the significance threshold, suggesting a potential interaction between glare discomfort and thermal acceptability that warrants further investigation. However, because this interaction effect was only marginally significant, this interpretation should be considered exploratory and interpreted cautiously.

For models P1 and P2, neither glare discomfort level, thermal acceptability, nor their interaction significantly influenced mean skin temperature ($Tskin_{avg}$) or the spatial variability of skin temperature ($Tskin_{SD}$). Thermal acceptability showed only a marginal positive association with $Tskin_{avg}$ in model P1 ($\beta = 0.379$, $p = 0.072$). These findings suggest that subjective perceptions of glare discomfort and thermal acceptability did not strongly correspond to measurable changes in skin temperature under the investigated exposure conditions.

The participant-specific random intercept variances further indicated inter-individual variability in physiological responses, particularly for Δbpm. This finding supports the use of linear mixed-effects models, as repeated observations within participants were not independent and baseline physiological responses varied across participants.

4. Limitations

The experiment sessions were conducted between April and May 2025 and early in the morning, the possible impact of seasonality and time of the day was not included in this study. The view out was constant during the experiment and it contained information about the sky, vegetation, and ground floor. The effect of different view quality on the subjective ratings might have affected the subjective ratings [69].

In our experiments, the temperature difference between high and low thermal stimuli (neutral: 21.6°C; slightly warm: 26 °C, standard deviation between 0.41 °C and 1.96 °C) might not have been enough to find cross-modal effects as another previous research [7,24,36]. While DGP is currently the most robust metric for quantifying daylight glare in office spaces, its relationship with subjective glare perception is not systematic and depends on contextual factors such as shading type and the presence of the sun directly in the field of view. Recent studies report that DGP tends to slightly overestimate perceived glare in such conditions. With fabric shades, the empirically derived disturbing-glare threshold (DGP $\approx$ 0.43) was higher than the standard 0.40 threshold [70]. Similarly, with electrochromic glazing, an average DGP of 0.49 corresponded to only 6% of participants reporting "intolerable" glare [22]. Our setup is methodologically closer to the latter. Accordingly, in our study, the high-glare condition was designed within the disturbing-to-intolerable DGP range (~0.40–0.45), whereas participants' subjective

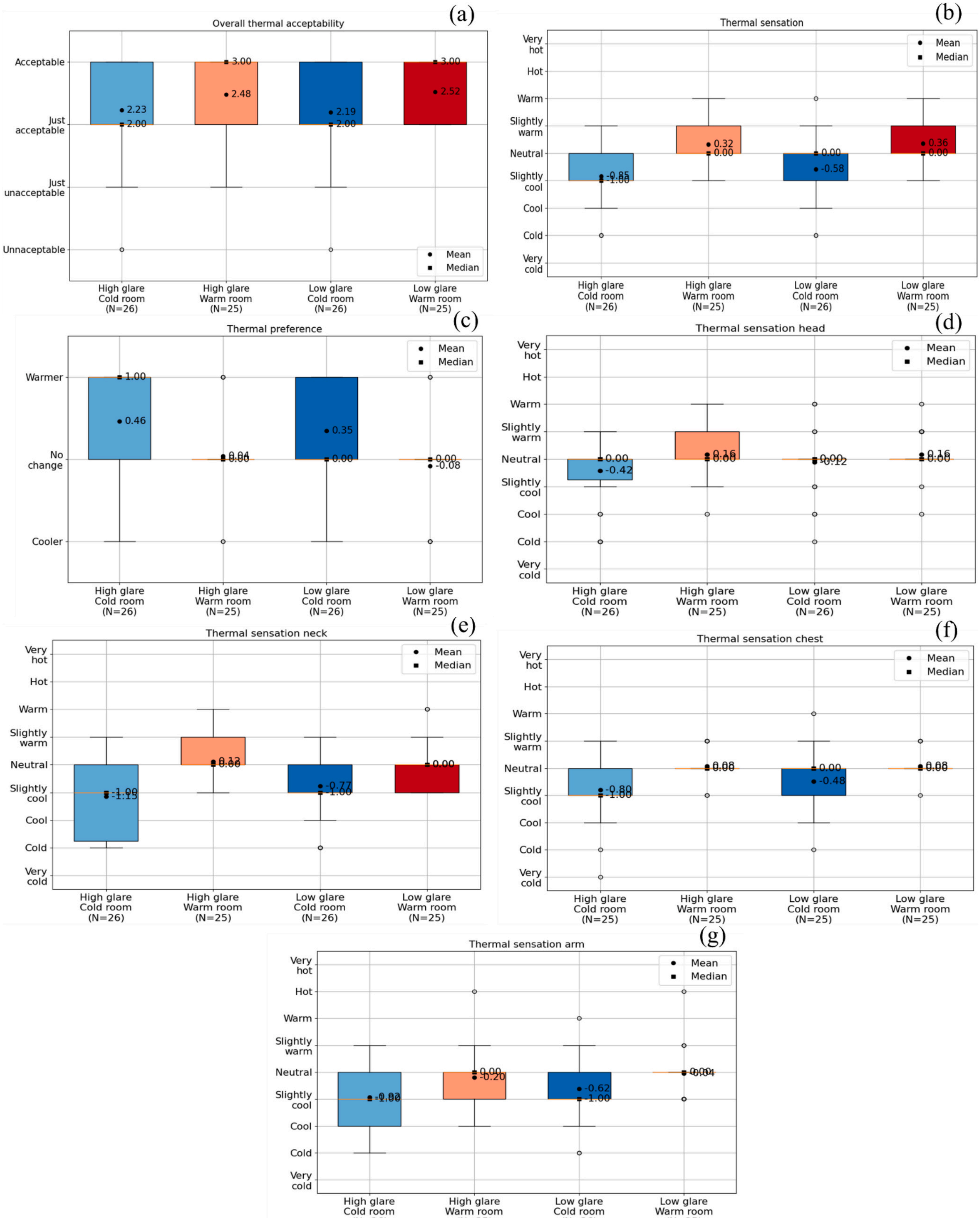

Fig. 7. Ratings of the thermal indoor variables for the different exposure conditions.

Table 7
Statistical analysis of thermal comfort ratings. High glare stimuli = h, low glare stimuli = l, high temperature level = b2, and low temperature level = b1. Statistically significant (p-value<0.05) = *. Effect sizes according to Ferguson's thresholds: minimum practically meaningful ($r \geq 0.20$), moderate ($r \geq 0.50$), and strong ($r \geq 0.80$).

Target variable	Condition X	Condition Y	Wilcoxon W	Wilcoxon p-value	Effect size ($r = \|z / \sqrt{n}\|$)
Overall thermal acceptability	h_b1 (N = 26)	l_b1 (N = 26)	6	0.766	0.200
	h_b2 (N = 25)	l_b2 (N = 25)	6	0.766	0.200
Thermal sensation	h_b1 (N = 26)	l_b1 (N = 26)	3.5	0.071	0.750
	h_b2 (N = 25)	l_b2 (N = 25)	12	0.777	0.143
Thermal preference	h_b1 (N = 26)	l_b1 (N = 26)	0	0.149	1
	h_b2 (N = 25)	l_b2 (N = 25)	3	0.233	0.600
Thermal sensation head	h_b1 (N = 26)	l_b1 (N = 26)	6	0.098	0.667
	h_b2 (N = 25)	l_b2 (N = 25)	18	1	0
Thermal sensation neck	h_b1 (N = 26)	l_b1 (N = 26)	15	0.053	0.615
	h_b2 (N = 25)	l_b2 (N = 25)	8	0.299	0.429
Thermal sensation chest	h_b1 (N = 25)	l_b1 (N = 25)	15	0.097	0.545
	h_b2 (N = 25)	l_b2 (N = 25)	1.5	1	0
Thermal sensation arm	h_b1 (N = 26)	l_b1 (N = 26)	9	0.052	0.673
	h_b2 (N = 25)	l_b2 (N = 25)	0	0.072	1.000

Table 8
Linear mixed-effect model predictors from analyses A1 and A2 run in Python. A1 = glare discomfort level & thermal sensation, A2 = glare discomfort level & thermal acceptability, both with overall comfort as dependent variable. * = statistically significant ($p < 0.05$). † = statistically marginal ($0.05 < p < 0.10$).

Predictor	Coefficient (β) (A1/A2)	Std. Error (A1/A2)	z (A1/A2)	P > |z| (A1/A2)	95% CI [Lower, Upper] (A1/A2)
Intercept	1.013 / -0.024	0.183 / 0.529	5.526 / -0.045	<0.001* / 0.964	[0.654, 1.372] / [−1.060, 1.013]
Glare Discomfort Level	−0.449 / -0.697	0.151 / 0.434	−2.969 / -1.607	0.003* / 0.108	[−0.745, −0.152] / [−1.548, 0.153]
Thermal sensation (A1) and Thermal acceptability (A2)	0.278 / 0.425	0.120 / 0.213	2.320 / 1.993	0.020* / 0.046*	[0.043, 0.513] / [0.007, 0.843]
Interaction	−0.074 / 0.114	0.121 / 0.181	−0.609 / 0.627	0.543 / 0.531	[−0.312, 0.164] / [−0.242, 0.469]
Random intercept variance (participant)	0.404 / 0.302	0.218 / 0.184	–	–	–

ratings were, on median, closer to the noticeable category — consistent with this known tendency. The conclusions of this investigation might not be generalized in different thermal and glare discomfort ranges or people with high sensitivity to indoor environmental factors.

Table 9
Model fit statistics for both linear mixed-effects model analyses A1 and A2 run in Python. A1 = glare discomfort level & thermal sensation, A2 = glare discomfort level & thermal acceptability, both with overall comfort as dependent variables.

Model Fit Statistic	Value (A1)	Value (A2)
Number of observations	113	113
Number of groups	35	35
Minimum group size	1	1
Maximum group size	4	4
Mean group size	3.2	3.2

Finally, the fixed glare exposure sequence represents an important methodological limitation of the present study. Participants were systematically exposed first to the high-glare condition and subsequently to the low-glare condition within each session. This design choice was intentional and aimed to reproduce a realistic office-related behavioral scenario in which occupants initially experience disturbing glare and subsequently adapt their workstation orientation or viewing direction to reduce discomfort. Nevertheless, this fixed exposure sequence introduces a potential confound between glare condition and exposure order. Consequently, observed differences between high- and low-glare conditions may have been partially influenced by adaptation effects, visual recovery, fatigue, learning effects associated with repeated cognitive tasks, or perceptual contrast effects. Although resting phases were included between exposures to reduce carryover effects, these influences cannot be fully excluded. Therefore, the glare-related findings of this study should be interpreted cautiously and not as fully independent causal effects of glare level alone.

5. Discussion

For RQ1, we did not find statistically significant impact of temperature levels on participants' perceptions of glare discomfort due to the sun in the FOV or their ratings of light levels under our experimental conditions. It is also worth noting that although the high-glare condition was designed to reach DGP values in the disturbing-to-intolerable range, participants' subjective glare ratings remained, on median, in the noticeable category. This suggests that DGP may not fully capture participants' subjective glare experience under these specific conditions (sun directly in the FOV through a controlled window filter).

For RQ2, we found no statistically significant impact of glare discomfort on participants' overall thermal comfort ratings (acceptability, sensation, preference, or body-part sensation). Some exploratory analyses of local body-part sensations yielded p-values close to the significance threshold, particularly for the neck and arm; however, these findings should be interpreted cautiously. Garretón et al. exposed the desks of their participants ($N = 19$) to direct sunlight patches under constant illuminance levels (2000–3000 lx) and more extreme thermal conditions (13 °C, 20 °C, and 28 °C), and found that perceived temperature significantly affected glare predictions [24]. Our study did not confirm Garretón et al.'s finding, possibly because our participants were exposed directly to the sun in their field of view, rather than to sun patches on the desk under controlled illuminance, and because our thermal conditions covered a narrower, less extreme range. Nevertheless, our findings suggest that this direct exposure to the sun in the field of view may itself be an important driver of overall comfort perception.

Regarding RQ3 (combined effect of sunlight discomfort glare and thermal comfort on overall comfort perception), glare discomfort level showed a significant negative association with overall comfort in Model A1, whereas this association was not statistically significant in Model A2 after accounting for thermal acceptability. Thermal sensation and thermal acceptability were both positively associated with overall comfort. We did not find significant interaction effects between glare discomfort and thermal perception variables, suggesting limited

Table 10
Linear mixed-effects model predictors from analyses P1 ($Tskin_{avg}$), P2 ($Tskin_{SD}$), and P3 (Δbpm) run in Python. * = statistically significant ($p < 0.05$). † = statistically marginal ($0.05 < p < 0.10$).

Predictor	β coef. (P1)	β coef. (P2)	β coef. (P3)	p (P1)	p (P2)	p (P3)
Intercept	31.688	1.457	8.377	<0.001*	<0.001*	0.157
Glare discomfort level	0.510	0.169	−9.882	0.273	0.247	0.049*
Thermal acceptability	0.379	0.074	−2.950	0.072†	0.294	0.214
Interaction (Glare discomfort level × Thermal Acceptability)	−0.233	−0.049	3.481	0.232	0.404	0.092†
Random intercept variance (participant)	0.179	0.539	32.129	–	–	–

Table 11
Model fit statistic for linear mixed-effects model analyses P1, P2, and P3 run in Python.

Model Fit Statistic	P1	P2	P3
Dependent Variable	Mean Skin Temp	SD Skin Temp	Heart Rate ΔBPM
No. of Observations	110	113	107
Number of groups	34	35	33
Minimum group size	1	1	1
Maximum group size	4	4	4
Mean group size	3.2	3.2	3.2
Scale	0.5803	0.0581	84.0

evidence that the relationship between glare discomfort and overall comfort depended on thermal conditions within the investigated range. This might be due to the clear presence of the sun as the main glare source and **dominant factor influencing participants' overall comfort perception.**

Regarding RQ4 (combined impact of sunlight discomfort glare and thermal comfort on human physiological responses, we did not find cross-modal effects of sunlight glare discomfort and thermal acceptability on skin temperature variables. However, an exploratory analysis indicated a negative association between glare discomfort and cardiovascular activation (Δbpm). Because this result was isolated, close to the significance threshold, and obtained within a broader set of statistical tests, it should be regarded as preliminary until replicated in future studies.

6. Conclusions

When the sun is in the field of view (presence of short-wave radiation), most common assessment metrics are not reliable enough. The presence of the sun could lead to a different sensitivity of occupants to experience glare discomfort. Moreover, the overall comfort could be influenced by glare/thermal discomfort. This is the first study that explores the cross-modal effects between thermal, visual, and overall comfort and physiological variables in office spaces with the sun in the field of view. This research advances the understanding of **cross-modal comfort interactions** and informs strategies for IEQ control that better support occupant well-being. The findings also provide a basis for refining predictive comfort models and for guiding architectural and operational decisions in daylit office spaces where occupants are regularly exposed to direct solar gains. Our key findings related to temperature levels falling on the range 21.6–26 ± 1.96 °C and mean daylight glare discomfort level between non-perceptible and noticeable are summarized as follows:

- When the sun was in the field of view (FOV), temperature levels did not significantly affect participants' glare discomfort, overall visual environment, visual sensation, light pleasantness, or visual preference. Moreover, glare discomfort from sunlight did not significantly influence participants' overall thermal acceptability, thermal sensation, thermal preference, or thermal sensation of the head or chest. Nevertheless, localized effects were observed for thermal sensation of the neck and arm, particularly under low-temperature conditions, possibly due to direct solar exposure of these body regions.
- There were no significant cross-modal effects between glare discomfort and thermal acceptability on average skin temperature or the spatial variability of skin temperature. However, a non-intuitive significant negative association between glare discomfort and heart rate variation (Δbpm) was observed, suggesting that higher glare discomfort was associated with lower cardiovascular activation under the investigated exposure conditions.

Furthermore, glare discomfort level showed a negative association with overall comfort, while thermal sensation and thermal acceptability were positively associated with overall comfort. No significant interactions were observed between glare discomfort and thermal variables. These findings suggest that discomfort glare from the sun in the field of view was associated with lower overall comfort under the tested conditions. The results therefore highlight the importance of providing effective shading devices to protect occupants from glare and support comfort and well-being in daylit office environments.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the author(s) used Microsoft Copilot (GPT-5) for language editing, grammar improvement, and manuscript text refinement. The author(s) reviewed and edited the output as needed and take full responsibility for the content of the published article.

CRediT authorship contribution statement

Abel Sepúlveda: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Caroline Karmann:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We want to thank Ritick Sethi, Hruthik Reddy, Shruti Sakshi Sinha, Andreas Wagner, Seyed Mohammad Hooshmand, Isabel Miño-Rodríguez, and Emiliano Aldrett for their valuable help and support during the experiment set up. The research is funded by the Federal Ministry of Education and Research (BMBF) and the Baden-Württemberg Ministry of Science as part of the Excellence Strategy of the German Federal and State Governments.

Data availability

Data will be made available on request.

References

[1] M.C. Mewomo, J.O. Toyin, C.O. Iyiola, O.R. Aluko, Synthesis of critical factors influencing indoor environmental quality and their impacts on building occupants health and productivity, 2023, https://doi.org/10.1108/JEDT-10-2021-0595.

[2] P.M. Bluyssen, Towards an integrated analysis of the indoor environmental factors and its effects on occupants, Intell. Build. Int. 12 (3) (2020), https://doi.org/10.1080/17508975.2019.1599318.

[3] R.J. Cureau, I. Pigliautile, I. Kousis, A.L. Pisello, Multi-domain human-oriented approach to evaluate human comfort in outdoor environments, Int. J. Biometeorol. 66 (10) (2022), https://doi.org/10.1007/s00484-022-02338-7.

[4] A.M. Atzeri, F. Cappelletti, A. Tzempelikos, A. Gasparella, Comfort metrics for an integrated evaluation of buildings performance, Energ. Buildings 127 (2016), https://doi.org/10.1016/j.enbuild.2016.06.007.

[5] L. Bedocs, Comment 2 on 'Effect of thermal conditions and light source type on visual comfort appraisal' by C Laurentin, V Berrutto and M Fontoynont, Light. Res. Technol. 33 (2) (2001), https://doi.org/10.1177/136578280103300214.

[6] H.W. Brink, M.G.L.C. Loomans, M.P. Mobach, H.S.M. Kort, A systematic approach to quantify the influence of indoor environmental parameters on students' perceptions, responses, and short-term academic performance, Indoor Air 32 (10) (2022), https://doi.org/10.1111/ina.13116.

[7] G. Chinazzo, J. Wienold, M. Andersen, Daylight affects human thermal perception, Sci. Rep. 9 (1) (2019), https://doi.org/10.1038/s41598-019-48963-y.

[8] M. Frontczak, P. Wargocki, Literature survey on how different factors influence human comfort in indoor environments, Build. Environ. 46 (4) (2011), https://doi.org/10.1016/j.buildenv.2010.10.021.

[9] E. comission, BS EN 17037:2018: Daylight in buildings, 2018 [Online]. Available: https://www.en-standard.eu/bs-en-17037-2018-daylight-in-buildings/.

[10] M. Knoop, et al., Daylight: what makes the difference? Light. Res. Technol. (2019) https://doi.org/10.1177/1477153519869758.

[11] S. Lechner, C. Moosmann, A. Wagner, M. Schweiker, Does thermal control improve visual satisfaction? Interactions between occupants' self-perceived control, visual, thermal, and overall satisfaction, Indoor Air 31 (6) (2021), https://doi.org/10.1111/ina.12851.

[12] J. Nie, et al., The effects of dynamic daylight-like light on the rhythm, cognition, and mood of irregular shift workers in closed environment, Sci. Rep. 11 (1) (2021), https://doi.org/10.1038/s41598-021-92438-y.

[13] J.A. Jakubiec, G. Quek, T. Srisamranrungruang, Long-term visual quality evaluations correlate with climate-based daylighting metrics in tropical offices – a field study, Light. Res. Technol. 53 (1) (2021), https://doi.org/10.1177/1477153520926528.

[14] J.K. Day, B. Futrell, R. Cox, S.N. Ruiz, Blinded by the light: occupant perceptions and visual comfort assessments of three dynamic daylight control systems and shading strategies, Build. Environ. 154 (2019), https://doi.org/10.1016/j.buildenv.2019.02.037.

[15] R.G. Hopkinson, Glare from daylighting in buildings, Appl. Ergon. 3 (4) (1972), https://doi.org/10.1016/0003-6870(72)90102-0.

[16] W.K.E. Osterhaus, Discomfort glare assessment and prevention for daylight applications in office environments, Sol. Energy (2005), https://doi.org/10.1016/j.solener.2004.11.011.

[17] J. Wienold, J. Christoffersen, Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras, Energ. Buildings (2006), https://doi.org/10.1016/j.enbuild.2006.03.017.

[18] C. Pierson, J. Wienold, M. Bodart, Daylight discomfort glare evaluation with evalglare: influence of parameters and methods on the accuracy of discomfort glare prediction, Buildings (2018), https://doi.org/10.3390/buildings8080094.

[19] N.S. Shafavi, Z.S. Zomorodian, M. Tahsildoost, M. Javadi, Occupants visual comfort assessments: a review of field studies and lab experiments, 2020, https://doi.org/10.1016/j.solener.2020.07.058.

[20] C. Pierson, M. Sarey Khanie, M. Bodart, J. Wienold, Discomfort glare cut-off values from field and laboratory studies, 2019, https://doi.org/10.25039/x46.2019.op41.

[21] S. Jain, J. Wienold, M. Lagier, A. Schueler, M. Andersen, Perceived glare from the sun behind tinted glazing: comparing blue vs. color-neutral tints, Build. Environ. 234 (2023), https://doi.org/10.1016/j.buildenv.2023.110146.

[22] S. Jain, C. Karmann, J. Wienold, Behind electrochromic glazing: assessing user's perception of glare from the sun in a controlled environment, Energ. Buildings 256 (2022), https://doi.org/10.1016/j.enbuild.2021.111738.

[23] I. Konstantzos, A. Tzempelikos, Daylight glare evaluation with the sun in the field of view through window shades, Build. Environ. 113 (2017), https://doi.org/10.1016/j.buildenv.2016.09.009.

[24] J.Y. Garretón, R. Rodriguez, A. Pattini, Effects of perceived indoor temperature on daylight glare perception, Build. Res. Inf. 44 (8) (2016), https://doi.org/10.1080/09613218.2016.1103116.

[25] P.O. Fanger, Thermal comfort. Analysis and applications in environmental engineering., 1970.

[26] T. Cheung, S. Schiavon, T. Parkinson, P. Li, G. Brager, Analysis of the accuracy on PMV–PPD model using the ASHRAE global thermal comfort database II, Build. Environ. 153 (2019) 205–217.

[27] Y. Yao, Z. Lian, W. Liu, C. Jiang, Measurement methods of mean skin temperatures for the PMV model, HVAC R Res. 14 (2) (2008), https://doi.org/10.1080/10789669.2008.10391001.

[28] L.G. Ioannou, et al., The impacts of sun exposure on worker physiology and cognition: multi-country evidence and interventions, Int. J. Environ. Res. Public Health 18 (14) (2021), https://doi.org/10.3390/ijerph18147698.

[29] Z. Wang, Y. Fu, W. Gao, The crossed and interaction effects of indoor light and thermal factors on human perceptions, Dev. Built Environ. 17 (2024), https://doi.org/10.1016/j.dibe.2024.100339.

[30] E. Arens, T. Hoyt, X. Zhou, L. Huang, H. Zhang, S. Schiavon, Modeling the comfort effects of short-wave solar radiation indoors, Build. Environ. 88 (2015), https://doi.org/10.1016/j.buildenv.2014.09.004.

[31] Y. He, et al., Modeling solar radiation on a human body indoors by a novel mathematical model, Build. Environ. 187 (2021), https://doi.org/10.1016/j.buildenv.2020.107421.

[32] R.L. Hwang, P.L. Fang, W.A. Chen, Impact of solar radiation on indoor thermal comfort near highly glazed façades in a hot-humid subtropical climate: an experimental evaluation, Build. Environ. 243 (2023), https://doi.org/10.1016/j.buildenv.2023.110725.

[33] B. Song, L. Bai, L. Yang, Analysis of the long-term effects of solar radiation on the indoor thermal comfort in office buildings, Energy 247 (2022), https://doi.org/10.1016/j.energy.2022.123499.

[34] N. Wang, J. Wang, A spectrally-resolved method for evaluating the solar effect on user thermal comfort in the near-window zone, Build. Environ. 202 (2021), https://doi.org/10.1016/j.buildenv.2021.108044.

[35] C. Laurentin, V. Bermtto, M. Fontoynont, Effect of thermal conditions and light source type on visual comfort appraisal, Light. Res. Technol. 32 (4) (2000), https://doi.org/10.1177/096032710003200406.

[36] G. Chinazzo, J. Wienold, M. Andersen, Influence of indoor temperature and daylight illuminance on visual perception, Light. Res. Technol. 52 (3) (2020), https://doi.org/10.1177/1477153519859609.

[37] G. Chinazzo, J. Wienold, M. Andersen, Variation in thermal, visual and overall comfort evaluation under coloured glazing at different temperature levels, J. Int. Color Assoc. 23 (2019) 45–54.

[38] G. Chinazzo, J. Wienold, M. Andersen, Effect of indoor temperature and glazing with saturated color on visual perception of daylight, LEUKOS 17 (2) (2021), https://doi.org/10.1080/15502724.2020.1726182.

[39] G. Chinazzo, K. Chamilothori, J. Wienold, M. Andersen, Temperature–color interaction: subjective indoor environmental perception and physiological responses in virtual reality, Hum. Factors 63 (3) (2021), https://doi.org/10.1177/0018720819892383.

[40] M. te Kulve, L. Schellen, L.J.M. Schlangen, W.D. van Marken Lichtenbelt, The influence of light on thermal responses, 2016, https://doi.org/10.1111/apha.12552.

[41] M. te Kulve, L. Schlangen, W. van Marken Lichtenbelt, Interactions between the perception of light and temperature, Indoor Air 28 (6) (2018), https://doi.org/10.1111/ina.12500.

[42] G. Chinazzo, J. Wienold, M. Andersen, Combined effects of daylight transmitted through coloured glazing and indoor temperature on thermal responses and overall comfort, Build. Environ. 144 (2018) 583–597.

[43] A. Sepúlveda, I. Miño-Rodríguez, P. Balakrishnan, C. Karmann, "A simulation study on the impact of window filters on the non-image forming effects of light, visual comfort, and thermal sensation.," in Cate 2024, Seville, Spain, 2024.

[44] G. Chinazzo, et al., Quality criteria for multi-domain studies in the indoor environment: critical review towards research guidelines and recommendations, 2022, https://doi.org/10.1016/j.buildenv.2022.109719.

[45] J.A. Jakubiec, C.F. Reinhart, The 'adaptive zone'-a concept for assessing discomfort glare throughout daylit spaces, Light. Res. Technol. (2012), https://doi.org/10.1177/1477153511420097.

[46] S.T. Mueller, B.J. Piper, The psychology experiment building language (PEBL) and PEBL test battery, J. Neurosci. Methods 222 (2014), https://doi.org/10.1016/j.jneumeth.2013.10.024.

[47] AT Delta-T Devices, SPN1 Sunshine Pyranometer, 2026.

[48] PCE Instruments, Class 1 Data-Logging SPL Meter PCE-430, 2026.

[49] ALHBORN, Datenlogger ALMEMO® 2890–9, 2026.

[50] Manualslib, Jeti specbos 12 1 Series Operating Instructions Manual, 2026.

[51] Maxim Integrated, iButton® temperature logger DS1922L: Data sheet, 2026.

[52] Movisens GmbH, EcgMove 4 – ECG and activity sensor: Technical specifications and user manual, 2026.

[53] N.L. Ramanathan, A new weighting system for mean surface temperature of the human body, J. Appl. Physiol. 19 (1964), https://doi.org/10.1152/jappl.1964.19.3.531.

[54] D. Mitchell, C.H. Wyndham, Comparison of weighting formulas for calculating mean skin temperature, J. Appl. Physiol. 26 (5) (1969), https://doi.org/10.1152/jappl.1969.26.5.616.

[55] I. S. O. ISO, "9886: 2004," Ergonomics-Evaluation of thermal strain by physiological measurements, vol. 13, 2004.

[56] M. Hollander, D.A. Wolfe, E. Chicken, Nonparametric statistical methods, 2015, https://doi.org/10.1002/9781119196037.

[57] F. Wilcoxon, Individual comparisons by ranking methods author (s): Frank Wilcoxon published by : International Biometric Society, Biometrics 1 (6) (1945).

[58] M.F. Fuller, W.J. Conover, J.D. Gibbons, Practical nonparametric statistics, Statistician 22 (4) (1973), https://doi.org/10.2307/2986830.

[59] C.J. Ferguson, An effect size primer: a guide for clinicians and researchers, Prof. Psychol. Res. Pr. 40 (5) (2009), https://doi.org/10.1037/a0015808.

[60] S. Seabold, J. Perktold, Statsmodels: Econometric and Statistical Modeling with Python, *Proceedings of the 9th Python in Science Conference*, 2010, https://doi.org/10.25080/majora-92bf1922-011.

[61] G. Norman, Likert scales, levels of measurement and the 'laws' of statistics, Adv. Health Sci. Educ. 15 (5) (2010) 625–632.

[62] G.M. Sullivan, A.R. Artino Jr., Analyzing and interpreting data from Likert-type scales, J. Grad. Med. Educ. 5 (4) (2013) 541–542.

[63] S.E. Harpe, How to analyze Likert and other rating scale data, Curr. Pharm. Teach. Learn. 7 (6) (2015) 836–850.

[64] M. Rhemtulla, P.É. Brosseau-Liard, V. Savalei, When can categorical variables be treated as continuous? A comparison of robust continuous and categorical SEM estimation methods under suboptimal conditions, Psychol. Methods 17 (3) (2012) 354.

[65] International Organization for Standardization, ISO/CIE 11664–2:2022, Colorimetry — Part 2: CIE Standard Illuminants. Geneva, Switzerland, 2022.

[66] J. Wiendold, evalglare 2020, 2026 [Online]. Available: https://www.radiance-online.org/learning/documentation/manual-pages/pdfs/evalglare.pdf/view.

[67] F. Tartarini, S. Schiavon, Pythermalcomfort: a Python package for thermal comfort research, SoftwareX 12 (2020), https://doi.org/10.1016/j.softx.2020.100578.

[68] F. Tartarini, S. Schiavon, T. Cheung, T. Hoyt, CBE thermal comfort tool: online tool for thermal comfort calculations and visualizations, SoftwareX 12 (2020), https://doi.org/10.1016/j.softx.2020.100563.

[69] M.B.C. Aries, J.A. Veitch, G.R. Newsham, Windows, view, and office characteristics predict physical and psychological discomfort, J. Environ. Psychol. 30 (4) (2010), https://doi.org/10.1016/j.jenvp.2009.12.004.

[70] C. Karmann, J. Wienold, J.A.Y. Garreton, A.M. Villalba, A.E. Pattini, M. Andersen, User evaluations of fabric shades with sun in the field of view: glare model performance and implications for EN14501 classification, Build. Environ. 282 (2025) 113259.