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Glare and cognitive performance in screen work in the presence of sunlight

RG Rodriguez PhD, **JA Yamín Garretón BDes** and **AE Pattini** PhD
Laboratorio de Ambiente Humano y Vivienda, Instituto de Ciencias
Humanas, Sociales y Ambientales, Consejo Nacional de Investigaciones
Científicas y Técnicas, Mendoza, Argentina

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Research concerning the effects of glare on distraction is scarce. We designed a 2 × 2 repeated measures experiment ($n = 32$) in order to examine the influence of a large area glare source and glare sensitivity on reported discomfort glare and cognitive performance. Daylight glare probability was the within-subjects variable and glare sensitivity was the between-subjects variable. We found a statistically significant difference in glare sensation votes between scenarios, without statistically significant differences in glare ratings due to glare sensitivity. We found some statistically significant effects on our participants' reaction times. Also, we calculated their effect sizes, which had practical relevance. Our results encourage further research in an issue that has been suggested since the early stages of glare research but has never been systematically and consistently addressed.

1. Introduction

Driven by the desire for sustainable building practices, codes and standards are increasingly pushing for daylighting in buildings. Daylight 'performance indicators' are part of voluntary environmental rating systems, such as the BRE Environmental Assessment Method (UK), the Leadership in Energy and Environmental Design (US) and the Green Star Certification (Australia), used worldwide. With green building incentives, daylighting is receiving much greater attention in building design than it has previously.[1] However, without a full understanding of the side-effects of daylighting (such as discomfort glare) there is the risk of achieving poor occupant comfort, which in turn may negatively impact energy savings.[2]

Daylight also affects task performance.[3,4] The effect of lighting on visual performance is well established;[5] however, no task is purely visual, having also cognitive and motor components which interact and overlap. Research concerning the effects of lighting on the cognitive components of the task is scarce.[6,7] Considering that the widespread use of technology in modern workplaces imposes a constant cognitive processing load on the individual[8] under a multi-task paradigm,[9] and that at the same time standards encourage the adoption of green building practices, there is a need to determine the possible effects of daylighting on cognitive performance in working environments.

The introduction of information and communication technologies (ICT) in office settings provides complex work environments with network-based information and computer-mediated interactions and communication.[10] The interaction between the user and a computer is mainly visual, by means of a visual display terminal (VDT). A typical

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Address for correspondence: Roberto Germán Rodriguez, Laboratorio de Ambiente Humano y Vivienda – INCIHUSA CONICET, Avenida Ruiz Leal S/N Parque General San Martín – Ciudad de Mendoza, Mendoza, Argentina.
E-mail: rgrodriguez@mendoza-conicet.gov.ar

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visual scene consists of many objects and events, however, only a fraction of those stimuli are relevant to our behavioural goals. While working with a computer, it is essential that only the relevant information be processed while irrelevant information is either suppressed or ignored while in the presence of potential interference from secondary environmental distracters,[11] such as flicker, veiling reflections or glare. The objective of this experimental research is to explore the possible relationship between glare from a natural light source and performance on a cognitive task of VDT operators. Our first hypothesis is that a glare source will become an environmental distracter affecting performance in a task that requires attention.

Individual differences contribute a significant amount of variance when addressing the impact of the built environment in human behaviour.[12] Although a large body of knowledge has been developed around discomfort glare,[13] a large variation of glare responses is normally found when comparing individual subjects.[14] More than forty years ago, Stone and Harker[15] wrote about the scientific and practical reasons to gain a deeper understanding of the basic factors that make some people more sensitive to light than others. A relationship between ocular pigmentation and the light scattering in the retina has been established.[16,17] Light eyes (i.e. green, blue) have greater intraocular scatter than dark eyes. This effect will impact the quality of the retinal image and therefore result in a greater vulnerability of people to light. Other factors influencing the tolerance limits to glare are individual expectations and preferences,[18] cultural differences,[19] climate,[20] age[17] and time of day.[21] Also, the amount of light reaching the eye was associated with personal variability in the reported level of visual discomfort by Smolders *et al.*,[22] while Boyce *et al.*[23] analyzed the interactions between visual sensation, duration of exposure, user control, surface reflectance and task characteristics. A previous study conducted by the authors showed that self-perceived tolerance to glare was associated with glare sensation ratings.[24] Thus, our second hypothesis is that people who consider themselves glare-sensitive will be more distracted by a glare source.

2. Theoretical framework

Glare is caused by high luminances or by high luminance contrasts within the visual field.[25] The two forms of glare commonly experienced by people are disability glare and discomfort glare. Disability glare is the effect associated with a reduction in visual performance due to the masking effect caused by light scattered in the ocular media which produces a veiling luminance over the field of view, reducing the contrast and hence the visibility of the object.[26] Discomfort glare refers to the sensation of annoyance or pain caused by high luminances in the field of view. Boyce[27] states that '*these two forms of glare, disability glare and discomfort glare, are simply two different outcomes of the same stimulus pattern, namely a wide variation of luminance across the visual field*'. Despite the accepted theoretical separation between both forms of glare, the effect associated to the reduction of visual performance might be coupled with discomfort sensations whereas the discomfort sensation perceived may be coupled with a possible reduction of visual performance.[27] Four factors are known to participate in the perception of discomfort glare: luminance of the glare source, size of the glare source, position of the source in the field of view and luminance of the background.[25] Those factors define many empirical systems to predict discomfort glare from artificial and natural sources. The daylight glare index (DGI)[28] was developed from the Cornell formula to predict glare from large sources and diffuse sky and, according to Tuaycharoen and Tregenza,[29] it is the most cited window glare formula. It is widely used by researchers and practitioners despite its known limitations: DGI is not reliable when direct light or specular reflections are present in the field of view. Research has tried to overcome its shortcomings by proposing some other indices such as predicted glare sensation vote (PGSV)[30] or DGI_n.[31] More recently, daylight glare probability (DGP) has been developed.[32] Because large area glare sources themselves have an impact on visual adaptation, DGP assumes that the adaptation level is not independent of the source and therefore uses the vertical illuminance at the eye as a measure for the adaptation level, as it was found to be a much more reliable estimator. This index performs better than other existing metrics in very bright scenes and in the presence of direct sunlight[33] making it the most appropriate metric for our experimental setting.

Discomfort glare might have distracting effects. An early study by Hopkinson and Longmore[34] was concerned with human phototropism, a tendency to turn towards the light. Their experimental setup used general artificial lighting to enable a uniform visual field and lamps acting as sources of distraction within the field of view. They registered the participants' ocular movements while performing a visual task and found different ocular behaviour as a function of the size and intensity of the sources. The task of this early experiment was not a cognitively demanding one, and could not be extended to workplaces lit with natural sources.

The relationship between glare and distraction was explored by Lynes.[35] In his paper, he argued that distraction was likely to be a function of the threshold of detectability of the potential sources of distraction and developed a prediction formula based on Piper's or Ricco's laws (depending on the size of the source) acknowledging the limitations of his proposal for large area sources and inviting further research. More recently, Raynham *et al.*[36] proposed a study in which observers were presented with a relatively easy task in terms of size and contrast, carried out in a 'neutral environment' and then in the presence of discomfort glare. They proposed the change in the time taken to perform the task as a metric in assessing the significance of the glare stimulus as an attentional distracter. Similarly, in our experiment, participants performed a divided attention Stroop task[37] while performing a working memory span task. This task design includes the essential features of office work with computers: HIgh working memory demands and divided attention. Their performance was compared between a neutral environment (daylit scenario) and a glare demanding environment (sunlit scenario).

3. Material and methods

3.1. Participants

The study was performed among staff members of the Human and Built Environment Laboratory. We defined a set of requirements to be eligible for our study: All of our participants were younger than 40 years and had normal colour vision (tested with the Ishihara colour plates). None of them was under medication of any kind nor pregnant. Although our participants were PhD students and early career researchers, they were naive in the field of lighting. In order to participate, the selected volunteers were required to sign an informed consent form. A sample of 7 men and 25 women ($n = 32$) ranging from 22 to 38 years of age ($M = 30.63$ years; $SD = 4.07$ years) participated in this experiment. As part of a basic demographic data questionnaire, we asked to our participants if they considered themselves as glare sensitives (Yes/No) and divided the sample into two groups: self-defined glare-sensitives (53.1%) and glare-insensitives (46.9%).

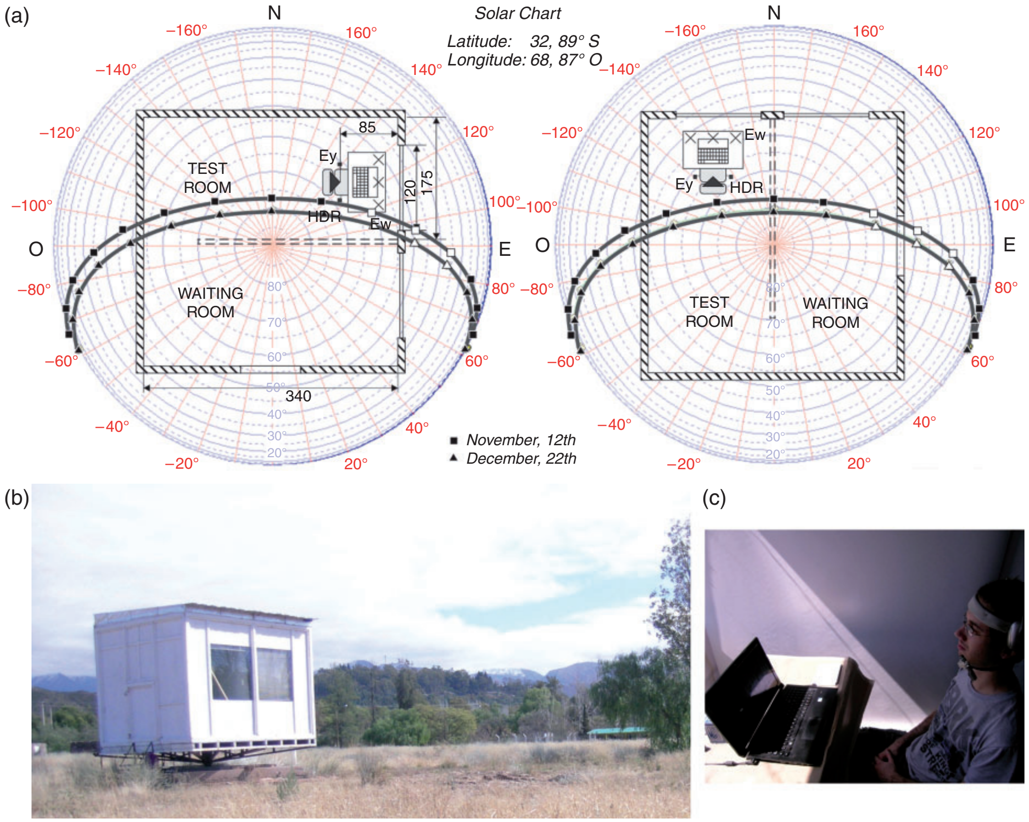

Figure 1 (a) Experimental Light Laboratory plan (dimensions are in cm) and sun position during this research. (b) Exterior of the Experimental Lighting Laboratory. **(c)** Participant at the workstation in the test room

3.2. Setting

The experiment was carried out in the experimental lighting laboratory (Figure 1) at CCT-Mendoza, Argentina (latitude 32°53′S; longitude 68° 52′ W). The room's orientation can be changed by rotating its structure around a central axis under its floor which allows a wide range of different sun altitudes and azimuths to be studied. We defined two treatments: an East-oriented scenario with direct sunlight on the work plane (potentially more glare inducing) and a North-oriented one with diffuse daylight on the work plane (potentially less glare inducing). Although no solar shading devices were attached to the window and the experiment was carried out on clear sky days, the sun was not visible through the window in either of the experimental treatments. The experimental orientations coincided with the cardinal directions East and North (+/− a few degrees correction due to the hourly and daily change in sun altitude and azimuth during the research, to avoid a direct view of the sun in the East condition and to keep constant the pattern of light and shadows inside the chamber). This choice made it easy to achieve the same position of the experimental chamber. The laboratory has two sections with white walls (reflectance $r = 0.91$), a black floor ($r = 0.07$) and a black ceiling ($r = 0.06$). Both sections have identical geometrical features (1.75 m wide, 3.4 m deep, 2.7 m high): The first section was occupied by the experimenters (waiting room), and the other (test room) was equipped with one workstation (a desk, an office chair and a computer) in which the participants performed the required tasks (Figure 1) with a Lenovo B570 notebook (keyboard reflectance = 0.327). Its 15.6″ reflective display with LED backlight has an average brightness of 188 cd/m^2, which is sufficient for indoor use but might confront the user with distracting reflections during outdoor use. Its black value amounts to 0.96 cd/m^2, which leads to a contrast of 209:1. We chose a portable PC because these devices are increasingly replacing the traditional desktop PC. In order to achieve a friendlier environment, we used actual office furniture and some decorative elements outside the visual field of our participants (a picture on an adjacent wall and an interior plant). The desk surface was placed 0.74 m from the floor and had a matte finish. The workstation was next to the window and the participants were seated 0.85 m away from the window, facing it. The only light source is the window (sill height = 0.8 m), a 1.2-m wide and 1.14 m high glass area with an apparent size of 1.89 steradians. Its arrangement was typical for today's design of windows in office buildings. The window was a 4-mm single-glazed clear glass with visible transmittance (VT) = 89%. A low-density built area and scarce vegetation surrounding the structure allowed no obstructions in the window and full access to sunlight.

3.3. Instruments and procedure

The Stroop task presents stimuli to participants in which the relationship between meaning and colour is manipulated so that it is congruent (e.g. the word RED presented in colour red) or incongruent (e.g. the word BLUE presented in colour green), resulting in a delay in the colour processing of the word, increasing reaction time and promoting errors. This semantic interference is called the Stroop effect and its magnitude is an indicator of selective attention by requiring participants to respond selectively to a particular type of goal-oriented information while ignoring distraction. The robustness of the test has earned its name as the 'gold standard' of attentional measures.[37] This primary task was presented on the VDT through PsychoPy open source software. Stimuli (RED, GREEN, BLUE) were presented in the centre of the VDT, in Arial 16-point font colours (red, green and blue) resulting in apparent size of 0.00115 sr. The amounts of congruent and incongruent stimuli were balanced and text/colour combinations were randomly presented. Our participants were instructed to report the 'ink' colour in which the stimuli were displayed. The response of the participants was recorded using their right hand (index, middle and ring fingers) and the computer cursor keys (left, down and right keys). The training consisted of four blocks of 12 repetitions, while the experimental session consisted of eight blocks of 12 repetitions.

The secondary task loaded the volunteers working memory. First, participants read from a card situated to the left of the computer keyboard. This memory set consisted of three words (red, green, blue) printed in black Arial 16-point font randomly arranged. The volunteers were instructed to remember the order of the three words while performing the Stroop task for later recall. Once the primary task was finished, the participants had to choose another card to the right of the computer keyboard. Each card had a printed number, from one to eight, presented in black 24-point Arial font. If the number was even, they had to recall the memory set in the same order it was presented at the beginning of the experiment. If it was odd, the volunteers had to recall the memory set in reverse order.

We monitored illuminance with a LMT Pocket Lux 2 light meter at the beginning and at the end of each trial. In the test room, we measured the horizontal illuminance on the workstation (E_d) from three measuring points. This allowed us to calculate the mean illuminance on the desk and the illuminance uniformity

$$E_{dmin}/\ E_{dmax} > 0.5 < 0.7 \qquad (1)$$

where E_{dmin} is the minimum desk illuminance and E_{dmax} is the maximum desk illuminance.

We generated luminance maps from high dynamic range images (HDRI).[38,39] A series of low dynamic range images (LDRI) were taken with a Nikon Coolpix 5400 camera with a Nikon FC-E9 fish eye lens mounted on a tripod together with a vertical illuminance sensor measuring the illuminance at the eye (E_y). Vertical illuminance at the eye shows a reasonable correlation with subjective glare perception[32] and can be used as a measure for the adaptation level, achieving higher correlation than background luminance for the adaptation term in the general glare formula. The workstation geometry of notebook workstations differs from traditional PC workstations. We considered the fact that the direction of gaze is slightly directed downwards when obtaining the HDR images: Each image was taken from an approximate position of the participants' eyes, pointing to the centre of the VDT. The HDR images were built from the LDRI using Photosphere software. As every pixel contained within the HDRI corresponds to a photometric value of luminance, this technique replaces point measurements taken with a luminance meter. However, we used a Minolta LS100 luminance meter to obtain control luminances to calibrate the scenes. We visualized the HDRI with the *ximage* program from Radiance in order to evaluate the task and window mean luminances. Finally, we processed the HDRI with Evalglare.[40]

This program has three different glare source detection algorithms implemented. We used the 'task luminance' method as threshold for glare source detection. It calculates the average luminance of a given zone (task area) and counts every section as a glare source that is x-times higher than the average luminance of this zone. In the case of VDT tasks, a circular zone with a specific opening angle was used as a target task-zone. The task zone was chosen so that it covers most of the computer screen and parts of the desk, while the window is not a part of the zone. Evalglare also calculates the average luminance, the solid angle and the position within the picture for each glare source. We introduced our E_y measurements as the adaptation term of the DGP formula by means of Evalglare -i option. Evalglare processes many existing glare indexes, among them DGP, so we calculated DGP for each scene. Temperature and humidity were monitored throughout the experiment, at the beginning and the end of each trial with an LMT 8000 environmental measurement device.

The assessment method chosen for discomfort glare was semantic differential scaling, in which glare sensation is a function of the time the participant could stand the sensation of discomfort. This method has been widely used since the introduction of Hopkinson's Scale.[41] We used glare sensation vote (GSV), as it was used in the experiment conducted by Wienold and Christoffersen.[32] We instructed our participants to associate the magnitude of glare on this four-point scale with pre-defined glare criteria: Imperceptible Glare (IMG), Noticeable Glare (NG), Disturbing Glare (DG), Intolerable Glare (IG). The ratings DG and IG indicate the participant is disturbed by the glare source. A printed sheet of paper that included a definition for each point of the glare scale was available for the participants during the experiment. The glare categories were connected to the approximate period of time that a given degree of glare would be tolerated.[42]

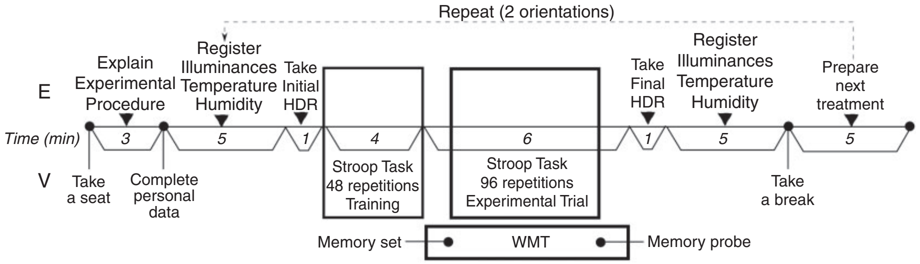

Figure 2 Experimental flow

Data collection lasted 40 mornings (from 8:00 a.m. to 10:00 a.m., solar time) with clear sky, from November 12th to December 22nd, 2012. Overall, each volunteer spent about 50 minutes inside the experimental chamber performing the required tasks. They were scheduled at 8:00 a.m. or 9:00 a.m. to participate in the experiment. We balanced the scenario presentation order to avoid order effects.

Figure 2 shows the sequence of activities performed during the experiment, and the approximate time each stage demanded. In its upper part the graphic shows the actions done by the experimenters (E) and in the lower part the tasks required by the volunteers (V). Once inside the laboratory, each volunteer was asked to take a seat, then the experimenter explained the procedure and asked him to fill in a form with basic demographic data. Meanwhile, the experimenter registered the initial environmental and photometric data and took the initial HDRI in the test room. Once the experimenter left the test room, the Stroop task training began followed by the first experimental trial, where the Stroop task was performed simultaneously with the working memory task (WMT). Once both tasks were completed, the experimenter recorded the final environmental conditions and took the final HDRI for the treatment. Finally, the experimenter prepared the following scenario, giving the volunteer a 5-minute break.

4. Results

We performed an exploratory analysis of our data. The statistical inspection by means of the Shapiro-Wilk normality test revealed that most of our variables were not normally distributed around the mean ($p < 0.05$), thus violating one of the assumptions for a parametric test. However, some variables showed a normal distribution ($p > 0.05$): Temperature and humidity were normally distributed in both scenarios; in the daylit treatment, DGP and the Stroop effect DGP were normally distributed while in the sunlit treatment the reaction times of our participants were also normally distributed (incongruent RT, congruent RT and Stroop effect RT). Furthermore, the non-parametric Levene's test of homogeneity of variance showed statistically significant differences ($p < 0.05$) between variances of many variables. Hence, we adopted non-parametric tests, which rely on less stringent assumptions than their parametric counterparts.

Table 1 shows the distribution of the demographic variables in glare sensitives ($n = 17$) and glare insensitives ($n = 15$). Gender distribution was similar between glare-sensitive and glare-insensitive groups. Overall, women outnumbered men; however, no gender differences in GSV have been found in previous studies.[43] Both groups showed different visual correction. About half of our glare-sensitive participants

Table 1 Distribution of basic individual variables within groups for gender; visual correction; eye colour and handedness

	Gender (%)		Visual correction (%)		Eye colour (%)		Handedness (%)	
	Female	Male	Yes	No	Dark	Light	Left	Right
Glare-Sensitives	76.5	23.5	47.1	52.9	52.9	47.1	23.5	76.5
Glare-Insensitives	80.0	20.0	20.0	80.0	86.7	13.3	93.3	6.7

Table 2 Environmental factors descriptive statistics

	Daylit		Sunlit	
	Mean	SD	Mean	SD
Temperature (C)	29.8	2.3	30.2	2.0
Humidity (%)	39.2	4.6	40.0	5.5
Initial E_d (lux)	1882	413	47,091	8789
Final E_d (lux)	1816	479	46,590	6217
Mean E_d (lux)	1849	364	46,842	6714
Initial E_y (lux)	2470	626	18,683	10,926
Final E_y (lux)	2794	589	20,521	10,588
Mean E_y (lux)	2632	560	19,602	9900
Uniformity E_d ratio	0.4	0.1	0.1	0.2

(47.1%) had corrected vision (contact lenses or eyeglasses) while 20.0% of glare-insensitive persons had corrected to normal vision. Overall, 15.6% of our participants were left-handed. Hand preference was not evenly distributed between groups. Because our participants used the computer cursor keys in the Stroop task, all of them responded to the stimuli with their right hand. We performed a Mann-Whitney test and found no statistically significant differences in Stroop task performance between left-handed and right-handed participants ($p > 0.05$ for all variables).

4.1. Environmental factors

We measured E_d in a three-point row on the desk, at the beginning and the end of each trial (Table 2). We averaged the initial and final desk illuminance and we named the new variable mean E_d. Daylit mean E_d was 1849 lux (SD = 364 lux) and sunlit mean E_d was 46842 lux (SD = 6714 lux). The Wilcoxon matched-pairs test performed resulted in a statistically significant difference ($Z = -4.937$; $p < .001$) in E_d. Also, based on equation (1), daylit and sunlit scenarios were defined as non-uniform in terms of the E_d spatial distribution.

Desk horizontal illuminances were much greater than the usual VDT recommendations: An international comparison identified large variations in VDT work recommended E_h values, with 500 lux as the most frequent one.[44] Nabil and Mardaljevic[45] proposed the useful daylight illuminance (UDI), a dynamic daylight performance measure based on work plane illuminance. They suggested a range based on reported occupant preferences in daylit offices, with a lower threshold of 100 lux and an upper threshold of 2000 lux. When the UDI is exceeded (>2000 lux), the appearance of glare is likely. Based on these criteria, our daylit treatment was below the glare threshold while the sunlit scenario was above it. Slater and Boyce[46] focused on the uniformity of the desk and suggested a minimum to maximum illuminance ratio between 0.7 and 0.5. Some authors have argued that these criteria may not be appropriate for interiors lit by side windows, where the tolerance to illuminance non-uniformity may be greater than in the case of electric lighting.

We also measured E_y at the beginning and the end of each trial (Table 2). We averaged the initial and final desk illuminance and we named the new variable Mean E_y. Daylit mean E_y was 2632 lux (SD = 560 lux) and sunlit mean E_y was 19,602 lux (SD = 9900 lux).

Table 3 Luminance and luminance ratio descriptive statistics

	Diffuse daylight		Direct sunlight	
Mean	SD	Mean	SD	
Desk luminance (cd/m^2)	300	85.6	8791	660
Window luminance (cd/m^2)	3174	978	8693	4366
Task luminance (cd/m^2)	263	125	4771	3249
Window/task luminance ratio	14.1	7.6	7.0	20.6

The Wilcoxon test performed resulted in a statistically significant difference ($Z = -4.937$, $p < 0.001$) in E_y between sunlit and daylit treatments.

We generated luminance maps from high dynamic range imaging for each participant in both scenarios. Using the Radiance *ximage* program we determined window and task mean luminances in the visual field of our volunteers (Table 3). Sunlit scenes were brighter than the daylit ones, with higher window and task mean luminances. Because the task area is not only the VDT, but a portion of the keyboard and the desk itself, the task luminance as it was defined in this experiment was not affected by the luminance of the screen alone. Daylit scenes in our experiment had higher luminance contrasts between the source and the task. DGP for the diffuse daylight scenario was 0.32 (SD = 0.003) while DGP for the direct sunlight scenario was 0.96 (SD = 0.094). Based on the proposed DGP–GSV correlation,[32] DGP qualified the level of glare for the direct sunlight scenario as 'Intolerable' and for the diffuse daylight as 'Noticeable'. Our Wilcoxon matched-pairs test results showed statistically significant different mean DGPs between the scenarios ($Z(31) = -4.937$, $p < 0.001$).

Both scenarios had similar mean temperature and humidity. We measured 29.8°C (SD = 2.3) and 39.2% (SD = 4.6) humidity in the daylit scenario and 30.2°C (SD = 2.0) with 40.0% (SD = 5.5) humidity in the sunlit scenario. As these variables showed a normal distribution, we performed a *t*-test, which showed no statistically significant differences between daylit and sunlit scenarios in temperature ($t(31) = -1.264$, $p = 0.216$, CI[−0.934, 0.219]) and in humidity ($t(31) = -1.479$, $p = 0.149$, CI[−1.914, −1.479]). We estimated a metabolic rate of 1 met (sitting – quiet) and a worn thermal insulation of 0.5 clo (typical summer clothing). For those thermal variables, Fanger's method[47] predicted a slightly warm sensation (predicted mean vote = 1.37; predicted percentage of dissatisfied = 44%) in the daylit scenario and also a slightly warm sensation (predicted mean vote = 1.49; predicted percentage of dissatisfied = 50%) in the sunlit scenario.

4.2. Individual differences in glare

Figure 3 shows the GSV results. Glare in the diffuse daylight scenario was mostly rated as 'Imperceptible', with a 47% of glare sensitives and a 53% of glare insensitive participants unable to perceive any glare source. In contrast, most of our participants considered that glare in the direct sunlight scenario was 'Disturbing' (59% of glare sensitive participants and 47% of glare insensitive participants). A visual inspection of Figure 3 suggests that there were no differences in rating scores between glare sensitives and glare insensitives for our experimental conditions. In order to confirm this appreciation, we performed a Mann-Whitney *U* test, which showed no statistically significant differences in GSV between glare sensitives and glare insensitives (daylit GSV: $Z = -0.350$, $p = 0.727$; sunlit GSV: $Z = -0.687$, $p = 0.492$).

4.3. Individual differences in task performance

In performance analysis, a primary division of the dependent variable is often split

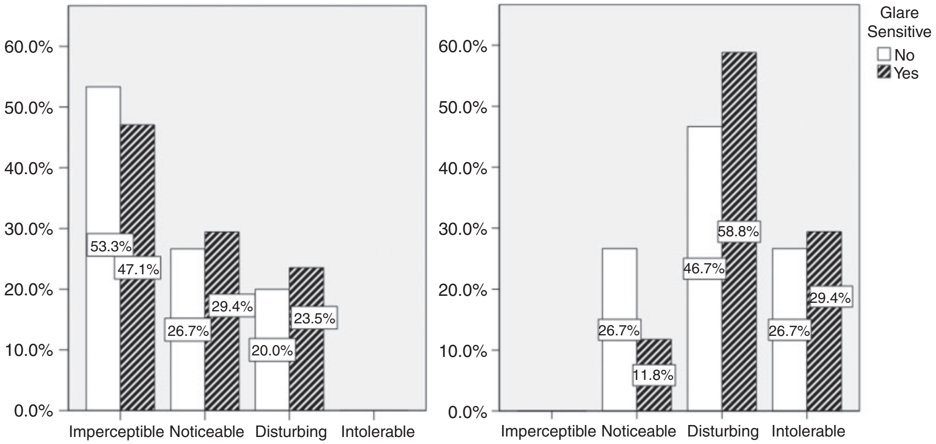

Figure 3 Glare sensation vote (GSV) responses. Left: Daylit scenario. Right: Sunlit scenario

Table 4 Stroop task descriptive statistics

	Diffuse daylight		Direct sunlight	
	Mean	SD	Mean	SD
Glare Sensitives (n = 17)				
Incongruent RT (s)	1.040	0.336	1.189	0.358
Congruent RT (s)	0.951	0.356	1.070	0.263
Stroop Effect RT	0.088	0.139	0.119	0.175
Incongruent ER	2.4%	2.9	4.5%	8.1
Congruent ER	1.1%	1.9	1.7%	3.9
Stroop ER	1.4%	2.9	2.8%	6.6
Glare Insensitives (n = 15)				
Incongruent RT (s)	0.857	0.151	0.905	0.147
Congruent RT (s)	0.786	0.135	0.830	0.142
Stroop Effect RT	0.071	0.064	0.075	0.139
Incongruent ER	1.1%	1.3	1.9%	1.8
Congruent ER	0.9%	1.5	1.3%	1.8
Stroop ER	0.1%	1.8	0.5%	1.6

RT: Reaction Time; ER: Errors

between the speed of a response and the accuracy of that response. Table 4 shows the Stroop task results (reaction times in seconds and percent error rates) for glare-sensitive and glare-insensitive participants. At a descriptive level of analysis, reaction times in the Stroop task were consistent with previous studies[37,48] showing longer reaction times when stimuli were incongruent in both scenarios. Glare-insensitives performed better than glare sensitives in both scenarios with faster response times and lower error rates. There was higher Stroop interference in the sunlit scenario but the difference between daylit and sunlit was higher for glare-sensitive individuals in terms of reaction times and errors

Glare-insensitive participants performed equally on the secondary task (73.3% of task success rate) in the presence of direct sunlight and higher adaptation luminances in relation to a friendlier daylit visual environment. However, the success rate of glare sensitive individuals was affected by the different glaring scenarios. We observed a drop in performance between the diffuse daylight scenario (94.1%) and the direct sun light scenario (70.6%).

4.4. Repeated-measures analysis of variance

In order to verify the statistical significance of our results we performed a repeated-measure ANOVA with DGP as the within-subject independent variable and glare sensitivity as the between-subject variable. The dependant variables were GSV, Stroop interference (reaction times and error rates), Stroop task performance (congruent and

Table 5 Analysis of variance within-subjects effects

	Type III SS	Df	MS	F	Sig.	Eta^2
DGP						
GSV	30.025	1	30.025	92.616	0.000	0.755
Stroop RT	0.005	1	0.005	0.271	0.606	0.009
Incongruent RT	0.155	1	0.155	4.938	0.034	0.136
Congruent RT	0.106	1	0.106	3.296	0.079	0.097
Stroop ER	13.079	1	13.079	0.863	0.360	0.022
Incongruent ER	32.564	1	32.564	1.820	0.187	0.052
Congruent ER	4.368	1	4.368	1.042	0.315	0.000
WM Task	0.221	1	0.221	1.461	0.236	0.044
DGP * Sensitive						
GSV	0.025	1	0.025	0.076	0.785	<0.001
Stroop RT	0.003	1	0.003	0.165	0.688	0.006
Incongruent RT	0.040	1	0.040	1.279	0.267	0.035
Congruent RT	0.022	1	0.022	0.674	0.418	0.020
Stroop ER	4.079	1	4.079	0.269	0.608	0.000
Incongruent ER	6.314	1	6.314	0.353	0.557	0.017
Congruent ER	0.243	1	0.243	0.058	0.811	0.002
WM Task	0.221	1	0.221	1.461	0.236	0.044

incongruent reaction times and error rates) and working memory task success rate.

Table 5 shows the results of the within-subjects effects. The different glare demands imposed by each scenario had a significant effect on GSV ($F(1,30)=92.616$, $p<0.001$, $MSE=0.324$, $Eta^2=0.755$) and on reaction times of incongruent stimuli ($F(1,30)=4.938$, $p=0.034$, $MSE=0.031$, $Eta^2=0.136$). We found no differences in secondary task success rate between scenarios. Finally, we found no interaction effects between DGP and glare sensitivity.

Table 5 also shows ANOVA effects sizes. Eta^2 is a measure of effect size for use in ANOVA. Eta is often interpreted in terms of the percentage of variance accounted for by a variable or model. Ferguson[49] defined an Eta^2 of 0.04 as the recommended minimum practically significant effect size, 0.25 as a moderate effect size and 0.64 as a strong effect size. Effect sizes are resistant to the influence of sample size, and thus provide a truer measure of the magnitude of effect between variables.[49] It is a scale-free measure that reflects the practical meaningfulness of the difference or the relationship among variables.[50]

Table 6 shows the results of the between-subject effects. Individual differences on glare sensitivity had a significant effect on reaction times of incongruent stimuli ($F(1,30)=7.349$, $p=0.011$, $MSE=0.118$, $Eta^2=0.197$) and on reaction times of congruent stimuli ($F(1,30)=7.380$, $p=0.012$, $MSE=0.090$, $Eta^2=0.194$). No statistically significant effects of glare sensitivity were found on either the Stroop interference or error rates. We found no success rate differences in the secondary working memory task. Glare sensation votes were not affected by glare sensitivity in our experimental conditions.

5. Discussion

We planned an experiment testing the hypothesis that a large area glare source will become an environmental distractor affecting attention; and, secondly, that attention for glare-sensitive persons should be more affected by a glare source.

Table 6 Analysis of variance between-subjects effects

Source	*Type III SS*	*Df*	*MS*	*F*	*Sig.*	*Eta*^{2}
Incongruent RT	0.866	1	0.866	7.349	0.011	0.197
Congruent RT	0.653	1	0.653	7.380	0.012	0.194
Stroop RT	0.015	1	0.015	0.769	0.388	0.025
Incongruent ER	0.007	1	0.007	2.798	0.105	0.089
Congruent ER	<0.001	1	<0.001	0.118	0.733	0.003
Stroop ER	0.005	1	0.005	3.359	0.077	0.100
GSV	0.300	1	0.300	0.358	0.554	0.012
WM Task	0.130	1	0.130	0.670	0.420	0.022

By means of Fanger's method[47] we predicted a slightly warm sensation (predicted mean vote = 1.37; predicted percentage of dissatisfied = 44%) in the daylit scenario and also a slightly warm sensation (predicted mean vote = 1.49; predicted percentage of dissatisfied = 50%) in the sunlit scenario. Fanger's method takes a passive, non-adaptive approach irrespective of the exterior temperature that disregards location and habituation to specific climates, so it is possible that our predicted levels of thermal comfort were overestimated.

Thermal stressors adversely affect perceptual, cognitive and psychomotor response capacities in terms of speed and accuracy, with the highest impact on perception, the next highest on psychomotor response and the smallest on cognitive tasks.[51] The experiment's thermal environment was constant between scenarios. Hancock and Vercruysse[52] proposed three thermal performance zones which differentiate the limits of human behavioural efficiency under heat stress: a zone of thermal intolerance, a zone of thermal tolerance limits and a zone of thermal equilibrium. They included a fourth zone labeled inertial interval, in which the core body temperature resists sudden change irrespective of the intensity of the heat stress exposure. These zones are defined by the effective temperature and the exposure time. Considering the temperatures measured in the experimental chamber (Table 2) and the length of the experiment (around 45 minutes), our participants could be situated in the inertial interval, where no detrimental effects of the thermal environment on cognitive and neuromuscular performance are expected.

We found a statistically significant effect of the lighting environment (DGP within-subject variable) on our participant's glare sensation. The size of DGP effect on GSV was eta^2 = 0.755, defined as large according to the benchmarks proposed by Ferguson.[49] As DGP uses vertical eye illuminance as input in the first half of its glare formula, it is capable of predicting discomfort glare in exceedingly bright scenes such as the ones presented in our experiment. By means of computer simulations, Jakubiek and Reinhart[33] compared the results of the normalized scores of various glare metrics (i.e. DGI, UGR, VCP and CGI) and found that when direct sunlight is present in the scene and the visible sky from the window is very bright, DGP performs better than other existing metrics, predicting a much higher likelihood of discomfort glare. They concluded that DGP is the most robust glare metric. In our experiment, we were able to confirm the robustness of GSV with an actual window and user assessments in very bright scenes. Indeed, in our two experimental scenarios, the absolute mean luminance of the source and luminance ratios were greatly above the usual recommendations.[53,25] An overcast sky as seen through an office window can have luminances higher than 10 000 cd/m^2, reaching up to 100,000 cd/m^2 with a clear sky. Therefore, the recommended values appear to be not applicable in real workspaces.[54] The luminance ratios in real-world offices are usually far from the recommended 3:1 and 10:1 ratios, yet users were still satisfied with the lighting conditions in a number of different luminance distributions.[55] Our results agree with the literature, with more than half of our participants considering the daylit treatment as a glare-free scenario.

We classified our participants in relation to their self-perceived tolerance to glare, obtaining two groups; those glare sensitive and those glare insensitive. To the best of our knowledge, the only available questionnaire to asses glare sensitivity was proposed by Gerbaldo *et al.*[56] It was designed to asses light intensity preference in psychiatric patients. Because this questionnaire included some items regarding abnormal light-related behaviour, it failed to diagnose either photophobia or photophilia in healthy control subjects. Given that, we decided to ask our participants directly about their light intensity preference. Some concerns might rise from this methodological choice but self-report assessments are the only way to establish most individual differences. Although self-assessment has shortcomings, it is a practical approach, more direct than behavioural proxies such as sunglass usage. Also, it is non-intrusive in relation to proposed objective glare measurement methods (e.g. measuring the electrical activity associated with facial muscles).[57] Eye colour has been correlated with glare sensitivity.[58] According to Seldin *et al.*,[59] in Argentina, the mean European genetic contribution is 78%, while the Amerindian contribution is 19.4% and the African contribution is 2.5%. Massive European migrations in the late 19th century and in the first half of the 20th century are the main causes of our ethnic distribution. Considering this, it is not surprising that more than half of glare-sensitive persons had dark eyes since dark coloured irises are more common than green or blue coloured ones. However, a higher proportion of light-eyed volunteers were found in the glare-sensitive group (47.1%) than were found in the glare-insensitive group (13.3%).

In a previous study,[24] we found that glare-sensitive people consistently reported higher sensation of discomfort glare in the presence of a large area glare source situated in central vision when compared to a group of glare-insensitive persons. We also found that source luminance and its size had similar main and interaction effects on glare sensation for both groups. However, in this study, we found no statistically significant effects of glare sensitivity in glare sensation pointing to the existence of a glare sensitivity threshold. Considering window size and its position in the visual field of the volunteers, and the absence of solar control devices associated with the window, the eye adapted to luminances within an order of magnitude to the window luminance causing glare effects that should be attributed to the absolute luminance values, not the relative ones. Results from a recent study[60] using existing glare equations and HDRI along with radiance simulations proposed a threshold method for absolute and relative glare determination. They identified three specific zones for absolute glare, relative glare and no glare at all. The absolute glare factor zone starts from luminance values higher than 5500 cd/m^2. The sunlit scenario falls into this category, while the daylit scenario is slightly above the no-glare zone. Under high luminances and uncontrolled sunlight, individual differences in glare sensation disappear.

Performance on many neuropsychological tests, including the Stroop test, is influenced by demographic variables such as age, sex[61] and handedness.[62] The extensive literature regarding gender differences in the Stroop test[63] has been inconclusive. For every study that reported a significant gender difference, there seems to be one that claims the opposite. Even so, there is general consensus that females tend to have shorter latency for colour-naming.[64] In our sample, the results of the Mann-Whitney test showed no statistically significant differences between men and women in colour-naming latency in the daylit scenario (incongruent RT: $Z = -1.254$, $p = 0.210$; congruent RT: $Z = -1.208$, $p = 0.227$; Stroop RT: $Z = -0.251$, $p = 0.802$) or in the sunlit scenario (incongruent RT: $Z = -1.687$, $p = 0.092$; congruent RT: $Z = -1.185$, $p = 0.236$; Stroop RT: $Z = -0.524$, $p = 0.600$). We also found that even though all of our participants used their right hand for the Stroop task, the Mann-Whitney test showed no statistically significant effects of handedness in task performance, neither in the daylit scenario (incongruent RT: $Z = -0.389$, $p = 0.697$; congruent RT: $Z = -0.753$, $p = 0.452$; Stroop RT: $Z = -1.064$, $p = 0.287$) nor in the sunlit scenario (incongruent RT: $Z = -0.026$, $p = 0.979$; congruent RT: $Z = -0.078$, $p = 0.938$; Stroop RT: $Z = -0.078$, $p = 0.938$).

The probability of discomfort glare occurrence had a small effect on reaction times for incongruent stimuli ($Eta^2 = 0.136$), which was above the recommended minimum practically significant effect size. In many circumstances, speed is sacrificed for accuracy and vice versa;[65] however, in our experiment we did not find a speed-accuracy tradeoff, so differences in performance would not represent a strategic change but an actual reduction in response capacity. Comparing daylit and sunlit scenarios, reaction times were lower in the former scenario, only for incongruent stimuli. The worse performance could be caused by a veiling effect of high ambient illumination. Considering that the computer used in this experiment has a reflective display with LED backlight, it is possible that in our experimental conditions the surrounding light sources and direct sunlight could have been reflected onto the screen surface. This results in contrast reduction between the target (the exposed text) and its immediate background, which goes below the minimum necessary value or minimum required contrast, also lowering reaction times on both congruent and incongruent trials. However, if longer reaction times in the sunlit scenario could be explained only by a loss of luminance contrast in the VDT task, then light-eyed participants should be more affected than dark-colored ones. Mann-Whitney *U* tests showed no differences in reaction times between light and dark eye coloured participants (daylit scenario congruent stimuli $Z = -0.041$, $p = 0.968$; incongruent stimuli $Z = 0.325$, $p = 0.745$; Stroop RT $Z = -0.122$, $p = 0.903$ and sunlit scenario congruent stimuli $Z = -1.789$, $p = 0.074$; incongruent stimuli $Z = -1.281$, $p = 0.200$). Considering the between-subjects variable, our results showed statistically significant effects of glare sensitivity on congruent and incongruent reaction times in the presence of direct sunlight. The effect size of glare sensitivity on reaction times was small, but practically relevant (incongruent RT $Eta^2 = 0.197$; congruent RT $Eta^2 = 0.194$).

Null-hypothesis significance testing (NHST) has long been regarded as an imperfect tool for examining data.[66] Limitations of NHST include sensitivity to sample size, inability to accept the null hypothesis and the failure of NHST to determine the practical significance of statistical relationships. Effect sizes are important outcomes of empirical studies because they allow researchers to present the magnitude of the reported effects in a standardized metric that allows researchers to communicate the practical consequences of the findings for daily life.[67] Some of our dependant variables showed practical effect sizes; however, statistical significance was not detected. This is the case of DGP on congruent RT ($p = 0.079$; $\mathrm{eta}^2 = 0.097$), and also the case of glare sensitivity on incongruent ER ($p = 0.105$; $\mathrm{eta}^2 = 0.089$) and on

Stroop ER ($p = 0.077$; $\text{eta}^2 = 0.100$), suggesting that we might have underestimated our sample size.

Our results are limited to relatively young visual systems. As older people are more sensitive to glare, it is possible that the differences found could be wider.[68] Sessions ranged from 30 to 45 minutes, which was sufficient in allowing participants time to make judgments after actually working under each lighting scenario, but short enough to minimize radical changes in the lighting conditions due to changing sky or sun angle conditions. Also, the experimental setup is not fully representative of an actual office environment, in favour of more control in the relevant variables.

5. Conclusions

The ability to remain focused on a task is vital for any coherent cognitive function, such as ICT clerical work, especially when there might be potential interference from task-irrelevant distracters such as a glare source. Although it is suggested in the glare literature, the research concerning the effects of lighting on the cognitive components of tasks is scarce and has lacked continuity. We planned an experiment testing the hypothesis that a large area glare source will become an environmental distractor affecting attention, and, secondly, that attention for glare-sensitive persons should be more affected by a glare source. We found performance differences in a cognitive task under two different glare-demanding scenarios. Although performance was affected in terms of reaction times, we did not find any significant change in the magnitude of the Stroop effect, which was the variable selected to measure the effects on divided attention.

This paper also dealt with a topic too often considered as a nuisance variable: how individual differences in aptitudes interact with the varying circumstances found in today's complex technological environments.[69] There are relatively few human factor studies published concerning these issues with the exception for gender and more recently age differences. In this experiment we found some differences in performance between two relatively homogeneous subgroups while working on a VDT under a dual-task paradigm. Our GSV results encourage us to continue our research on glare sensitivity, aiming to find a glare sensitivity threshold by means of a specific psychophysical experiment. Although specialists agree on the factors that cause glare and the basic trends, the analytic methods available do not consider, among other issues, the different tolerance of people to glare.

Published research in our field often relies heavily on analyses that determine whether the observed effect is real or attributable to chance, that is, the statistical significance, without fully considering the strength of the relationship between those variables.[70] We included the effect size analysis in this research to determine the practical significance of our results. The association between DGP and GSV ($\text{Eta}^2 = 0.755$) was above Ferguson's benchmark for a strong effect size. This means that the variations in the glare environment explained 75.5% of the variations in our participant glare ratings. This result demonstrates the robustness of DGP and helps to validate this metric in actual very bright scenarios. Although the observed association between the glare environment and cognitive performance on the one hand and between glare sensitivity with cognitive performance were not so conclusive (i.e. the independent variables were able to explain in the best cases around 20% of the variation in the cognitive task outcomes), these results encourage us to continue in this path. The relation between glare and distraction has been suggested since early stages of glare research[34] but has never been systematically and consistently addressed until now.

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