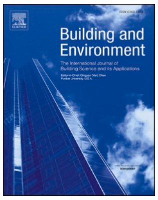
Building and Environment 228 (2023) 109707

Contents lists available at ScienceDirect

Building and Environment

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



User assessment of fabric shading devices with a low openness factor

Caroline Karmann [a,b,*], Giorgia Chinazzo [c], Andreas Schüler [d], Krishna Manwani [d], Jan Wienold [a], Marilyne Andersen [a]

[a] Laboratory of Integrated Performance in Design (LIPID), École Polytechnique Fédérale de Lausanne (EPFL), Switzerland
[b] Laboratory of Architecture and Intelligent Living (AIL), Karlsruhe Institute of Technology (KIT), Germany
[c] Department of Civil and Environmental Engineering, Northwestern University, Evanston, USA
[d] Solar Energy and Building Physics Laboratory (LESO PB), École Polytechnique Fédérale de Lausanne (EPFL), Switzerland

ARTICLE INFO

Keywords:
Discomfort glare
View out
Fabrics shading
User assessment
Daylight
Occupant behavior

ABSTRACT

Providing adequate glare protection and a view to the outside through fabric shading devices is challenging because these two objectives require conflicting material properties for a fully lowered shading. In a semi-controlled office-like experiment involving 32 participants, we investigated four types of neutrally-colored fabrics (charcoal and gray) with Openness Factors (OF) smaller than 7% focussing on view clarity, discomfort glare with the sun in the field of view, and participants' behavior when it comes to blind control. The results show that fabrics with OF$<3\%$ could provide adequate glare protection but no satisfactory view out. The charcoal-colored fabric with OF$>6\%$ resulted in lower glare protection but higher quality of view out. Our results show inconsistencies with the EN14501 blind classifications for glare and visual contact (i.e., view clarity), but acceptable agreement with the view clarity index, especially for the fabrics with the highest light transmittance. During the final session, three quarters of participants raised the blinds to allow an average of 10° view to the outside, reporting as primary motivations the wish for more light and view out. Despite the relatively small rise of the fabric (15% of the total shade), daylight levels and view out were significantly improved, suggesting that operable blinds should not be controlled nor described according to the "all-or-nothing" approach. The change in fabric height did not compromise glare perception. These results suggest that if the control of shading height is effectively provided to occupants, then the fabric material could be selected primarily based on glare requirements.

1. Introduction

Windows perform essential functions in the built environment, primarily giving visual access to (and sometimes direct air exchange with) the outdoors and enabling daylight penetration. Access to natural light has been shown to positively impact work performance [1,2] and occupant preference, with approximately 80% of occupants stating that they prefer daylight to electric lighting [3–7]. While daylight is highly desirable, it is also necessary to protect building occupants against excessive daylight and glare, and ensure that solar radiation is managed properly to reduce overheating risks. Designers have been resorting to various shading solutions towards this end, including fabric shades, venetian blinds, switchable electrochromic (EC) glazing, or ceramic fritted glass with embedded decorative patterns. Among these, shading fabrics offer many practical advantages to both designers and occupants: they remain commonly perceived as low-tech systems and are therefore easy to find in a wide range of variations and potentially inexpensive. Shading fabrics also offer a high level of customization to designers. For instance, the color, openness factor (OF, i.e., the fraction of holes to the total area), visible light transmittance (τ_V), and reflectivity are all properties that can typically be customized. From the occupant's perspective, control over fabric blinds is also possible as long as they are installed on a manually operable system (e.g., roller blind), as this gives the occupants the ability to adapt their environment to their needs.

The European standard EN14501:2021 [8] assigns fabrics to classes related to their anticipated impact on visual comfort based on six criteria: "darkening performance", "glare control", "night privacy", "visual contact with the outside", "daylight utilization" and "rendering of colors". Classes are further refined into 5 levels: class 0 ("very little effect"), class 1 ("little effect"), class 2 ("moderate effect"), class 3 ("good effect") and class 4 ("very good effect"). The criteria “glare control”, “visual contact with the outside”, and “daylight utlization” are all

---

* Corresponding author. Laboratory of Architecture and Intelligent Living (AIL), Karlsruhe Institute of Technology (KIT), Germany.
E-mail address: caroline.karmann@kit.edu (C. Karmann).

https://doi.org/10.1016/j.buildenv.2022.109707
Received 20 June 2022; Received in revised form 15 September 2022; Accepted 11 October 2022

related to visual comfort under daylight conditions, and all depend on the fabrics' visual transmittance, either normal-normal ($\tau_{v,n\text{-}n}$), normal-diffuse ($\tau_{v,n\text{-}dif}$), or diffuse-hemispherical ($\tau_{v,dif\text{-}h}$) (see supplementary material). Based on this standard, only fabrics with low $\tau_{v,n\text{-}n}$ (<0.05) and low $\tau_{v,n\text{-}dif}$ (<0.25) would be able to meet the criteria for glare protection. However, these same indices must be high to meet the criteria for visual contact.

The present study is based on this contradictory classification and focuses on fabrics with a "low OF" (here defined as less than 7%), installed on a manually operable roller blind system. The following section brings together key literature on the importance of view out, glare protection, and occupant control of their visual conditions, which are the parameters considered here in evaluating different shading options.

1.1. State of the art

Research in environmental psychology and building science has shown the positive impacts of providing building occupants with a view out [9–15]. Known effects typically include increased workplace satisfaction, productivity, cognitive performance, stress modulation, and patient recovery time [1,9,10,12,13,16–20]. In addition, views also satisfy fundamental human needs for visual information about location, time, weather, and activities outside the building [21,22]. Research on view out has emphasized the importance of having multiple layers (e.g., ground, landscape, and sky) in one's field of view (FOV) [23,24], a constraint meanwhile implemented in EN 17037:2018 [25]. More recently, Ko et al. developed a framework for assessing the quality of window views that has the advantage of being based on three primary variables: "view content" (the assessment of visual features seen in the window view); "view access" (the measure of how much of the view can be seen through the window from the occupant's position); and "view clarity" (the assessment of how clear the view content appears in the window view when seen by an occupant) [26]. Of particular interest in the context of shading devices is the view clarity, which reminds us of the "visual contact with the outside" defined by the EN14501:2021 standard, and which raises many considerations such as identification and color rendering of objects located outside.

Contrary to the view out quantification, glare has been characterized and modeled for many more years. The International Commission on Illumination (CIE) defines glare as the "condition of vision in which there is discomfort or a reduction in the ability to see significant objects, or both, due to an unsuitable distribution or range of luminances or to extreme contrasts in space or time" [27]. This definition encompasses both the notion of disability glare, which impairs vision, and of discomfort glare also defined as "glare that causes discomfort without necessarily impairing the vision of objects" [28]. Discomfort from daylight glare is common in workspaces, where the either the total amount of light reaching the eye or the luminance contrast between the visible light source and the eye's adaptation level can be too high. It represents a source of disturbance for building occupants [9] and can affect one's perceived level of productivity [29]. Multiple metrics have been established to characterize discomfort glare from daylight from objective measurements. These can be divided into three categories [30]:

- Metrics solely based on the saturation effect (e.g., vertical illuminance Ev, average luminance, Simplified Daylight Glare Probability (DGPs) [31]),
- Metrics dominated by the contrast effect (e.g., Daylight Glare Index (DGI) [32], Unified Glare Rating (UGR) [33], and CIE Glare Index (CGI) [34])
- Hybrid metrics based on both effects (e.g., Daylight Glare Probability (DGP) [35], Predicted Glare Sensation Vote (PGSV) [36]).

Several studies have shown DGP to be a robust and widely reliable metric [30,37] and the same metric was also adopted for daylight glare prediction in the European standard EN 17037:2018 [25].

In recent years, the influence of shading fabrics on view out and/or glare has started to attract research interest as well. In 2015, Konstantzos et al. developed an index to describe the clarity of the view out through different types of fabrics [38]. The authors tested 14 fabrics of various OF and τ_v, which they re-measured to ensure the reliability of the fabrics' optical properties. They relied on optotype reading performance tests and subjective responses to derive the View Clarity Index (VCI), which ranges from 0 to 1, with 0 referring to perfectly diffuse fabrics and 1 to perfectly clear views. Flamant et al. critically evaluated the VCI and the visual contact categories of the EN14501:2021 in a study involving 50 participants and 9 fabrics [39]. They suggested a revised View Clarity Index (which we will refer to as VCI*) and new categories for the EN14501:2021. The VCI and the VCI* are, together with the classification of "Visual contact with the outside" from the EN14501:2021, the only metric we found to describe the clarity of the view out. Konstantzos and Tzempelikos thereafter used the same set of fabrics to study discomfort glare from the sun [40]. While that paper was primarily oriented toward glare metrics evaluation, their results showed that fabrics of~7% (τ_v of 0.07 and 0.13) could not prevent discomfort from glare from the sun in the participant's field of view.

In parallel, Chan et al. developed a systematic method for selecting roller shade properties for glare protection, based on measurements (using the saturation-based DGPs metric) completed by simulations [41]. Their results showed that OF below 6% and τ_v below 0.10 would be needed to remain with an annual discomfort glare frequency below 5%. Garretón et al. characterized roller blinds with the sun in the FOV based on physical measurements of nine fabrics [42]. They relied on manufacturers' data for the fabrics' OF and τ_v and DGP for glare assessment. Their results showed that OF~5% (τ_v of 0.07 and 0.13) could prevent discomfort due to glare from the sun in the participants' FOV. We should note that these studies show some inconsistency in the necessary optical properties required of fabrics to reach comfort regarding glare, which highlights the need for more extensive testing of fabrics – particularly in the OF<7% range – to better understand where the comfort threshold lies.

Following the observation that more than one aspect of comfort is needed to agree on the adequacy of a fabric in addressing visual comfort [37], Chan et al. looked simultaneously at annual continuous daylight autonomy and glare (DGPs) through measurements and simulation [41], and Garretón et al. investigated view out (VCI), discomfort glare (DGP), and useful daylight illuminance (UDI) through measurements [42]. In both studies, the authors confirmed the need for a trade-off between illuminance and glare requirements but none of the two studies involved occupants.

Overall, in the various studies on fabric shading mentioned above, while fabric shadings are commonly installed in an operable roller system, the questions of occupant control of the blinds and their preferences were always left out of the picture. The fabrics were considered entirely down, ignoring the possible change of fabric height on indoor illuminance, the participant's potential desire for views out and/or for a connection to the outside, and discarded the influence of glare. Literature has repeatedly, however, emphasized the influence of occupant daylight control on their satisfaction [29,43,44]. Van den Wymelenberg, for instance, reviewed the patterns of occupant interaction with window blinds [45], which was not solely focused on fabrics but also on venetian blinds. Among the identified research gaps, this paper listed the need to adequately address "blind occlusion" that shall reflect both "blind height and tilt" (in the case of venetian blinds) as both factors considerably affect view out, daylight provision, and glare. In the case of fabrics, such occlusion factors would need to account for both the height and the clarity. Control over blinds also allows occupants to increase the amount of view, which can in turn influence glare perception. As noted by Tuaycharoen and Tregenza, people with a view rated as more desirable showed a lower glare sensation than those with a less desirable view, despite the fact that the DGI remained constant [46,47]. While not formally included in the proposed view quality index, Ko et al. also highlighted the need to address the dynamics of shading systems since this occlusion changes view clarity [26]. To our knowledge, no papers in the literature yet have, however, jointly discussed discomfort glare, control of shading fabric, and view out.

1.2. Objectives

The objectives of this study are threefold: (1) assess the effectiveness of low OF fabric shadings at addressing view clarity and glare protection and compare the findings with the rating of the EN14501:2021 as well as with the VCI, (2) assess the effect of manual blind usage on glare

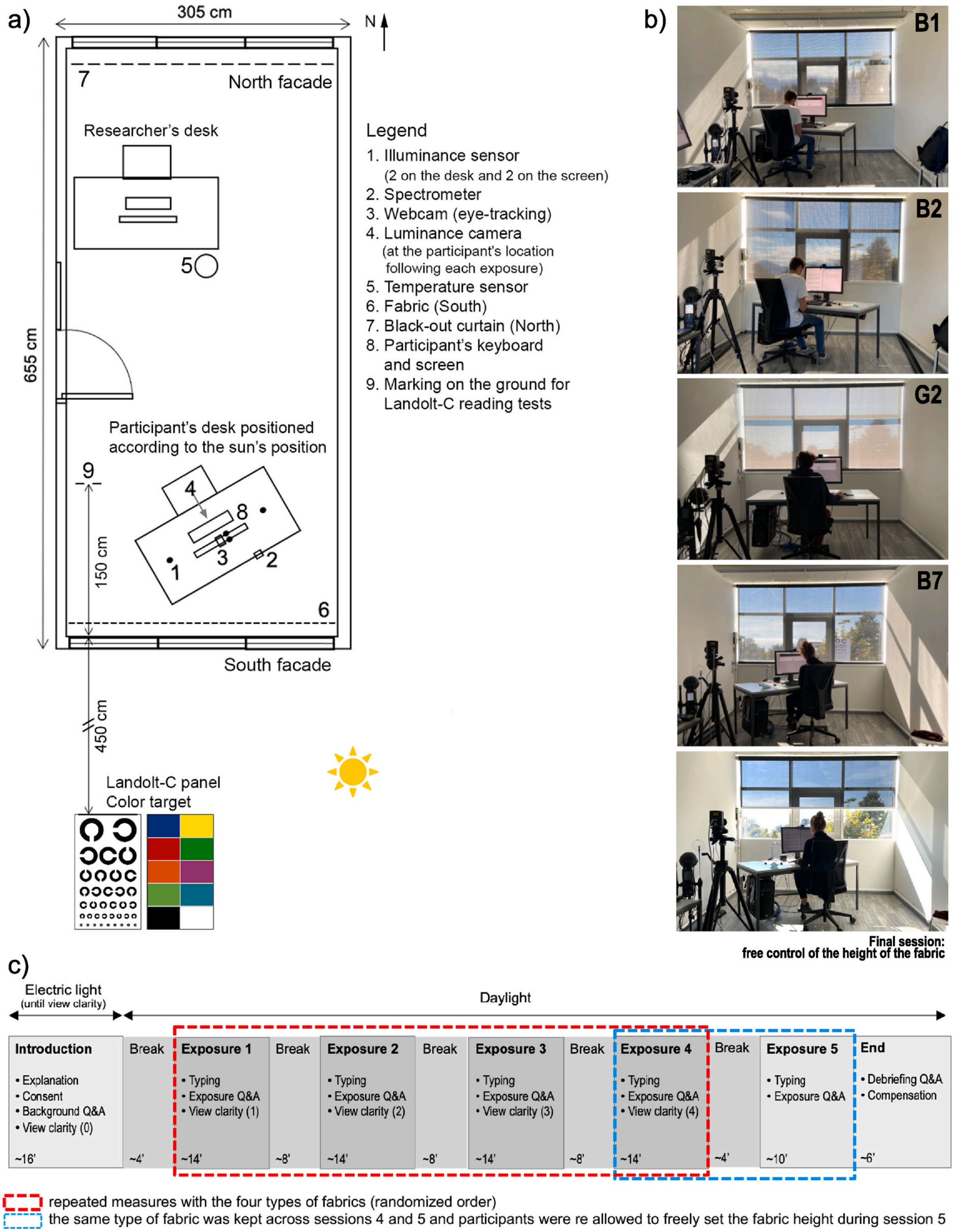


Fig. 1. a) Test room layout; b) Photographs of the fabrics during the test sessions; and c) experimental protocol. The labels B1, B2, L2, B7 refer to the four fabrics of this study whose properties are detailed in Table 1.

perception, and (3) evaluate occupants' motivation as it goes to manual control of shading fabrics.

2. Method

We conducted human subjects experiments in a semi-controlled office-like setup with pre-defined visual scenarios, involving four types of fabrics installed on an operable roller blind system on the South opening of the test chamber. The four shading fabrics differ in their properties (i.e., OF, τ_v and color). Following a psychophysical approach, participants were asked to provide subjective evaluations of the experienced conditions, and, in some sessions, were invited to change the blind position while indoor environmental conditions were monitored. The study was conducted between December 2020 and October 2021 under stable sunny sky conditions with critical sun positions, i.e., located in the center of the participants' FOV (right above their computer screen). The experimental procedure was approved by the Human Research Ethics Committee at EPFL (ref. No. HREC 035–2019).

2.1. Experimental design

The study follows a single-blind, within-subject design with repeated measurements, where every subject is exposed to five visual scenarios experienced as a sequence of exposure sessions (see Fig. 1c). The first four sessions involved specific glare exposures using four low OF shading fabrics fully down (i.e., covering the entire window) experienced by the participants in a randomized order. In the fifth session, the participants' behavior in terms of blind usage was assessed using whatever fabric they were exposed to in the previous (fourth) session. Each participant could then choose to keep the fabric down or raise it to the height they prefer. The within-subject design chosen for this study required fewer participants and increased the statistical power. We derived the sample size from Gpower calculator tool 3.1.9.4 [48] for repeated measurements, within factors test with one group and four measures, assuming an effect size of 0.30, an alpha of 5 and a power of 0.95. This calculation resulted in a sample size of 24 participants.

We selected young, healthy participants (between 18 and 30 years old) with normal color vision, full or corrected vision, and no known visual impairment (e.g. cataract). We required them to have an English proficiency level (C1 or higher), to not use drugs, with no abuse of alcohol. Potential participants that studied disciplines related to the investigated field (i.e., architecture or civil engineering) were excluded to avoid response bias. We paid the participants at the end of the experiment.

In total, 33 participants took part in the experiment. Some experimental sessions were not considered in the analysis due to unstable weather conditions. We excluded sessions during which variations in outdoor global horizontal irradiance (GHI) exceeded 25%: GHI was measured each second by a pyranometer located on the EPFL campus. The formula for calculating the variation range is: $[(GHI_{max} - GHI_{min})/GHI_{mean}]$ though whenever only a few data points were found beyond the 25% range in short bursts and during the typing task period, the results were kept as long as these were followed by stable conditions during the questionnaire period. With these filtering criteria, we ultimately had to remove 19% of the experimental sessions for sessions 1 to 4 and 27% for sessions 1 to 5 (as we wanted to have our criteria verified over two consecutive sessions). Of the 33 participants, we could keep partial data from 32 participants for sessions 1–4 and 24 participants for sessions 4–5.

2.1.1. Test facility

We conducted the experiments in a test unit (d*w*h = 6.55 m*3.05 m*2.65 m) located on the EPFL campus in Lausanne, Switzerland. The room is North-South oriented and has openings on the North and the South facades (window-to-wall ratio of 62% with a glazing transmittance of 79%) but the North façade was entirely covered with an internal black-out curtain (white color towards the inside of the space). The South façade was equipped with movable external venetian blinds. The shading fabrics were mounted inside the space on the South façade on a roller blind with a velcro, which allowed to switch the fabrics quickly. The roller blind system also allowed for a manual control of the fabric's height. A layout of the space is shown in Fig. 1a).

2.1.2. Selection of the types of fabrics

We looked for four fabric types from which we would expect either good glare protection or good visual contact according to the classification categories of EN14501:2021 (see Ref. [8], Tables 7 and 9 of the standard). We chose fabrics of different openness factors (≤5% originally desired as this is the upper threshold in EN14501:2021 for achieving some glare protection) and brightness (dark and light gray). We obtained the detailed optical properties from the manufacturer, which allowed us to move away from the rounded data (to 0.01) of the description sheets. In addition, we conducted measurements using the goniophotometer from Realistic Graphics Lab (RGL), EPFL to derive $\tau_{v,n-h}$ and $\tau_{v,n-n}$, which we then validated with measurements using the integrative sphere from the Solar Energy and Building Physics Laboratory (LESO-PB), EPFL.

The goniophotometer used to derive the visual properties of the fabrics is a scanning goniophotometer, Model "pgII" by Pab Advanced Technologies Ltd [49], which measures the Bidirectional Transmittance Distribution Function BTDF and allows intensive refinement of selected regions of interest – in our case in beam direction. In order to calculate the hemispherical transmittance $\tau_{v,n-h}$, we mathematically integrated the measured BTDF-data over the hemisphere using the so-called "mountain-tool" provided by the pgII manufacturer. In a nutshell, the mountain tool applies linear interpolation through Delaunay triangulation. To derive normal-normal transmittance $\tau_{v,n-n}$, we integrated the BTDF over a 6° cone around the beam [50]. We also measured the BTDF for different angles of incidence (between 60° and 75° in 1° steps) and derived $\tau_{v,n-n}$ by also integrating in a 6° cone around the beam. The angle when $\tau_{v,n-n}$ falls below 0.5% is called "cut-off-angle" [8], indicating that sun-rays are nearly completely blocked by the fabric.

We performed additional transmittance (specular and diffuse) measurements to confirm the accuracy of goniophotometer measurements. To this end, specular (direct) transmittance was determined using a Zeiss diode array spectrometer in the wavelength range from 350 to 2100 nm. In this spectrometer, the light source consists of quartz tungsten halogen and UV fluorescent lamps in an aluminum enclosure with a diffusing front glass. A collimator is then used to concentrate the transmitted light onto an optical fiber that guides the light to two diode array spectrometers, UV–Vis and NIR (MCS 601 and MCS 611 from Zeiss) [51]. In addition, diffuse transmittance was measured with a light trap in an integrating sphere at an angle of incidence of 8°. It can be noted that both source and spectrophotometer exhibited a thermal drift of ±0.5%, regardless of transmittance measurement. The spectral properties of these fabrics were then used to determine the coefficient of solar visible light transmittance (τ_v) using the equation from EN 410 standard [52]:

$$\tau_v = \frac{\sum_{\lambda=380\ \mathrm{nm}}^{780\ \mathrm{nm}} D_\lambda \tau(\lambda) V(\lambda) \Delta\lambda}{\sum_{\lambda=380\ \mathrm{nm}}^{780\ \mathrm{nm}} D_\lambda V(\lambda) \Delta\lambda}$$

where D_λ represents the relative spectral distribution of the CIE standard illuminant D65, $\tau(\lambda)$ is denoted as the spectral transmittance, $V(\lambda)$ is the spectral luminous efficiency for photopic vision defining the standard observer for photometry, and $\Delta\lambda$ represents the wavelength interval. It is worth noting that, in diffuse transmittance measurements, the surface area of the entrance port is relatively small compared to the total sphere surface area (i.e., ratio of entrance port area to sphere surface area is 1/144). Therefore, the effect of internal reflection from the sample is negligible with respect to the thermal drift of spectrophotometer.

Finally, we noted that the reported OF reported by the manufacturer was often higher than $\tau_{v,n-h}$, which is physically impossible. We tested

Table 1

Fabric properties based on manufacturer's data and measured data, and derived indices based on the fabric's properties.

Fabric type	Color	Fabric properties						Derived classes and indices[d]				
		$\tau_{v,n\text{-}n}$[a] (6°)	$\tau_{v,n\text{-}dif}$[a]	$\tau_{v,n\text{-}h}$[a]	$\tau_{v,dif\text{-}h}$[b]	OF	Cut-off angle[c] (H/V)	EN14501 Glare class	EN14501 Visual contact class	EN14501 Daylight utilization class	View clarity index (VCI)	Revised View clarity index (VCI*)(e)
B1	charcoal	0.017	0.002	**0.019**	0.002	**1.7%**	**50**° (62°)	4[g]	2	0	0.55	0.59
B2[f]	charcoal	0.023	0.003	**0.026**	0.017	**2.43%**	61° (**69**°)	3	2	0	0.57	0.63
G2	gray	0.037	0.031	**0.068**	0.045	**2.43%**	**61**° (69°)	1	2	1	0.21	0.53
B7	charcoal	0.061	0.007	**0.068**	0.053	**6.1%**	**62**° (69°)	0	3	1	0.72	0.71

Acronyms: $\tau_{v,n\text{-}h}$ = Visible light transmittance normal-hemispherical (a.k.a., τ_v, since hemispherical = total), $\tau_{v,n\text{-}n}$ = Visible light transmittance normal-normal, $\tau_{v,n\text{-}dif}$ = Visible light transmittance normal-diffuse, $\tau_{v,n\text{-}dif}$ = Visible light transmittance diffuse-hemispherical.

[a] Value derived from measurements of the Bidirectional Transmittance Distribution Function (BTDF), conducted with a scanning goniophotometer (Model "pgII" by Pab Advanced Technologies Ltd [49]) at the EPFL.

[b] Values provided by the manufacturer.

[c] The cut-off angle was measured in the horizontal (H) and vertical (V) directions. Since B2 was mounted in the transversal direction, we relied on the value of the vertical cut-off angle (bolded).

[d] We relied on the goniophotometer measurements to derive the EN14501 glare class, the EN14501 visual contact class, the VCI, and on the manufacturers' data to derive the EN14501 daylight utilization class.

[e] The revised VCI is valid for transmittance factors $0.01 \leq \tau_{v,n\text{-}n} \leq 0.10$ and $0.01 \leq \tau_{v,n\text{-}dif} \leq 0.10$. Following the measured fabric properties, VCI* might not be applicable for B1 B2 and B7.

[f] B2 was positioned in the transversal direction because of the availability of the product for the desired width.

[g] According to the standard EN14501, the glare class moved up by one because of the low cut-off angle.

the diffraction of the charcoal fabrics using a laser. Since we did not observe any diffraction, we considered OF equal to $\tau_{v,n\text{-}n}$ for the dark fabrics and assumed that our gray fabric (labeled as G2) had the same OF as the charcoal fabric from the same production series (B2). We decided to rely on the values from the goniophotometer measurements to derive the EN classes and VCI.

The manufacturer's data and the details of these tests are reported in the supplementary material while the fabric properties used to calculate the EN14501:2021 classes, the VCI and the VCI* are summarized in Table 1. The VCI is calculated from OF and τ_v ($=\tau_{v,n\text{-}h}$) and is based on Eq. (1) (applicable for OF≤τv) [38], and the VCI* is calculated from $\tau_{v,n\text{-}n}$ and $\tau_{v,n\text{-}dif}$ and is based on Eq. (2) [39].

$$VCI = 1.43 \bullet OF^{0.48} + 0.64 \bullet \left(\frac{OF}{\tau_v}\right)^{1.1} - 0.22 \tag{Eq. 1}$$

$$VCI^* = -0.461 \bullet e^{-66.6 \bullet \tau_{v,n-n}} - 0.467 \bullet \frac{\tau_{v,n-dif}^{0.296}}{\tau_{v,n-n}^{0.222}} + 0.921 \tag{Eq. 2}$$

2.2. Experimental procedure

Considering the orientation of the chamber, the sun position over time, and the location of surrounding buildings, we could only conduct our experiments between October and March from 9:00 a.m. to 3:00 p.m. to ensure that each of the participants had the sun in the FOV while sitting at their desk. The complete procedure lasted about 2 h and is summarized in Fig. 1c). A maximum of two sessions were possible in one day, with one participant at a time.

Each test consisted of an introductory phase, four exposure sessions with different shading fabrics fully down (presented in randomized order), and a fifth exposure session keeping the same shading fabric as in the fourth exposure but offering the participants the opportunity to control its position (height). For each exposure, we positioned the participants' desk so that the sun stayed in the center of their FOV without being shaded by the window frames. Each exposure session lasted between 12 and 15 min in which participants performed three tasks: (1) A typing task, (2) an exposure questionnaire, and (3) a view clarity task. The typing task lasted about 5 min and was meant to expose the participant to a typical office task before completing the survey. The text to be re-typed was shown on the same screen as the editor software used for the task (screen split into two). The exposure questionnaire followed the typing task. On average, participants needed about 5 min to complete the exposure questionnaire. The view clarity task consisted in an optotype reading task requiring the identification of Landolt-C directions of different sizes per line printed on a poster located outside of the chamber. During the introduction phase, this task was introduced without fabrics to verify the participant's vision (baseline) but was repeated in sessions 1 to 4 (fabrics fully down). The change of the position of the fabric by the participants in session 5 was only possible at the beginning of the session (before the typing task), and participants were not allowed to re-adjust the chosen height during the rest of the session. The exposure survey of this last session involved additional questions to understand the reasons behind the subjects' motivation to control the fabrics. During the breaks between each of the exposure sessions, participants remained in the room. We asked them to sit on a chair located at the back of the room, blindfolded them, and gave them a headset with a music player so they could listen to music while we took measurements, adapted the position of the desk, and changed the fabrics.

Daylight was the only source of light in the room during the experimental sessions. Although the test room was equipped with dimmable electric lights, we did not want to bring in an additional bias due to the potential impact of electric lighting on glare. The electric lights were thus only used during the introductory phase. On the other hand, while we generally blocked the light from the North façade with a black-out curtain, we also wanted to ensure an illuminance of about 300 lux on the participants' desks to be consistent with what is considered an acceptable lighting level for office tasks. Therefore, for the fabric types with low τ_v and OF, we usually had to partially open the black-out curtain on the North I as well as the side door (neither of them being in the FOV of the participants) so as to increase brightness.

2.3. Measurements

2.3.1. Environmental measurements

We utilized the following instruments to record the visual conditions in the space:

- One luminance camera *LMK 98–4 color High-Resolution* camera with a *Dörr Digital Professional DHG* fish-eye lens (equidistant projection) and a neutral density filter ND4, which was mounted on a tripod.
- Two handheld illuminance sensors *LMT Pocket-Lux 2* (Class B certified according to the DIN5032 part 7, with a total error <7%), one of

Table 2
Items from the exposure questionnaires we used to assess participants' perception of glare and their fabric preferences.

Category	Question	Type of scale and response items
Glare	At the moment, how would you describe glare in your field of view?	Osterhaus-Bailey (4 pt) Imperceptible, Noticeable, Disturbing, Intolerable
View clarity	How clear is your view to the outside through the window and roller blind?	Interval (11 pts) 0 (Not clear at all), 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 (Very clear)
Color perception	To what extent do you agree or disagree with the following statement: "I can distinguish the color of the moving cars on the street" "By looking outside the window, the environment and the elements look natural"	Likert agreement (7 pts) −3 (Strongly Disagree), −2, −1, 0, 1, 2, 3 (Strongly Agree)
Shading fabric – motivation for control (session 5 only)	If the participant raised the roller shading: Why did you change the position of your shading device?	Multiple choice (check all that apply): - I liked to have a change - More light in the room - More light on my desk - More light on my screen -A better view out -Other (free text field)
	If the participant raised the roller shading: Why did you decide not to change the position of your shading device?	Free text field
Shading fabric – wish for change	Assume you have to work all day from this space, would you like any changes to the shading configuration?	Multiple choice (only one can be selected): - No, I am comfortable and do not require changes of the shading configuration - No, even though I am slightly uncomfortable - I would like to freely roll up/down the fabric shading - I would like to change the fabric (color/openness) - I would like to change the type of shading device (e.g., use venetian blinds instead) - I have no preference

which was attached to the tripod right next to the luminance camera lens, and the other was free to be positioned as desired.

The tripod was manually positioned at the participant's location and the camera was raised to the participant's eye level to capture high dynamic range (HDR) images. This procedure was implemented just before and just after each exposure with the participant's screen on. We commonly relied on the image taken right after the exposure, which we judged to be more representative, and only used the images taken before the exposure as a substitute in the case of camera error or sudden weather change. We derived the commonly used glare prediction models, namely DGP, CGI, UGP and DGI, by running Evalglare version 3.02 [53,54] with default settings on the calibrated HDR images. The illuminance sensor attached on the tripod was used to simulataneously capture the vertical illuminance at eye level (Ev), while the second sensor was placed on the participant's desk to capture the desk illuminance during the time interval that the luminance camera was taking measurements (we took the average of the recorded value).

2.3.2. *Subjective measurements*

The participants provided their personal information and subjective feedback about the environment by completing three types of web-based questionnaires: (1) a background questionnaire completed during the introduction phase, (2) exposure questionnaires completed right after the typing task during each exposure session, and (3) a debriefing questionnaire completed at the very end.

The background questionnaire was used to collect baseline data from each participant. It involved e.g., demographics (e.g., age, gender, eye color), participant's mood, feelings, and physical state at the time of the testing, their perceived sensitivities in terms of heat, cold, bright light, and view to the outdoors. These questions were included to evaluate potential confounding factors, if any. The exposure questionnaires included questions about overall comfort, thermal comfort, visual comfort, view clarity, and color perception (see key questions in Table 2). The questions were answered based on either binary, categorial (Likert), or ordinal scales. We provided the definition of glare as "the sensation of visual discomfort caused by differences between light and dark areas, or by excessive brightness in your field of view" to the participants to minimize misunderstanding. In exposure session 5, we asked an additional question about motivation for the (non)control of the fabric. Finally, the debriefing questionnaire was used to obtain additional information about general comfort during the experience, satisfaction with the view, and open fields for further comments.

Subjective questions on view clarity were complemented with a series of objective measurements. These encompassed a reading performance test using Landolt-C optotypes (acuity performance) and objective color fidelity characterization of color samples placed outside the test room.

2.3.3. *Acuity performance test*

For the acuity performance test, we asked the participants to identify given orientations of Landolt-C optotypes printed in different sizes on a poster attached to a panel located outside the test room. The Landolt-C is a visual acuity test consisting of a ring with a gap (looking like the letter "C") oriented in different ways, more specifically with the gap facing left, right, bottom, top and the 45° positions in between. The test involves the determination of the orientation of the gap of different letters, whose dimensions decrease in each line. The distance between the target panel and the observer was 6 m, with the window (and fabric) located in-between (1.5 m from the participants and 4.5 m from the panel outside). This set-up was inspired from a previous study by Konstantzos et al. [38], where the target panel was also placed outside and 4.5 m away. In that study, two distances between the observer and the window were tested (1 and 2.4 m) and, while the authors did find an interaction effect between the fabric and the viewing distance (at least for some fabrics), they noted that the ranking of the fabrics was not altered by the distance between observer and window, which led us to consider one distance only. The acuity performance task of our study was conducted at the end of the introduction phase (without fabrics) and following each exposure with the shading fabrics fully down (exposures 1 to 4). All subjects were conducting the tests while standing at the same position (marked as "9" in Fig. 1a). We used different posters with various orientations of the Landolt-C optotypes that we changed between each exposure. The size of the optotypes was determined based on the Snellen's fraction so that the smallest Landolt-C (bottom line) corresponds to a vision of 6/12 and the largest Landolt-C (top line) corresponds to a vision of 6/120, with increments were set at 6/24.6/36, 6/48, 6/60, 6/90. These sizes were set so that participants could read the smallest line in the baseline condition (i.e., no fabric) but would likely fail to properly identify the optotypes in the middle intervals depending on the type of fabric. There were 7 lines on the posters and each line where the Landolt-C directions were all correctly identified was rewarded with 1 point, which led to results ranging from 0 to 7.

2.3.4. *Color fidelity characterization*

For the color fidelity characterization, we calculated the color shift of ten color samples, placed outside of the test room on the same target as the one used for the Landolt-C, by comparing their color coordinates measured with and without the fabrics. Conventionally, the color fidelity is related to the accuracy with which the color appearances of objects illuminated with a specific light source match their appearances under a reference illuminant (e.g., D65) [55]. In our case, the reference measurements corresponded with those without fabrics. For each color sample, we derived the CIE XYZ color coordinates from color-HDR images captured with the LMK camera and elaborated through the labsoft software [56]. The images were captured on October 23rd, 2021, between 9:45 a.m., and 10:07 a.m., i.e., right before one experimental session involving human participants, and on October 24th, 2021, between 2:45 p.m. and 3:08 p.m., i.e., right after one of these sessions. We captured an image of the color samples through each fabric immediately before or after capturing a reference image of the color samples without the fabric. All the images were captured with the sun directly shining on the fabric. However, we decided to also capture images in the shaded area of the fabrics, where the window mullion casts local shadows, to somewhat replicate Konstantzos et al.'s "cloudy" scenario [38] due to the described influence of sky conditions on view clarity for some of the considered fabrics. These "shaded" images were only taken in the morning due to the sun's position, casting much larger shades from the mullion on the fabrics. The CIE XYZ coordinates were converted into the CAM02-UCS color space [57] with the conversion equations described in TM-30-20 [58]. The CAM02-UCS color space, based on the CIECAM02 color appearance model [59], is a uniform color space defined by the J'a'b' directions, indicating the red-green, yellow-blue, and lightness dimensions, respectively [60]. The CAM02-UCS was chosen over other color spaces (e.g., CIE 1931 xy chromaticity) because it is the most suitable for computing chromaticity differences due to its well-documented uniformity [57]. Chromaticity differences can be computed as Euclidean distances considering all three directions of the color space (J'a'b'), denoted as ΔE_{Jab} [58]. However, considering the nature of our measurements and comparisons (of multiple color samples, fabrics, and time of the day) and the fact that about 95% of the total color shift happens to be in the a'b' directions [60], we decided to consider changes in the a'b' directions only. This choice was also driven by the fact that we investigated the color perception of participants, and such perception is strongly correlated with chroma and hue, functions of a' and b' [61,62]. The obtained color coordinates were plotted as single coordinates in the two-dimensional (a', b') graph for each fabric, highlighting the difference with and without fabric for each color. The proposed method is meant to quantify the relative shift in color brought by the different types of fabrics. All calculations and data visualizations were performed with a custom script in RStudio [63].

2.4. Statistical analysis

We relied on descriptive statistics to summarize most of our results. We reported the mean, median, standard deviation, and interquartile ranges through boxplots and tables and utilized barplots to indicate the spread of votes. We verified the normality of our samples using the Shapiro-Wilk test, performed statistical tests for repeated measures, and reported statistical significance and effect size for the Wilcoxon two-sample rank-sum test. We relied on Ferguson's thresholds to interpret the strength of association r, where 0.2 is considered a small association, 0.5 a moderate association, and 0.8 a strong association [64]. We performed our analysis in R [65] and Rstudio [63].

3. Results

The results are divided into four parts pertaining to the general thermal conditions in the space (3.1), the view clarity, including the fidelity of the colors seen through the fabric (3.2), the assessment of discomfort glare with the sun in the field for fabrics down (3.3), and free-

Table 3
Re-scaled subjective and objective performance metrics compared to VCI, VCI*, the EN14501 visual contact classes and proposed visual contact classes.

	Optotype test (rescaled to 0–1)	View clarity votes (rescaled to 0–1)	VCI	VCI*[a]	Visual contact class[a]	Proposed visual contact class[b]
B1	0.31	0.36	0.55	0.59	2	2
B2	0.39	0.49	0.57	0.63	2	2
G2	0.27	0.25	0.21	0.53	2	1
B7	0.8	0.78	0.72	0.71	3	4

[a] The revised VCI is valid for transmittance factors $0.01 \leq \tau_{v,n\text{-}n} \leq 0.10$ and $0.01 \leq \tau_{v,n\text{-}dif} \leq 0.10$. Following the measured fabric properties, VCI* might not be applicable for B1 B2 and B7.

[b] Classes of the EN14501:2021 are defined in 5 levels according to their effect on visual comfort: class 0 ("very little effect"), class 1 ("little effect"), class 2 ("moderate effect"), class 3 ("good effect") and class 4 ("very good effect").

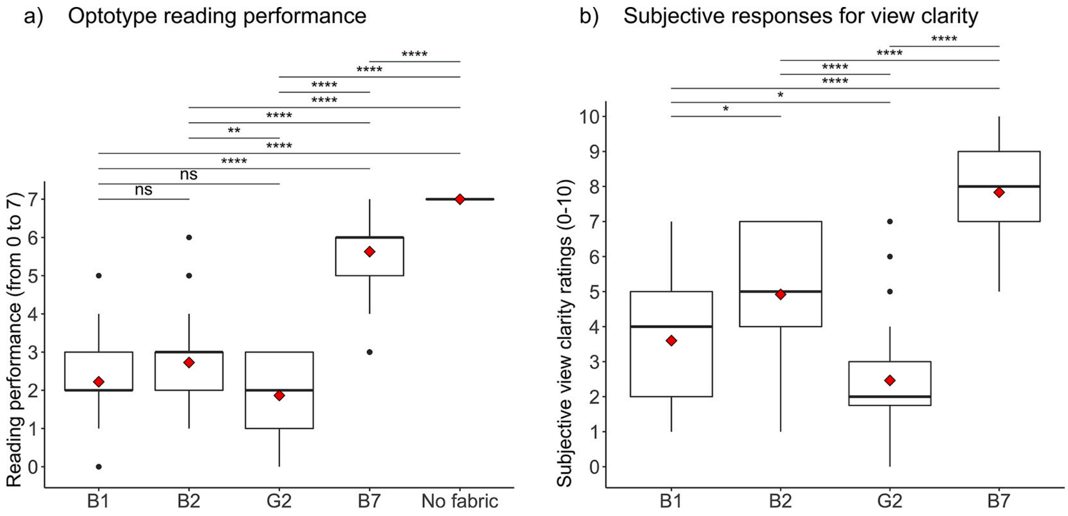


Fig. 2. a) Boxplot for the optotype reading performance, completed for all the data (n=33, Numeric scale from 0 to 7), and b) boxplot for the view clarity subjective responses (question: "How clear is your view to the outside through the blinds?" Interval scale from 0 to 7). Statistical significance levels: ****: $p<0.0001$, ***: $p<0.001$, **: $p<0.01$, *: $p<0.05$, ns: non significant.

Table 4
Pairwise comparison of the fabrics for the optotype reading test and subjective view clarity votes.

		Optotype reading test (scale: 0–7)					View clarity votes (scale 0–10)				
		mean group	mean group2	delta mean	stat. Sign. (p-value)	effect size	mean group	mean group2	delta mean	stat. Sign. (p-value)	effect size
B1	B2	2.2	2.7	−0.5	0.1791 (ns)	0.17	3.6	4.9	−1.3	**0.017***	**0.34**
B1	G2	"	1.9	0.4	0.1791 (ns)	0.16	"	2.5	1.1	**0.024***	**0.31**
B1	B7	"	5.6	−3.4	**<0.0001******	**0.83**	"	7.8	−4.2	**<0.0001******	**0.84**
B2	G2	2.7	1.9	−0.9	**<0.01****	**0.33**	4.9	2.5	2.5	**<0.0001******	**0.56**
B2	B7	"	5.6	−2.9	**<0.0001******	**0.78**	"	7.8	−2.9	**<0.0001******	**0.74**
G2	B7	1.9	5.6	−3.8	**<0.0001******	**0.86**	2.5	7.8	−5.4	**<0.0001******	**0.84**

positioning (3.4), and the participants’ preference for the fabrics and their motivations regarding their control (3.5).

3.1. General thermal comfort conditions

During the sessions, we tried to keep the indoor temperature between 20 and 22 °C and measured the indoor air temperature throughout our testing. However, our sensor being located next to the entrance door of the chamber, its reported temperature may have been affected by the fact that we often had to partially open the door to increase the daylight levels and ensure adequate ventilation (we conducted our tests during the Covid-19 pandemic). We thus decided to examine the participants’ reported thermal comfort as a way to check whether thermal conditions could have been variable enough to generate unwanted biases. This check led to the following findings: 94% of the participants voted either “slightly cool” (13%), “neither cool nor warm” (56%), or “slightly warm” (25%) on the thermal sensation scale, while the remaining 6% of the participants voted “cool” (3%) and “warm” (3%). None of the participants voted for the two extremes of “cold” and “hot”. This result is reflected in 86% of the participants judging the conditions as either “comfortable” (56%) or “very comfortable” (30%), and 14% “uncomfortable”. Given the randomization of our tests, and the fact that the majority of participants still considered the thermal conditions as comfortable, we concluded that

Table 5
Euclidean distance in the two-dimensional space (a’b’) between the color coordinates of the measurements with and without fabric. The different rows report the measurements performed, considering morning and afternoon and the shaded fabric.

	B1	B2	G2	B7
Sun on the fabric (average AM & PM)	26.60	24.40	29.30	18.98
Sun on the fabric (AM only)	27.22	24.69	28.69	19.36
Sun on the fabric (PM only)	25.97	24.11	29.90	18.59
Shaded fabric, but sun outside (AM only)	25.16	22.63	26.62	16.87
Difference no shaded-shaded (AM only)	2.06	2.07	2.07	2.49

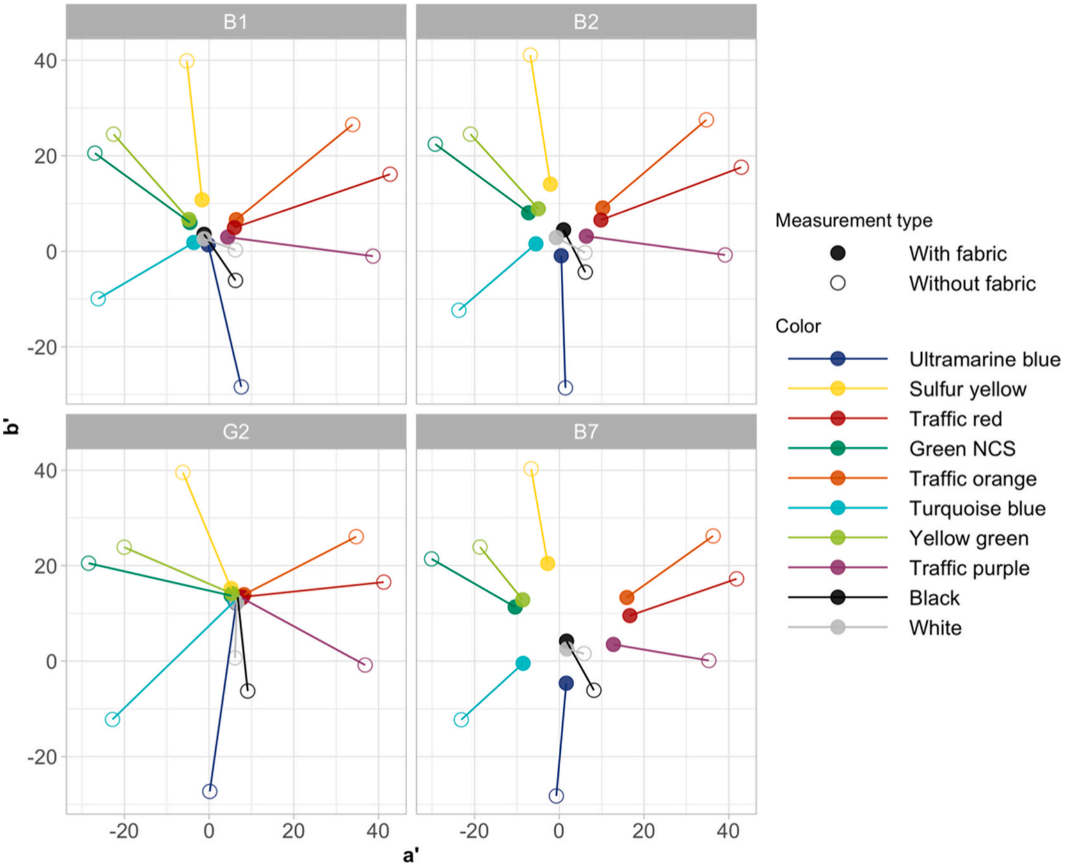


Fig. 3. A two-dimensional plot of the CAM02-UCS color space showing the color shift of the ten color samples measured with and without the fabrics for the four fabrics. Each data point represents the average values of the morning and afternoon measurements. The measurements in the shaded part of the fabrics (the "cloudy" conditions) are excluded from the plot. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

there was no evidence supporting the risk of a potential interaction effect between thermal and visual perception (i.e. to a point it could influence our results), that has been shown to be present in more extreme conditions in previous research [66,67].

3.2. *View clarity*

3.2.1. *Acuity performance*

The optotype reading test (Landolt-C) provided an objective set of responses on visual acuity throughout the fabric. The results are presented in Fig. 2a and Table 4. Considering the non-normality of this data and the fact that optotype reading was a repeated measure (within-subject), we used the non-parametric Wilcoxon test for each pair of fabric. High statistical significance ($p < 0.0001$) was found for all comparisons involving B7 and 'no fabric.' Effect size analyses confirmed the trends observed with a moderate effect size between B7 and 'no fabric' ($\rho > 0.5$) and a large effect size for the comparison between B7 and 'no fabric,' and B7 and all the other fabrics (B1, B2, G2) ($\rho > 0.8$). A small effect size was also observed between B2 and G2 ($\rho > 0.3$).

3.2.2. *Perceived view clarity*

Our survey involved a question directly pertaining to view clarity, which results are reported in Fig. 2b and Table 4. The distribution of the data was non-normal leading us to the same analyses as for acuity performace. The trend in subjective responses for visual clarity generally follows that observed for the acuity performance test, with the same ranking of fabrics (in order of most to least clear: B7, B2, B1, G2) and comparable effect size and statistical significances for the comparisons involving B7. Subjective view clarity also indicated a moderate effect size between B2 and G2 ($\rho > 0.5$), and a small effect size for the comparison between B1 and B2/G2 ($\rho > 0.3$). In general, the reading performance was more contained across B1, B2, and G2 than the subjective responses, suggesting that either a different sensitivity to small differences or that visual clarity cannot be summarized by an optotype reading test, but it involves other variables. When rescaling the acuity performance test and perceived view clarity votes to the same scale as the VCI (0–1), we observe a certain agreement between the tested metrics, the VCI and VCI* (see Table 3). Perceived view clarity votes are in closest agreement with the VCI for B7. For the fabrics with lowest OF, the discrepancy between the VCI and the participants' data does not go in the same direction depending on the color of the fabric: for charcoal fabric, the VCI is higher than the subjective responses (the metric overpredicts clarity), while for the gray fabric, VCI is lower (the metric underpredicts clarity). VCI* is generally less reliable than VCI. For the fabric G2, VCI* is substantially overpredicting clarity, which suggests that the new equation is sensitive to the diffuse transmittance. If we refer to the visual contact classes of EN14501:2021, we observe inconsistencies with our results, according to which it would be more logical to have G2 in class 1 ("little effect") and B7 in class 4 ("very good effect").

3.2.3. *Objective color fidelity*

The results of the color measurements are shown in Fig. 3 and Table 5. For each of the four fabrics, the color coordinates of the ten color samples are plotted for the images taken with and without fabrics, with each point representing the average value of the measurements taken in the morning and the afternoon with the sun shining on the fabric. This means that the shaded measurements are not displayed in the figure. The measurements without fabric (indicated with a hollow circle) show the actual coordinates of the color samples, while the measurements with fabrics (marked with a solid circle) show a shift of the color samples due to the use of the fabrics—the larger the color shift, the lower the color fidelity of the fabric. Therefore, the fabric B7 resulted in having the highest color fidelity (and the lowest color shift), followed by B2 and B1 fabrics, and the fabric G2 turned out to have the lowest color fidelity. Among all color samples, the white and black ones resulted in the smallest color shift through all the fabrics. The analysis of the measurements performed on the shaded area of the fabric (under the shade of the mullion) gave us, as expected, a better color fidelity of all fabrics and the ranking of the fabrics remained the same as in the unshaded conditions (from the highest to the lowest color fidelity: B7, B2, B1, G2). However, in contrast to the results described in Konstantzos et al. [38], we found that the improvement for the gray fabric was not greater than but equal to that for the charcoal fabrics B1 and B2, and that the improvement in color fidelity was most pronounced for B7. Overall, the tested method provides us with an objective measure of color fidelity that seems promising for future color-characterization of shadings.

3.2.4. *Perceived colors of the outdoors*

Questions about the color naturalness of the exterior (see Fig. 4a) and about the color recognition of moving cars (see Fig. 4b) led to significant differences between the fabrics. Overall, the fabric B7 resulted in the

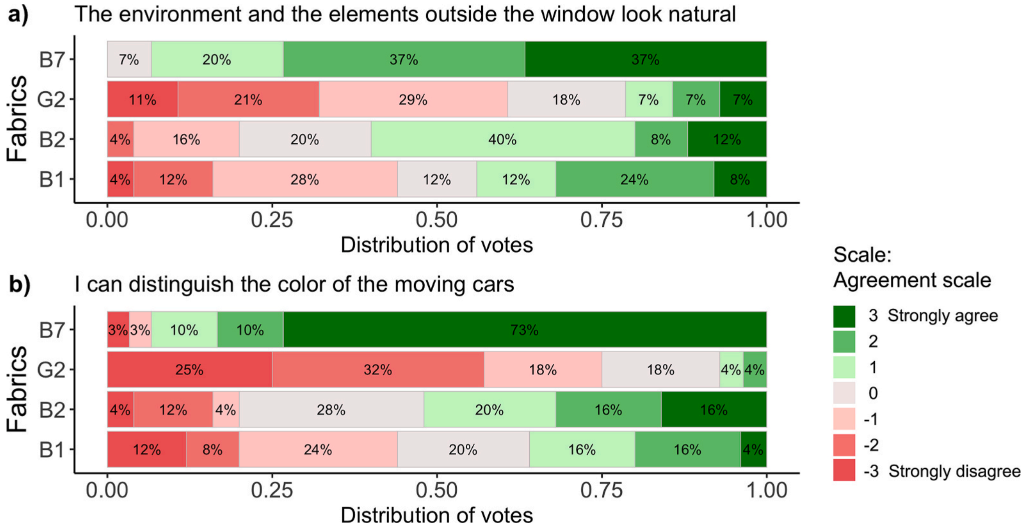


Fig. 4. Subjective responses pertaining to two agreement questions for the following statements: a) the color naturalness of the elements located outside the windows, and b) the recognition of color of the moving cars on the street, for the fabrics fully down on a 7-point agreement scale. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

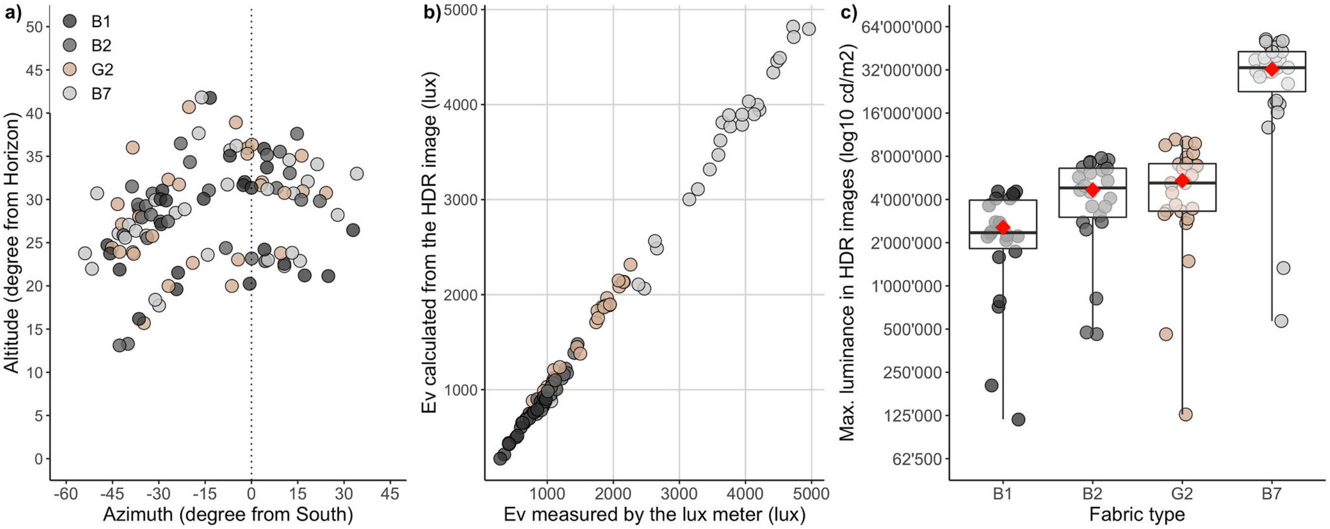


Fig. 5. a) Scatterplot of sun positions on azimuth-altitude axes, b) scatterplot of measured vs. image-derived vertical illuminances for different visual scenes, and c) boxplot overlaid with a scatterplot for the maximum luminance derived from the HDR images displayed in logarithmic scale.

Table 6
Maximum luminance derived from the HDR images.

		Sample size		Maximum luminance derived from the HDR images (cd/m^2)		
		n_{total}[a]	n_{HDR}[b]	Mean	Median	SD
Fabric (sessions 1–4)	B1	25	22	2′555′697	2′344′900	1′386′680
	B2	25	24	4′665′113	4′815′100	2′272′804
	G2	28	26	5′423′493	5′208′900	2′911′372
	B7	30	27	32′325′544	33′115′000	14′390′987
Sessions	4	24	22	10′996′295	4′815′100	15′052′435
	5	24	22	11′756′720	5′244′700	16′295′543

[a] Participant sample size after weather check.

[b] We discarded additonal data points due to errors with our HDR camera. Since the maximum luminance is derived from HDR images, the corresponding values in this table refer to this sample.

best color evaluation, followed by B2 and B1, and G2 resulted in the lowest color evaluation, which is in line with the objective color fidelity results. We however note that the spread of answers is more contrasted between B7 and G2 for the question on the color recognition of moving cars, which we can attribute to the constrained observation time embedded in this question (cars moving more or less quickly) as well as to reflections (cars' texture being commonly glossy).

3.3. *Glare assessment for fabric shading completely lowered*

This section reports the range of maximum luminance seen by the subjects, discomfort glare predicted by models, and associated subjective responses for each type of fabric for the experimental sessions when the fabrics were lowered entirely.

3.3.1. *Visual conditions*

The study was conducted under stable sunny sky conditions with the sun in the FOV of the participants. The angle between the main viewing direction and the sun was between 13° and 47° and the sun intensity varied depending on the time of day and clarity of the sky. The resulting variable daylight conditions and the fabrics led to different light conditions experienced by the users in the room. Fig. 5a displays the sun position, and Fig. 5c shows the maximum luminance derived from the HDR images (in log 10 cd/m2) for each type of fabric as boxplots. We

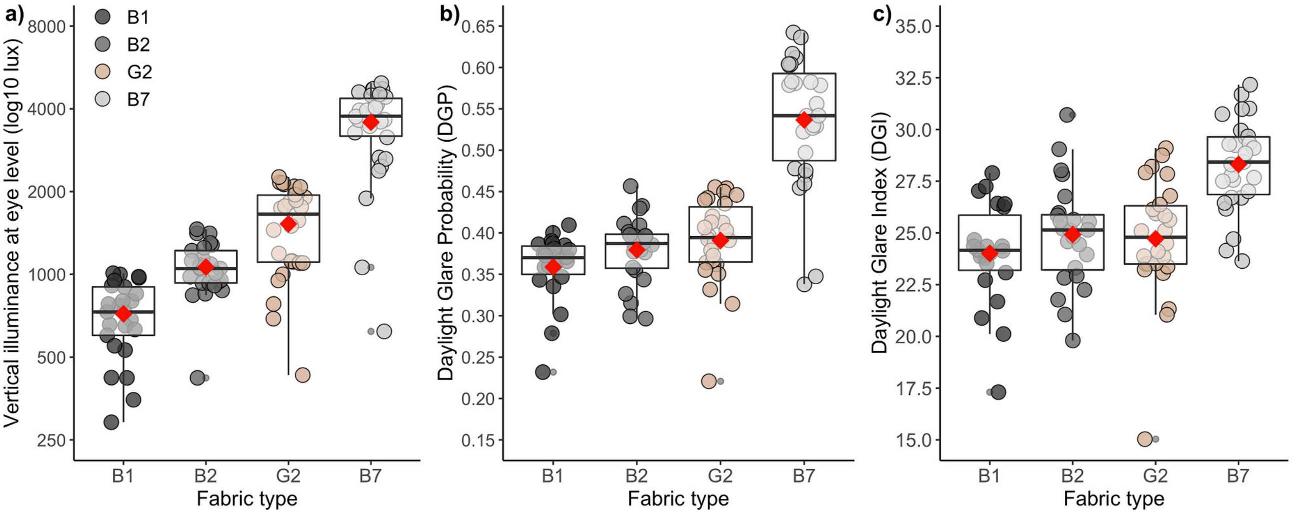


Fig. 6. Boxplots of Vertical illuminance (Ev) measured by the hand-held illuminance sensor (a), DGP derived from the HDR image (b), and DGI derived from the HDR image (c) reported for each type of fabric.

Table 7
Descriptive statistics values for Ev, DGP, and DGI by fabric and sessions & group of sessions.

		Ev (lux)			DGP			DGI		
		Mean	Median	SD	Mean	Median	SD	Mean	Median	SD
Fabric (sessions 1–4)	B1	718	730	209	0.36	0.37	0.04	24.0	24.2	2.5
	B2	1062	1050	224	0.38	0.39	0.04	24.9	25.1	2.5
	G2	1526	1655	517	0.39	0.39	0.05	24.7	24.8	2.9
	B7	3575	3760	1076	0.54	0.54	0.08	28.3	28.4	2.2
Sessions	4	1782	1285	1329	0.41	0.38	0.08	25.16	24.36	2.59
	5	3170	2220	2545	0.43	0.40	0.12	25.45	25.41	2.55
Group of sessions	1–4	1801	1130	1306	0.42	0.40	0.09	25.59	25.57	3.03
	4–5	2476	1810	2127	0.42	0.39	0.10	25.30	25.21	2.54

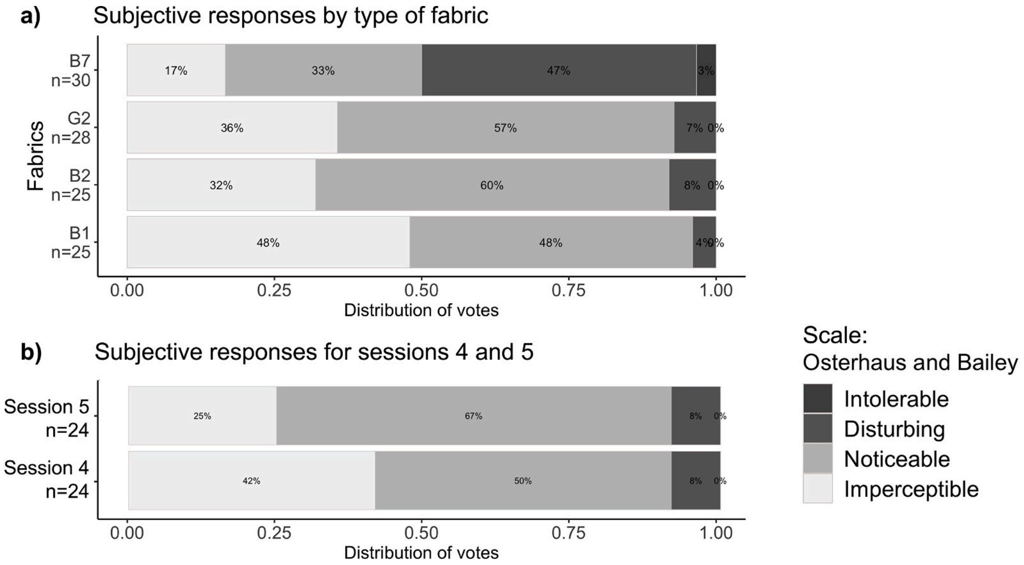


Fig. 7. a) Proportion of responses to the question “How would you describe the level of glare in your field of view?” on the Osterhaus and Bailey glare scale by fabrics (sessions 1-4), and b) by session for sessions 4 and 5.

utilized the logarithmic scale because it more adequately represents human perception and better shows the difference between B1, B2, and G2, which are considerably lower than B7. The maximum luminance levels derived for B7 are, on average, 5 to 11 times higher than the other fabrics. The observed difference between the mean maximum luminance of B2 and G2 is about twice that of B1 (1.83 between B2 and B1 and 2.12 between G2 and B1) (see Table 6).

Fig. 5b shows a scatterplot of vertical illuminance values derived from the HDR images compared to those measured with the handheld illuminance meter fixed right next to the camera. The results show almost perfect adequacy between the two values, which indicates good reliability of the HDR images. Fig. 6a shows boxplots of the vertical illuminance measured at eye level with the illuminance meter for each type of fabric on a logarithmic scale. We used the vertical illuminance to describe ambient lighting conditions because the values recorded on the desk were sensitive to the partial shading of objects (e.g., computer screen) and façade elements (e.g., mullions) resulting from the positions of the sun on the desk. The values were below 500 lux for a few instances (four for B1 and one for B2 and G2), despite the curtain opening on the Northside of the room to allow more light in the space.

3.3.2. *Predicted discomfort due to glare*

Fig. 5d Fig. 5e and f respectively show the range vertical illuminance, DGP, and DGI for the different fabrics, and Table 7 provides additional statistical values on the same metrics and scenario. Although the vertical illuminance is not among the best practices for describing glare, it is interesting to observe how the respective values spread out with respect to DGP and CGI for the different fabric types. Overall, the glare conditions show a wide range of overlap across fabrics and few outliers. The outliers present still valid data in terms of stable weather condition – the low values are caused by low sun positions and therefore low intensities due to athmospheric filtering of the direct solar radiation and acute angles between the sun and the fabric plane during the early morning sessions. For Ev, we observe an incremental increase of the value with the fabrics (B1<B2<G2<B7) while DGP and DGI show a different pattern, with B1, B2, and G2 being rated same range and B7 being substantially higher (B1≈B2≈G2<B7). The equivalence of B1, B2, and G2 is most visible with DGI.

3.3.3. *Users’ perception*

Fig. 7a shows the proportion of responses for daylight glare on the Osterhaus and Bailey glare scale by fabrics. As expected, B7 is the least protective in terms of glare. Across our experimental conditions, glare was perceived as “disturbing” or “intolerable” by 50% of participants for this fabric against 4–8% for the other fabrics. If we compare these results with the predicted glare, we see that the predictions of DGP and DGI reasonably follows with the response pattern of participants for whom fabrics B1, B2, and G2 are equivalent in terms of the disturbance caused.

3.4. *Glare assessment for free control over fabric position*

Exposure sessions 4 and 5 involved the same type of fabric, but session 5 was different in that the participants were free to choose the position of the fabric. The sample size is equal for sessions 4 and 5 because we only kept the sessions for which the weather was stable during both sessions. We could keep 24 sessions which cover the

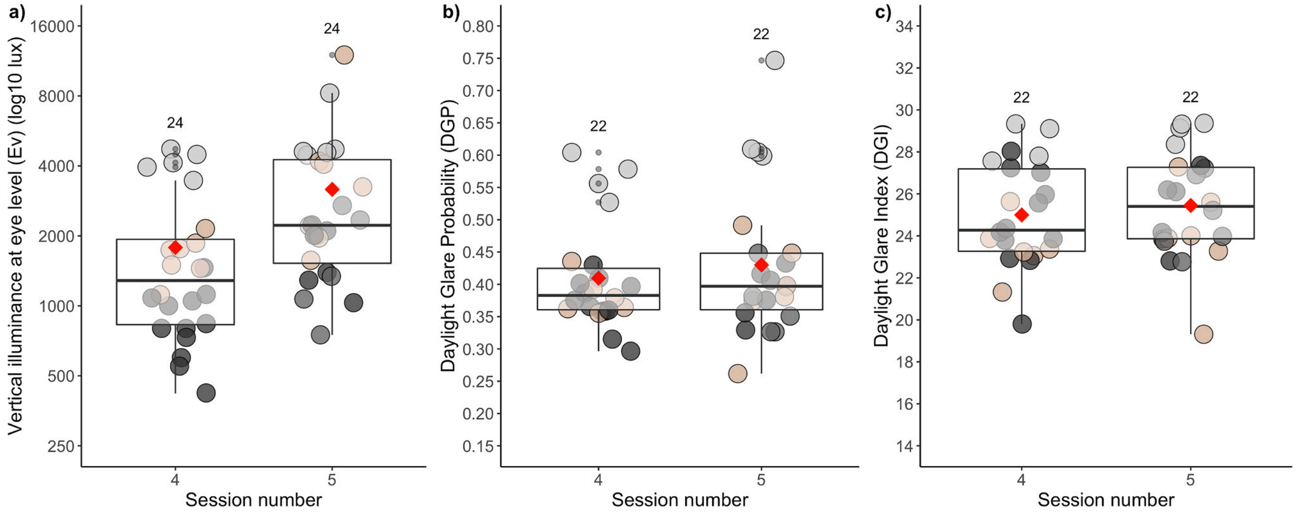


Fig. 8. a) Boxplots of Vertical illuminance (Ev) measured by the hand-held illuminance sensor (a), DGP derived from the HDR image (b), and DGI derived from the HDR image (c) reported for sessions 4 and 5 separately.

following fabric sample sizes: $n_{B1} = 6$, $n_{B2} = 6$, $n_{G2} = 7$, and $n_{B7} = 5$.

Eighteen of the 24 participants raised the roller blind in session 5. When raised, the height between the edge of the window sill and the bottom line of the blind was on average 25 cm (median 21 cm, min. 4 cm, max. 94 cm, sd 22 cm), resulting in an average 10° vertical opening angle of the blind, seen from the participants position. Six of the seven participants lifted the fabric when it was G2, five of the six lifted it when it was B1, and three of the five raised it when it was B7. Although the sample size per type of fabric is too small to draw any conclusions, we note that the less visually clear tissues tended to be lifted proportionally more often.

3.4.1. *Visual conditions*

The maximum luminance values derived from the HDR images across sessions 4 and 5 are reported in Table 6. Although similar between the two sessions (the slight increase is due to the increasing irradiance of the sun in the morning session, which was dominant), we note that the vertical illuminance was 1.8 times higher (on average) during session 5 (see Table 7 and Fig. 8). Opening the blinds directly impacts the vertical illuminance, but depending on the height at which it is raised, the maximum luminance will not be affected as long as the blind still covers the sun disk. Thus, these observations indicate a tendency to open the blinds but still maintain protection from the sun disk.

3.4.2. *Predicted discomfort due to glare*

Fig. 8 respectively show the range of vertical illuminance (a), DGP (b), and DGI (c) for sessions 4 and 5. Although Ev shows substantial differences between the two sessions, DGP and DGI increase only slightly between the sessions (see Table 7). This observation reveals the difference between a metric based solely on saturation (Ev) and metrics that involve a contrast term in their equation (DGP, DGI) and are therefore able to counteract the increase in saturation with a reduction in contrast for comparable glare between sessions.

3.4.3. *Users' perception*

The amount of participants reporting glare for each condition is displayed in Fig. 7b. We noted that only two participants reported “disturbing” glare for session 4 and that these participants were the only ones also to report “disturbing” glare in session 5. The number of participants reporting “noticeable” glare in session 4 increased to 16 reported in session 5, suggesting a slight increase in glare perception between sessions 4 and 5. The subjective responses somewhat echo the models' prediction using a contrast term (DGP and DGI), both of which show a slight increase in glare (median DGP going from 0.38 to 0.40 and median DGI from 24.36 to 25.41, see Table 7). We concluded that changes in fabric height did not increase perceived discomfort and that participants' subjective responses remained in agreement with the models, suggesting that control over fabric height did not alter their subjective judgment.

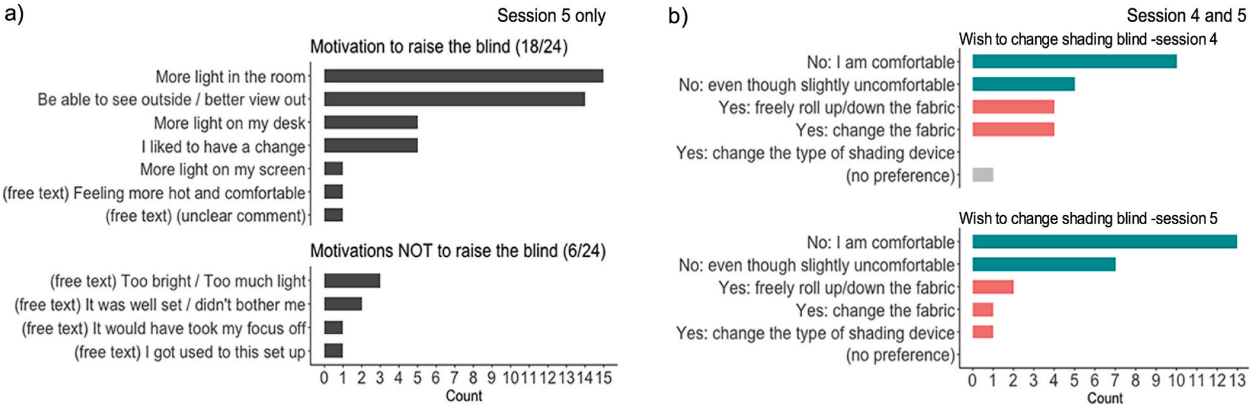


Fig. 9. a) Motivations behind blinds actions/inactions indicated during the survey of session 5, and b) Responses to the question: “Assume you have to work all day from this space, would you like any changes to the shading configuration?” for sessions 4 and 5.

3.5. Shading configuration preference

3.5.1. Motivations to operate the blinds

Participants were asked to indicate their motivation for controlling or not controlling the blinds based on suggested answers and free text fields (see Fig. 9a). The primary reasons for raising the blinds were "more light in the room" (15/18 participants) and "be able to see outside/better view out" (14/18). Some participants also indicated that they wanted more light on their desks (5/18) and/or wished for a change (5/18). Additional answers based on free text fields showed that one participant wanted a warmer space. Reported reasons for not raising the blinds indicate that participants found the conditions too bright (3/6) and/or that the conditions were good and did not bother them (2/6). One person stated that the view out (car passing) could bring them out of focus. Finally, one person indicated having gotten used to it and thus preferring to keep it that way.

The average vertical opening angle of 10° of the blind from the part'cipants' FOV to the outside allowed a view of the ground and landscape layers (as assumed to be important according to the literature [23]) but not of the sky, which may seem logical given the sunlight conditions tested. Glare perception was not affected because the increase in saturation was offset by the decrease in contrast between the glare source and ambient levels. The small change in height therefore provided benefits in terms of views to the exterior and light levels, without being negatively impacted by discomfort due to glare.

3.5.2. Effect of users' control on blind preference

We compared the results of the 'wish for change' question (considered to reflect participants' preference) between sessions 4 and 5. The results are reported in Fig. 9b. In total, 20 out of 24 participants were willing to keep the shading configuration of session 5 compared to the 15 participants during session 4. Two participants in session 5 wished to further control the height of the fabric (we only allowed them to change the height at the beginning of the exposure). These results suggest that offering control over users' fabric can effectively address acceptability with their visual conditions.

4. Discussion

4.1. Glare, daylight levels and view out

While the subjective responses for sessions 1–4 are unequivocal in terms of the glare protection provided by B1, B2, G2 compared to B7 when the sun is in the center of the FOV, annual assessments would be necessary to bring conclusive statements on the effect of the different types of fabrics over time. Indeed, participants always had the sun right in the center of the FOV resulting in a low position index (mean = 3.6, median = 3.7, sd = 1) (see Fig. 10), which correlates with higher glare prediction. As shown in a study based on electrochromic glazing using a similar experimental set-up [68], the change in position index from 2.5 to 6.2 (on average) between two similar façade scenarios was accompanied by a shift in glare perception from 54% to 21% on the binary glare scale (still considering stable sunny weather). Since building occupants are not accustomed to rotating their desks throughout the day to follow the sun's path, the naturally changing position of the sun over a day would likely make a significant difference in the overall (temporal) glare disturbance for B7. Further, the weather screening was oriented to provide ideal sunlight conditions, which is not necessarily representative of all geographical regions.

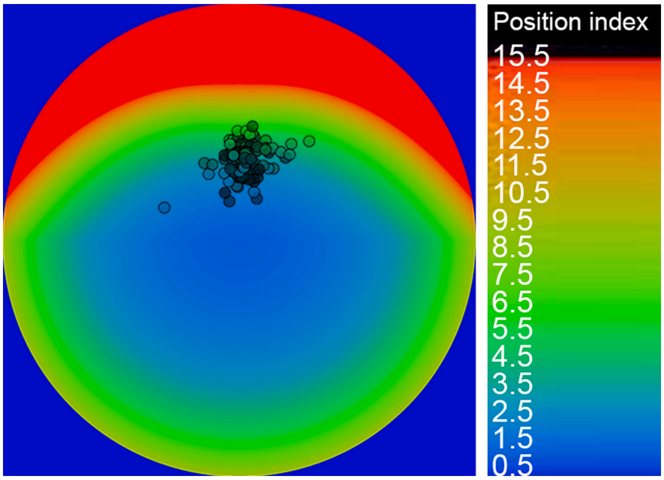


Fig. 10. Sun positions seen from the participant's FOV overlaid with the Guth position index, which is used in glare models.

Evalglare bases its glare evaluation by distinguishing the glare source from the rest of one's FOV according to a threshold value of 50′000 cd/m^2. This method works well when the glare source is clearly above that threshold and the other areas of the image are clearly below that threshold, which is the case of most glare configurations. However, in the case of glare from the sun seen though a fabric shading, the sunlight tends to propagate along the material through internal reflections leading to a continuity of luminance values around 50′000 cd/m^2. While we kept this default threshold for our analysis, we note the uncertainty provided by the component of the method, and the need to refine peak extraction thresholds in future research.

Previous literature had highlighted the presence of a possible 'forgiveness factor' for discomfort glare in the case where occupants are provided with a satisfactory view to the outside [46,47,69]. Considering the DGP value was rather constant between sessions 4 and 5, we could not observe this forgiveness effect, that should otherwise have resulted in a lower glare perception by the subjects in session 5. Our experiment, however, was actually not designed to emphasize such a forgiveness effect: sessions 4 and 5 were not randomized, and the fabric remained the same, allowing participants to remain on the same subjective assessment of glare. Possible forgiveness mechanisms, by definition unconscious, therefore could not take place. Conversely, the fact that neither the subjective responses nor the DGP increased does not necessarily imply the absence of forgiveness.

We only relied on daylight during our experimental sessions and often had to open the black-out curtain of the Northern side and/or the side door to increase the illuminance in the space. Despite this action, we sometimes could not meet our target of 300 lux for B1 and B2. Although this study did not focus on illuminance per se, it is important to note that fabrics with low OF and τ_v could not provide the desired illuminance levels when fully down despite the clear sky conditions. At the same time, B7 and G2 allowed for substantially more daylight penetration into the room. The EN14501:2021 daylight utilization class categorizes B1 and B2 as 0 (very little effect) and G2, and B7 as 1 (little effect) in terms of their effect on visual comfort. However, this classification is only based on the diffuse-hemispherical visual transmittance, which would correspond to a diffuse sky condition. The standard utilizes the diffuse transmittance to reflect the "global" ability to transmit light for all angles of incidence (hereby accounting for different sun positions, since fabrics have a strong angular dependance). While the resulting classes applied to our fabric properly reflect the gap between B1/B2 and G2/B7, the test conditions are still too remote to adequately comment on this classification.

Achieving the desired desk-level illuminance in an office can obviously also be done through the use of artificial lighting. Yet, in order not to fall into the paradox of using artificial light when the outdoor light levels would allow to do without it, the use of darker fabric types with low OF in buildings with automated blind controls should be accompanied by the adoption of control strategies that allow for partial opening and closing. As observed, even a small opening (15% of total window area) made a big difference in terms of daylight levels under the sky conditions of this study. Consideration of a combination of criteria –

implicating glare, view out and daylight in addition to examining heat gain – appears to be more meaningful than an operation based solely on energy concerns. Such an approach would also address the necessary trade-off recently highlighted in Lee et al. [70] on the importance of daylight and window views as a contributor to the health and well-being of building occupants while not losing sight of the implications on energy efficiency and carbon profile of buildings.

While 8 out of 24 participants chose to partially reopen the fabric blinds, none of them raised the blinds in a way that direct sun would be in their FOV. The free control of the blinds allowed us to highlight the important role of contrast in the perception of the glare. By opening the blinds, the occupants did not increase their discomfort rating due to glare despite the substantial increase in illuminance in the space. DGP and DGI remained at comparable glare levels, as did the respondents' responses, but Ev increased by a factor of 1.8, making it inadequate in such conditions where the increase in saturation is offset by the decrease in contrast.

4.2. Glare and view out classification schemes

The types of fabric tested globally behaved according to the logic “3 against 1”, where B1, B2, and G2 led to low visual clarity and high glare protection, while B7 led to substantially higher visual clarity and lower glare protection. At the first sight, the class 2 (“moderate effect”) assigned by the EN14501:2021 [8] to G2 regarding visual contact appears too optimistic, whereas the class 3 (“good effect”) assigned to B7 a little too strict. Based on the present findings, we would suggest G2 to be moved to class 1 ("little effect") and B7 to class 4 (“very good effect”). It would however be necessary to have more tests involving more fabrics to establish more general laws regarding the classification according to the fabrics' properties. By contrast, the VCI [38] ranked B1 at 0.55, B2 at 0.527, G2 at 0.21, and B7 at 0.75, This ranking is in general agreement with both the subjective visual clarity votes and the acuity performance test, however, with the 1VCI overestimating the clarity of the two least transmissive fabrics (B1 and B2). VCI* was further away than VCI. For discomfort glare protection, the EN14501:2021 [8] classified B1 as class 4 (“very good effect”), B2 as class 3 (“good effect”), and G2 as class 1 (“little effect”), while the three fabrics showed comparable glare protection. Our results showed some inconsistencies with the standard's classifications for visual contact and glare.

Both the EN14501:2021 classification and the VCI require data on fabric properties that must be accurate to enable reliable categorization. We were fortunate to obtain the detailed visual transmittance data from the manufacturer, which we could confirm and refine by running additional measures. However, the reported OF was off, and based on the manufacturer's data, the VCI would have been far from the current output (G2 ranked as offering higher clarity than B1, and B2 was not classifiable as its OF>τ_v). Overall, we could not find a reliable procedure for calculating the OF. Yet, the VCI is highly sensitive to OF, and just a difference of 1% can make a considerable change in VCI. We checked for the absence of diffraction and equated OF to τ_v in the case of opaque charcoal samples. Before that, we tested a method involving macro photography and pixel count, but it seemed more error-prone than the retained method. A reliable method for OF is missing, which constitutes a clear gap. More generally, having reliable data on OF (0.1% precision) and τ_v (0.001 precision) is an essential condition for the meaningful application of VCI in the practice.

We assume the inferior performance of VCI* is related to the usage of $\tau_{v,n\text{-}n}$ instead of the OF that is used by VCI. While the OF considers only the undistorted, non-scattered light passing through the material at normal incidence, $\tau_{v,n\text{-}n}$ is a measured quantity that also includes scattered light from the fabric-threads that is visible to the opening of either the light trap of integrating spheres or of a collimator measuring directly $\tau_{v,n\text{-}n}$. Both measuring methods have typical opening angles of 5°–8°, which means the measurement includes also partly scattered light. For the quantification of the view clarity only the undistorted, non-scattered light passing through the material at normal incidence is relevant to reconstruct an image by the eye, the scattered light actually reduces the seen contrast. For that reason, it is expected that the VCI* in its current form cannot reliably quantify the clarity through fabrics that scatter the light (which means all non-black colors). An additional potential reason of the weaker performance of VCI* is the usage of manufacturer provided optical data instead of measured data.

Three quarters of the participants chose to partially open the fabric blinds in session 5. According to the literature on occupant control, the question of changes in occupant behavior regarding blind operation is particularly relevant in shared office situations, where interactions with blinds have been observed to decrease when the number of people gets larger [71,72]. In addition, the fact that the researcher explicitly told the participants that they were allowed to control the height of the blinds according to their preferences may have influenced the participants' natural behavior, a phenomenon commonly defined as the "Hawthorne effect" [73]. Nevertheless, the action taken by the participants is the one that reflects their preferences in their particular setting and as such should not be overlooked. It is thus important to consider the system's operability in both automatic control strategies and future quantification measures related to view quality. While quantifying the clarity of a given fabric makes more sense with closed shades, the procedure for comprehensively quantifying the quality of a view out should reflect the operability of shading systems and the fact that even a small change in the height of the shading system (here from an average viewing angle of 10° at eye height) can strongly change the perception of the connection to the outside. This result echoes previous observation suggesting that even a very small window contributes to a feeling of safety by providing a continuous contact with the outside world [74]. These results can be also interpreted in a way, that if the control of the height of the fabric shading is effectively available to the users, then the fabric material could be chosen mainly according glare requirements– the view preferences could be then fulfilled by giving the height control.

4.3. Color measurements

To our knowledge, there is no established procedure for calculating the shift in outdoor colors caused by the use of fabrics as a shading device. We developed our method inspired by Ko et al. [75] through which coordinates of color samples attached to a board outside were calculated from images captured with and without the fabric. The chosen procedure developed in this paper used Euclidian distances based on the CAM02-UCS color space opens new perspectives for including objective metrics for color fidelity evaluation in view clarity assessment of fabrics. Studies have however highlighted the influence of light levels on color fidelity evaluation and preference [76-79]. Fabric shadings typically imply different light levels as observed in our experiment (see Fig. 6a). Although we observed agreement between objective color fidelity and subjective impressions of color naturalness, we did not assess the impact of light levels on perceived color fidelity and suggest future studies to address this gap.

4.4. Future metric developments

Finally, we believe that future view clarity indices could be developed based on photographic data and could include context recognition capability, a. k.a., outdoor view reconstructability [80], which would allow the comparison of different types of blinds (such as fabrics, venetian blinds, pattern shading). The operability of the shading devices is another important point. While the literature agrees on the importance of occupant control in office spaces, it is surprising that view clarity quantification scheme do not account for it, leading to a research gap. Lastly, it would be relevant to devote more attention to the "Hawthorne effect" in the field of building science and to develop test procedures that make the very presence of the study to become unnoticed.

5. Conclusion

This study focused on glare perception, view out, and blind control for shading fabrics with low OF and the sun in the FOV. It is based on human subject experiments and was conducted under stable sunny sky conditions with the sun close to the central part of the participants' FOV. It consisted of five exposure sessions with sessions 1 to 4, where different types of shading fabrics (roller shades) were installed entirely in random order; and session 5, where the last tested shading fabric (exposure 4) was kept for an additional session where control over the height of the fabric was left to the participants, to allow us to study participants' control preferences and motivations.

From sessions 1–4, we learned that fabrics with OF = 2.4% cannot provide an adequate view to the outside, but do provide proper protection from glare when the sun is in the center of the FOV. A virtually black (charcoal-colored) fabric of = 6.6% brought 50% discomfort glare votes (situation considered as "disturbing" or "intolerable") under our experimental set-up. Yet, since the sun position and the weather unevitably vary over time especially in real-life use, annual and climate-based studies would be necessary to judge such a fabric's overall glare protection efficiency. Fabrics with a nearly black color and with $OF \leq 2.4\%$ drastically reduced daylight levels in the room, and in the context of our test room, we could not manage to reach 300 lux on the participant's desk without opening additional blinds in the room. Our results also showed some inconsistencies with the EN14501:2021 [8] classifications for visual contact and glare but higher agreement with the VCI on view clarity [38]. It is important to note that the VCI overestimates the clarity of the two least transmissive fabrics (B1 and B2), that it is sensitive to its input indices (OF and τ_v) and that approximate values may make its application irrelevant. The newly developed VCI [39] (labelled as VCI* in this study) was not outperforming the VCI.

Three-quarters of the participants decided to partially raise the blinds in session 5, primarily to increase the brightness in the space and to have a view to the outside. Discomfort glare assessments showed that participants did not substantially change their perception between sessions 4 and 5. This result was in line with glare predictions models involving a contrast term (such as DGP and DGI), where the decrease in contrast can counteract the increase in the saturation. While the change in the blind opening was relatively small (15% of the total window area), it made a large difference in indoor daylight levels and participants' views out. As such, controlling the automated operable blinds systems according to the "all or nothing" approach would appear to be a bad practice, and the view quality indices would gain relevance if they included the benefit of operability in their quantification schemes.

CRediT authorship contribution statement

Caroline Karmann: Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization, Writing – original draft, Writing – review & editing. **Giorgia Chinazzo:** Visualization, Methodology, Formal analysis, Conceptualization, Writing – original draft, Writing – review & editing. **Andreas Schüler:** Methodology. **Krishna Manwani:** Formal analysis, Writing – review & editing. **Jan Wienold:** Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization, Writing – review & editing. **Marilyne Andersen:** Writing – review & editing, Supervision, Funding acquisition, 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.

Data availability

Data will be made available on a repository

Acknowledgments

This study was funded by Swiss National Foundation project (SNF) grant for the project "Visual comfort without borders: interactions on discomfort glare" number 200020_182151.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2022.109707.

References

[1] L. Heschong, R.L. Wright, S. Okura, Daylighting impacts on human performance in school, J. Illum. Eng. Soc. 31 (2002) 101–114.

[2] L. Heschong, D. Mahone, Windows and offices: a study of office worker performance and the indoor environment, California Energy Commission (2003) 1–5.

[3] J.H. Heerwagen, The psychological effects of windows and window design, in: Proceedings of the 21 St Annual Conference of the Environmental Design Research Association. Champaign-Urbana, Illinois, 1990, pp. 6–9.

[4] H.H. Alzoubi, A.H. Al-Zoubi, Assessment of building façade performance in terms of daylighting and the associated energy consumption in architectural spaces: vertical and horizontal shading devices for southern exposure facades, Energy Convers. Manag. 51 (2010) 1592–1599.

[5] J.A. Veitch, D.W. Hine, R. Gifford, End users 'knowledge, beliefs, and preferences for lighting, J. Interior Des. 19 (1993) 15–26.

[6] W.K. Osterhaus, Discomfort glare assessment and prevention for daylight applications in office environments, Sol. Energy 79 (2005) 140–158.

[7] A. Galatioto, M. Beccali, Aspects and issues of daylighting assessment: a review study, Renew. Sustain. Energy Rev. 66 (2016) 852–860.

[8] CEN, EN14501:2021 Blinds and Shutters – Thermal and Visual Comfort – Performance Characteristics and Classification, European Committee for Standardization, Brussels, Belgium, 2021.

[9] M.B. Aries, J.A. Veitch, G.R. Newsham, Windows, view, and office characteristics predict physical and psychological discomfort, J. Environ. Psychol. 30 (2010) 533–541.

[10] K.M. Farley, J.A. Veitch, A Room with a View: A Review of the Effects of Windows on Work and Well-Being, 2001.

[11] L. Heschong, Visual Delight in Architecture: Daylight, Vision, and View, Routledge, 2021.

[12] D. Li, W.C. Sullivan, Impact of views to school landscapes on recovery from stress and mental fatigue, Landsc. Urban Plann. 148 (2016) 149–158.

[13] R. Ulrich, View through a window may influence recovery, Science 224 (1984) 224–225.

[14] J.A. Veitch, A. Galasiu, The Physiological and Psychological Effects of Windows, Daylight, and View at Home: Review and Research Agenda, vol. 325, Canada: NRC-Construction IRC-RR-, 2012.

[15] D.L. Butler, P.M. Biner, Effects of setting on window preferences and factors associated with those preferences, Environ. Behav. 21 (1989) 17–31.

[16] C.-Y. Chang, P.-K. Chen, Human response to window views and indoor plants in the workplace, Hortscience 40 (2005) 1354–1359.

[17] V.F. Gladwell, D.K. Brown, J.L. Barton, M.P. Tarvainen, P. Kuoppa, J. Pretty, et al., The effects of views of nature on autonomic control, Eur. J. Appl. Physiol. 112 (2012) 3379–3386.

[18] J. Kim, J. Wineman, Are Windows and Views Really Better. A Quantitative Analysis of the Economic and Psychological Value of Views Lighting Research Center, Rensselaer Polytechnic Institute, New York, 2005.

[19] W.H. Ko, S. Schiavon, H. Zhang, L. Graham, G. Brager, I. Mauss, et al., The impact of a view from a window on thermal comfort, emotion, and cognitive performance, Build. Environ. (2020), 106779.

[20] L.M. Wilson, Intensive care delirium: the effect of outside deprivation in a windowless unit, Arch. Intern. Med. 130 (1972) 225–226.

[21] J. Christoffersen, K. Johnsen, E. Petersen, S. Hygge, Post-Occupancy Evaluation of Danish Office Buildings, vol. 133, Publications de La Commission Internationale de l'éclairage (CIE), 1999, pp. 333–337.

[22] William Lam, Perception and Lighting as Formgivers for Architecture, McGraw-Hill, 1977.

[23] H. Hellinga, Daylight and View: the Influence of Windows on the Visual Quality of Indoor Spaces, PhD Dissertation, TU Delft, 2013.

[24] T.A. Markus, The function of windows—a reappraisal, Build. Sci. 2 (1967) 97–121.

[25] CEN. 17037, Daylight of Buildings, European Committee for Standardization, Brussels, Belgium, 2018.

[26] W.H. Ko, M.G. Kent, S. Schiavon, B. Levitt, G. Betti, A window view quality assessment framework, Leukos (2021) 1–26.

[27] CIE, Discomfort Glare in the Interior Working Environment, Commission Internationale de l'Eclairage, Vienna, 1983.

[28] CIE, International Lighting Vocabulary, Bureau Central de la Commission Electrotechnique Internationale, 1987.

[29] J.K. Day, B. Futrell, R. Cox, S.N. Ruiz, A. Amirazar, A.H. Zarrabi, et al., Blinded by the light: occupant perceptions and visual comfort assessments of three dynamic daylight control systems and shading strategies, Build. Environ. 154 (2019) 107–121, https://doi.org/10.1016/j.buildenv.2019.02.037.

[30] J. Wienold, T. Iwata, M. Sarey Khanie, E. Erell, E. Kaftan, R.G. Rodriguez, et al., Cross-validation and robustness of daylight glare metrics, Light. Res. Technol. 51 (2019) 983–1013.

[31] J. Wienold, Dynamic Simulation of Blind Control Strategies for Visual Comfort and Energy Balance Analysis. Building Simulation, IBPSA Beijing, 2007, pp. 1197–1204.

[32] R.G. Hopkinson, Glare from daylighting in buildings, Appl. Ergon. 3 (1972) 206–215.

[33] CIE Technical Committee, CIE 117-1995 Discomfort Glare in Interior Lighting, International Commission on Illumination, Vienna, Austria, 1995.

[34] H. Einhorn, Discomfort glare: a formula to bridge differences, Light. Res. Technol. 11 (1979) 90–94.

[35] J. Wienold, J. Christoffersen, Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras, Energy Build. 38 (2006) 743–757, https://doi.org/10.1016/j.enbuild.2006.03.017.

[36] T. Iwata, M. Tokura, Examination of the limitations of predicted glare sensation vote (PGSV) as a glare index for a large source: towards a comprehensive development of discomfort glare evaluation, Int. J. Light. Res. Technol. 30 (1998) 81–88.

[37] J.A. Jakubiec, C.F. Reinhart, The 'adaptive zone'–A concept for assessing discomfort glare throughout daylit spaces, Light. Res. Technol. 44 (2012) 149–170.

[38] I. Konstantzos, Y.-C. Chan, J.C. Seibold, A. Tzempelikos, R.W. Proctor, J. B. Protzman, View Clarity Index: a new metric to evaluate clarity of view through window shades, Build. Environ. 90 (2015) 206–214.

[39] G. Flamant, W. Bustamante, A. Tzempelikos, S. Vera, Evaluation of view clarity through solar shading fabrics, Build. Environ. 212 (2022), 108750.

[40] I. Konstantzos, A. Tzempelikos, Daylight glare evaluation with the sun in the field of view through window shades, Build. Environ. 113 (2017) 65–77.

[41] Y.-C. Chan, A. Tzempelikos, I. Konstantzos, A systematic method for selecting roller shade properties for glare protection, Energy Build. 92 (2015) 81–94.

[42] J.Y. Garretón, A.M. Villalba, R.G. Rodriguez, A. Pattini, Roller blinds characterization assessing discomfort glare, view outside and useful daylight illuminance with the sun in the field of view, Sol. Energy 213 (2021) 91–101.

[43] A.D. Galasiu, J.A. Veitch, Occupant preferences and satisfaction with the luminous environment and control systems in daylit offices: a literature review, Energy Build. 38 (2006) 728–742, https://doi.org/10.1016/j.enbuild.2006.03.001.

[44] L. Heschong, Daylighting and human performance, ASHRAE J. 44 (2002) 65–67.

[45] K. Van Den Wymelenberg, Patterns of occupant interaction with window blinds: a literature review, Energy Build. 51 (2012) 165–176.

[46] N. Tuaycharoen, P.R. Tregenza, View and discomfort glare from windows, Light. Res. Technol. 39 (2007) 185–200, https://doi.org/10.1177/1365782807077193.

[47] N. Tuaycharoen, The Reduction of Discomfort Glare from Windows by Interesting Views, University of Sheffield, 2006.

[48] F. Faul, E. Erdfelder, A. Buchner, A.-G. Lang, Statistical power analyses using G* Power 3.1: tests for correlation and regression analyses, Behav. Res. Methods 41 (2009) 1149–1160.

[49] Pab Advanced Technologies Ltd, Gonio-Photometer pbII. http://www.pab.eu/?d=gonio-photometer, 2022. (Accessed 5 May 2022).

[50] P. Apian-Bennewitz, New Scanning Gonio-Photometer for Extended BRTF Measurements, vol. 7792, SPIE, 2010, pp. 185–204.

[51] R. Steiner, P. Oelhafen, G. Reber, A. Romanyuk, Experimental determination of spectral and angular dependent optical properties of insulating glasses, in: Proceedings, EPFL 2005, EPFL, Lausanne, Switzerland, 2005, pp. 441–446.

[52] EN. BS EN 410:2011 Glass in building, Determination of Luminous and Solar Characteristics of Glazing, International Standards Organization, Geneva, Switzerland, 2011.

[53] J. Wienold, Evalglare–A New RADIANCE-Based Tool to Evaluate Daylight Glare in Office Spaces, 2004.

[54] J. Wienold, M. Andersen, Evalglare 2.0–new Features Faster and More Robust Hdr-Image Evaluation, 2016.

[55] A. David, P.T. Fini, K.W. Houser, Y. Ohno, M.P. Royer, K.A. Smet, et al., Development of the IES method for evaluating the color rendition of light sources, Opt Express 23 (2015) 15888–15906.

[56] TechnoTeam. LMK LabSoft. Germany: TechnoTeam Bilderverarbeitung GmbH; (n. d).

[57] M.R. Luo, G. Cui, C. Li, Uniform Colour Spaces Based on CIECAM02 Colour Appearance Model vol. 31, Color Research & Application: Endorsed by Inter-Society Color Council, The Colour Group (Great Britain), 2006, pp. 320–330. Canadian Society for Color, Color Science Association of Japan, Dutch Society for the Study of Color, The Swedish Colour Centre Foundation, Colour Society of Australia, Centre Français de La Couleur.

[58] IES. IES-TM-30-20, IES Method for Evaluating Light Source Color Rendition, Illuminating Engineering Society, New York, NY, USA, 2020.

[59] A. Cie, Colour Appearance Model for Colour Management Systems: CIECAM02, vol. 159, CIE Publication, 2004, p. 2004.

[60] A. David, T. Esposito, K. Houser, M. Royer, K.A. Smet, L. Whitehead, A vector field color rendition model for characterizing color shifts and metameric mismatch, Leukos 16 (2020) 99–114.

[61] T. Esposito, K. Houser, Models of colour quality over a wide range of spectral power distributions, Light. Res. Technol. 51 (2019) 331–352.

[62] M. Wei, K.W. Houser, A. David, M.R. Krames, Colour gamut size and shape influence colour preference, Light. Res. Technol. 49 (2017) 992–1014.

[63] RStudio Team, RStudio: Integrated Development for R, RStudio, PBC., Boston, MA, USA, 2020.

[64] C.J. Ferguson, An effect size primer: a guide for clinicians and researchers, Prof. Psychol. Res. Pract. 40 (2009) 532–538.

[65] R Core Team, R: A Language and Environment for Statistical Computing, R Foundation for Statistical Computing, Vienna, Austria, 2021.

[66] G. Chinazzo, J. Wienold, M. Andersen, Influence of indoor temperature and daylight illuminance on visual perception, Light. Res. Technol. 52 (2020) 350–370.

[67] G. Chinazzo, J. Wienold, M. Andersen, Effect of indoor temperature and glazing with saturated color on visual perception of daylight, Leukos 17 (2021) 183–204.

[68] S. Jain, C. Karmann, J. Wienold, Behind electrochromic glazing: assessing user's perception of glare from the sun in a controlled environment, Energy Build. 256 (2022), 111738.

[69] N. Tuaycharoen, P.R. Tregenza, Discomfort glare from interesting images, Light. Res. Technol. 37 (2005) 329–338.

[70] E.S. Lee, B.S. Matusiak, D. Geisler-Moroder, S.E. Selkowitz, L. Heschong, Advocating for view and daylight in buildings: next steps, Energy Build. 265 (2022), 112079.

[71] G. Diaper, The Hawthorne effect: a fresh examination, Educ. Stud. 16 (1990) 261–267.

[72] M. Schweiker, A. Wagner, The effect of occupancy on perceived control, neutral temperature, and behavioral patterns, Energy Build. 117 (2016) 246–259.

[73] W. O'Brien, H.B. Gunay, The contextual factors contributing to occupants' adaptive comfort behaviors in offices–A review and proposed modeling framework, Build. Environ. 77 (2014) 77–87.

[74] P. Boyce, C. Hunter, O. Howlett, The Benefits of Daylight through Windows, Rensselaer Polytechnic Institute, Troy, New York, 2003.

[75] W.H. Ko, G. Brager, S. Schiavon, S. Selkowitz, Building Envelope Impact on Human Performance and Well-Being: Experimental Study on View Clarity, 2017.

[76] R. Hunt, The effects of daylight and tungsten light-adaptation on colour perception, J. Opt. Soc. Am. 40 (6) (1950) 362–371, https://doi.org/10.1364/JOSA.40.000362.

[77] R. Hunt, Light and dark adaptation and the perception of colour, J. Opt. Soc. Am. 42 (3) (1952) 190–199, https://doi.org/10.1364/JOSA.42.000190.

[78] M. Wei, W. Bao, H. Huang, Consideration of light level in specifying light source colour rendition, Leukos 16 (1) (2020) 55–65, https://doi.org/10.1080/15502724.2018.1448992.

[79] W. Bao, Change of gamut size for producing preferred colour appearance from 20 to 15000 lux, Leukos 17 (1) (2021) 21–42, https://doi.org/10.1080/15502724.2019.1587621.

[80] B. Abboushi, I. Elzeyadi, K.V.D. Wymelenberg, R. Taylor, M. Sereno, G. Jacobsen, Assessing the visual comfort, visual interest of sunlight patterns, and view quality under different window conditions in an open-plan office, Leukos 17 (2021) 321–337, https://doi.org/10.1080/15502724.2020.1785309.